The AGATA campaign at LNL

Simone Bottoni
Università degli Studi di Milano and INFN

on behalf of the GAMMA collaboration

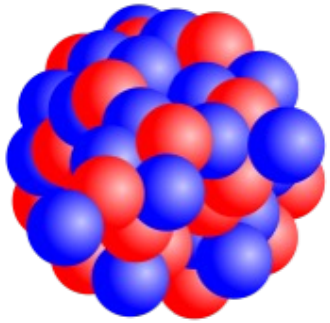
VI Incontro Nazionale
di Fisica Nucleare
Trento, 26-28/02/2024

The nuclear many-body problem

Simone Bottoni

Interacting many-body fermionic systems on a large energy scale

nuclear interaction is little known



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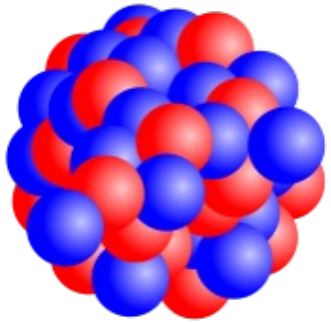

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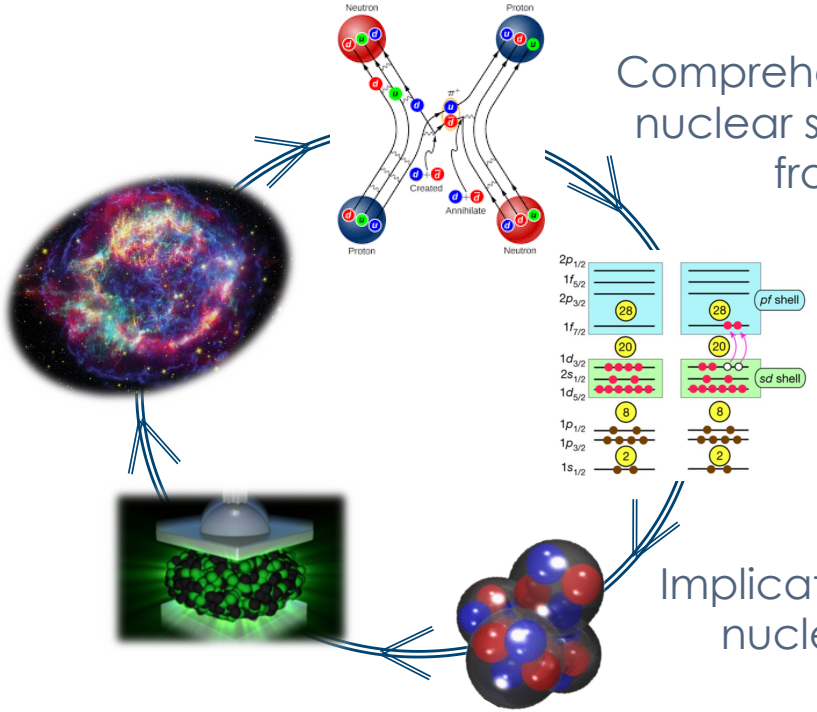
Study of nuclear structure and reactions



Comprehensive understanding of nuclear structure and dynamics from first principles

Nature of the nuclear forces and nuclear interactions

Implications for stellar nucleosynthesis

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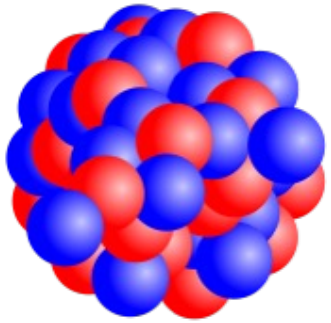
Interacting many-body fermionic systems on a large energy scale



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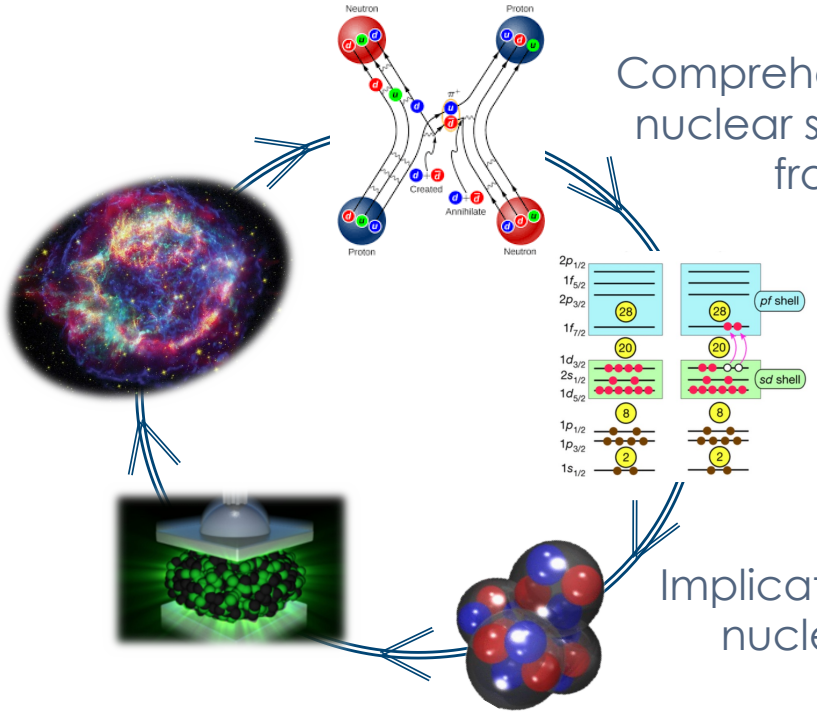


Comprehensive understanding of nuclear structure and dynamics from first principles

Nature of the nuclear forces and nuclear interactions

Implications for stellar nucleosynthesis

Synergy between experiments and theory

Different nuclear models
with different predictive powers

Shell Model calculations
E. Caurier *et al*, Rev. Mod. Phys. **77**, 427 (2005)

Density functional theories
G. Colò, Adv. Phys.-X **5**, 1740061 (2020)

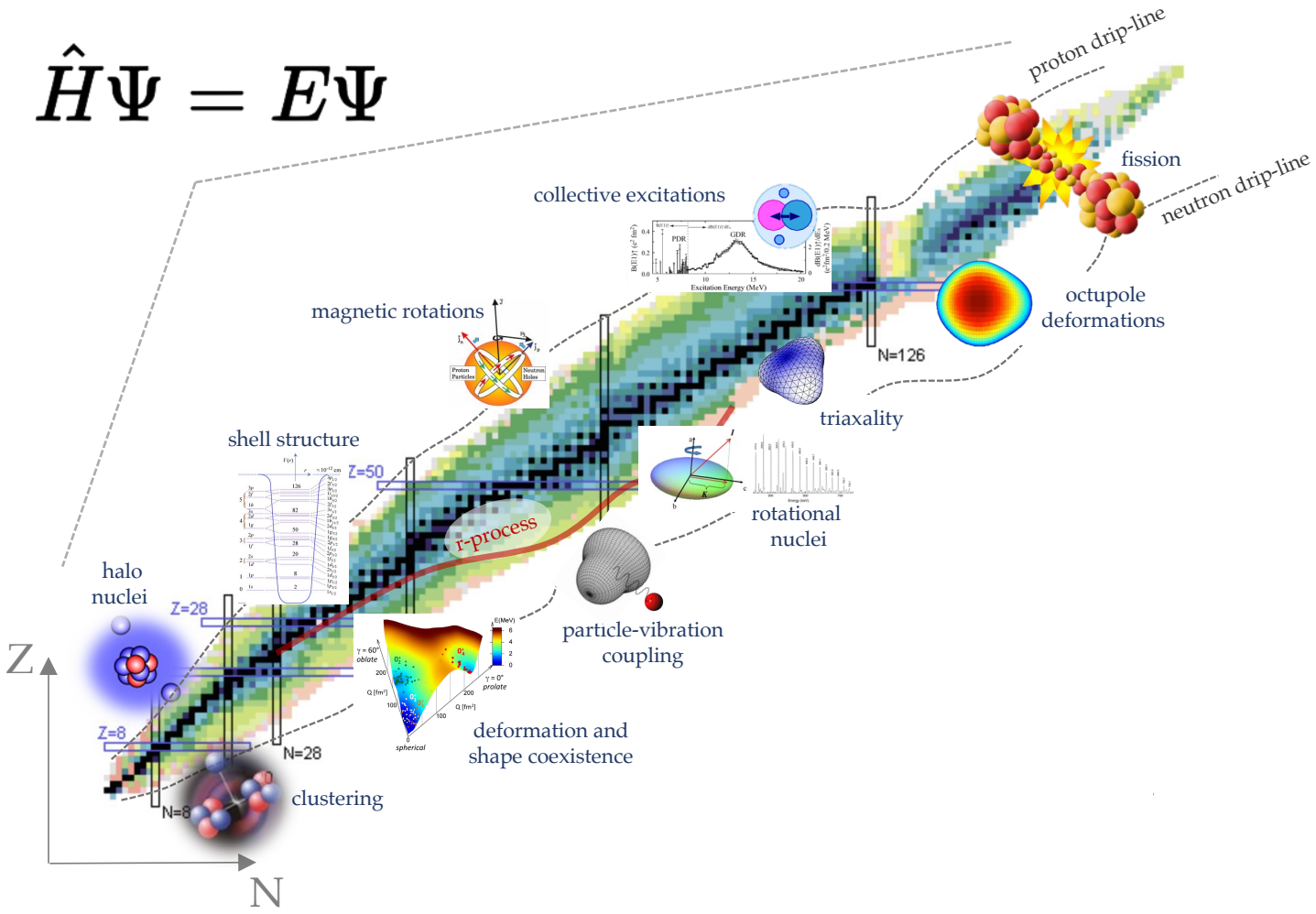
Ab initio methods
V. Somà, Frontiers in Phys. 8, 340 (2020)

The nuclear landscape

Emergent phenomena from the same Hamiltonian

underlying shell structure and nuclear forces

$$\hat{H}\Psi = E\Psi$$



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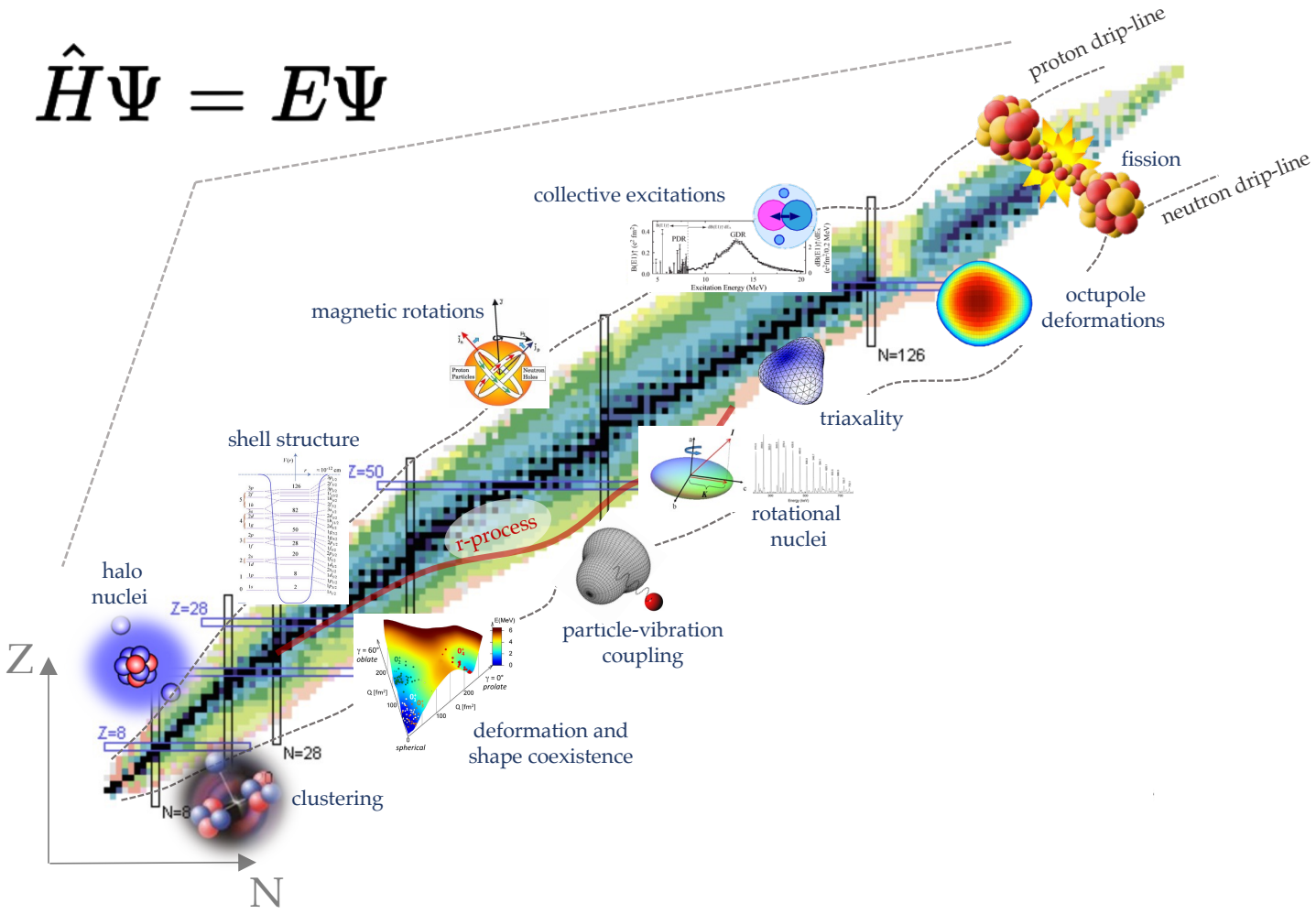

Evolution of nuclear structure

- Energy and angular momentum
- Proton-to-neutron ratio (isospin)
- Nuclear reactions to produce exotic species
- Measurement of different decay modes
- Study of nuclear excitations

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Emergent phenomena from the same Hamiltonian

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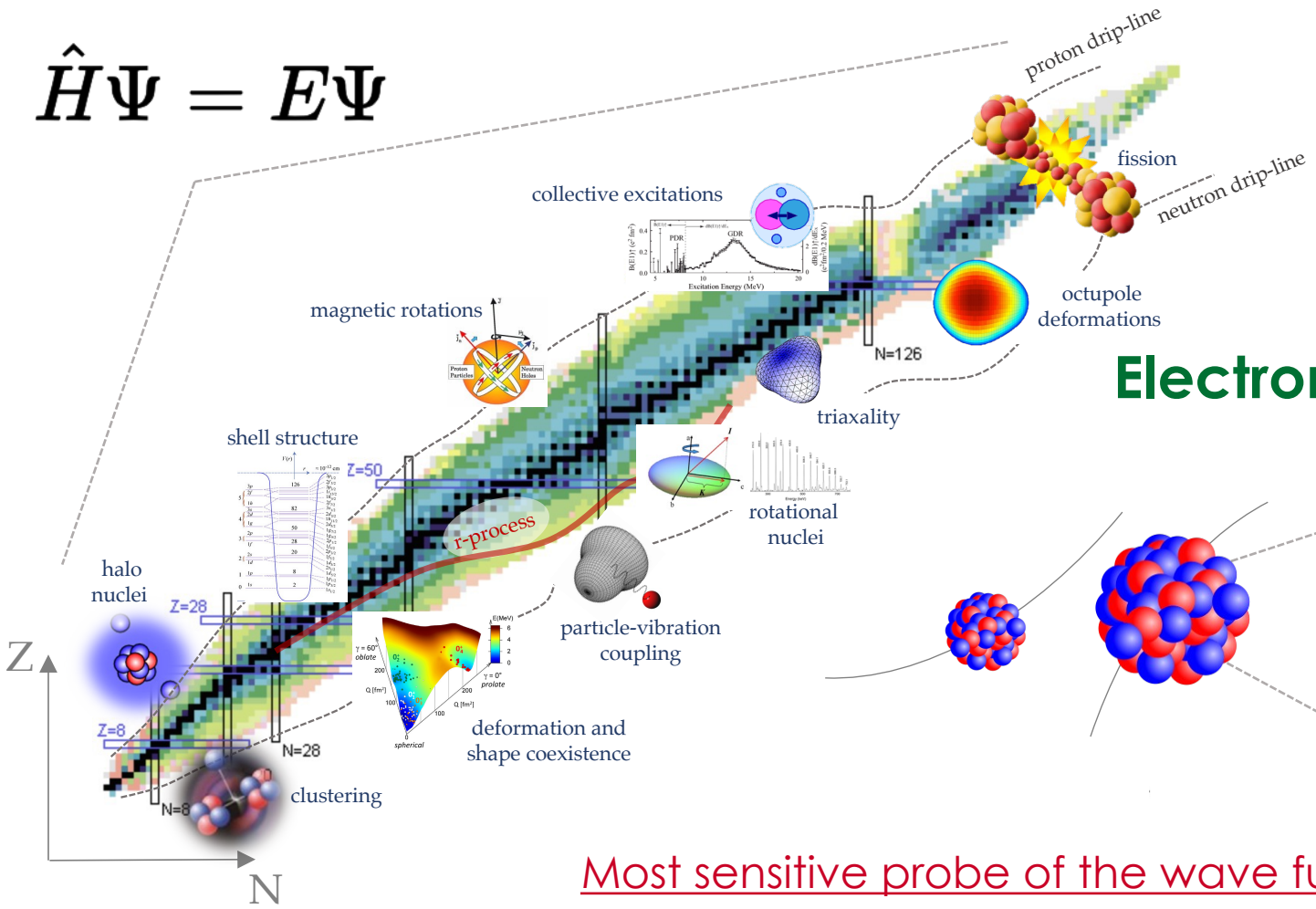

Evolution of nuclear structure

- Energy and angular momentum
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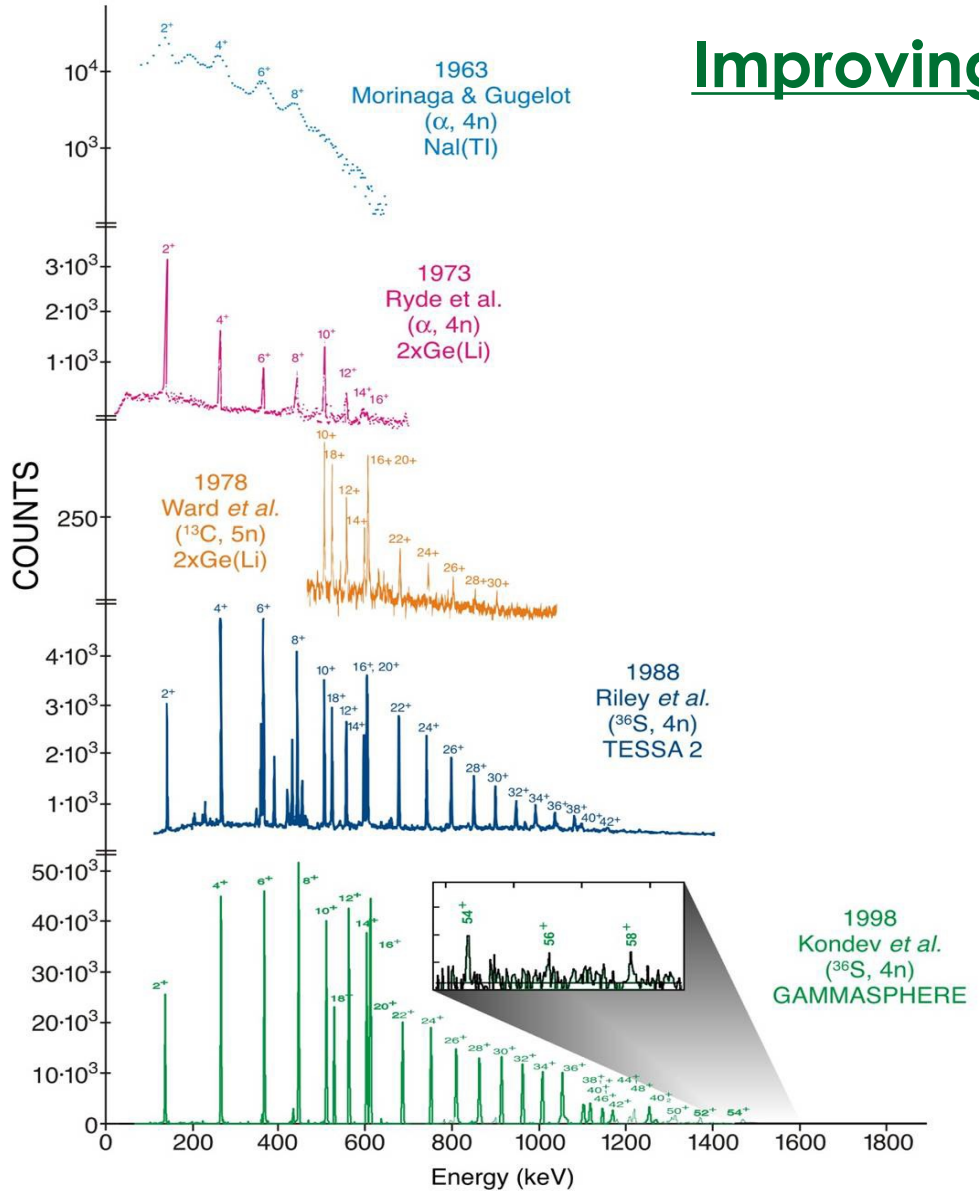
- Study of nuclear excitations

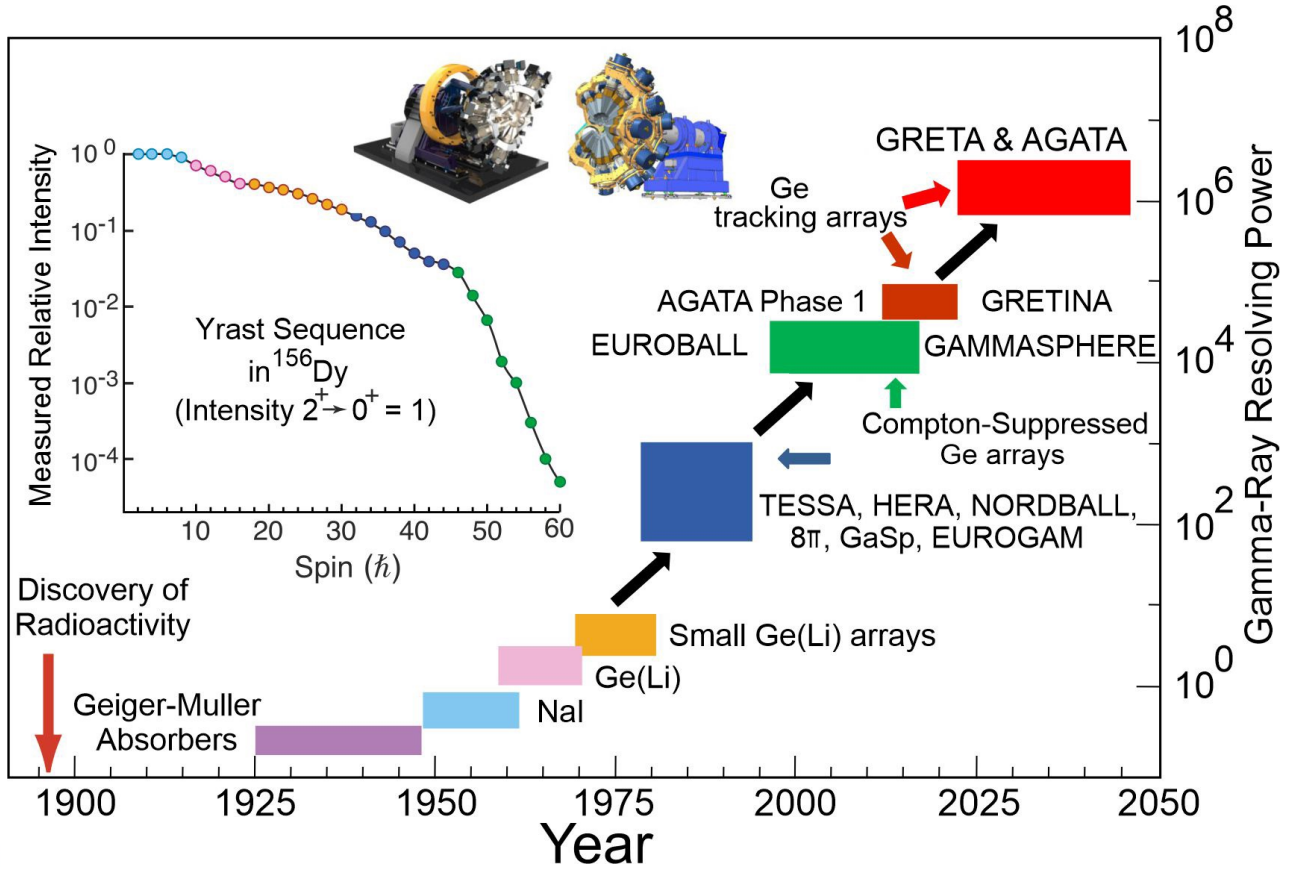
Electromagnetic decay of excited states

Deeper understanding of atomic nuclei

Most sensitive probe of the wave function of excited states

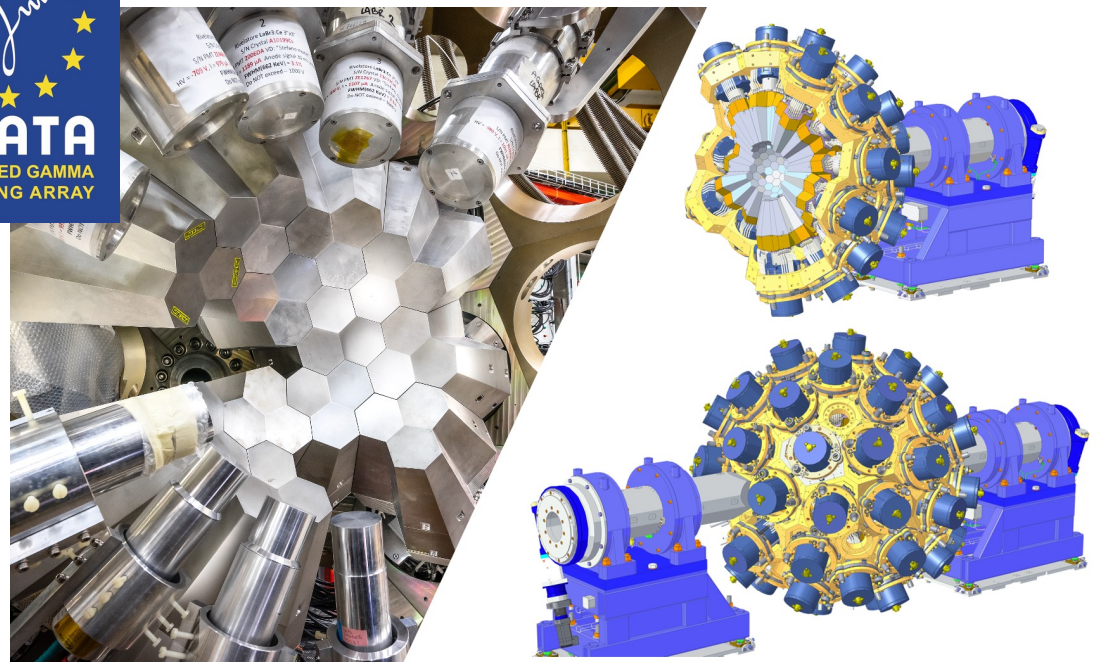
Improving the resolving power over the years





The AGATA design

S. Akkoyun et al., NIMA 668, 26 (2012)



- **Continuous array**
- **180** hexagonal crystals in 60 ATCs
- Solid angle coverage:82 %
- 36-fold segmentation: 6480 segments

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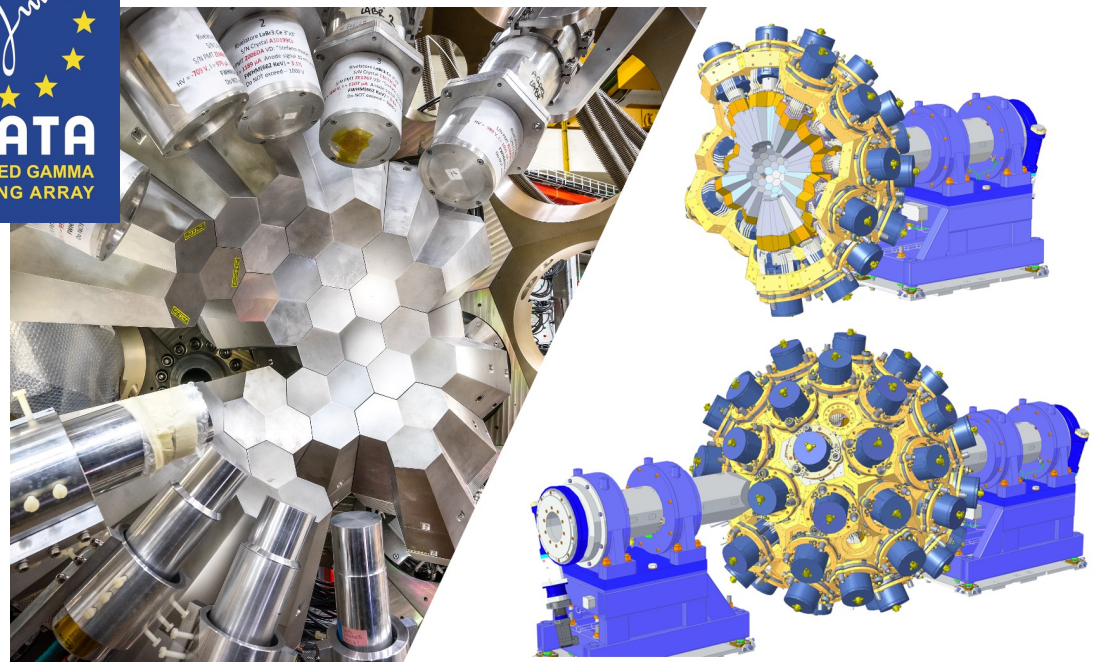

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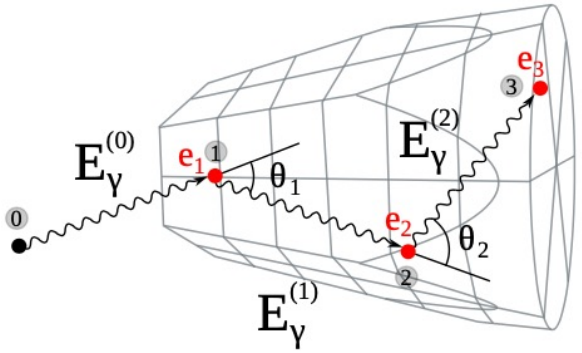
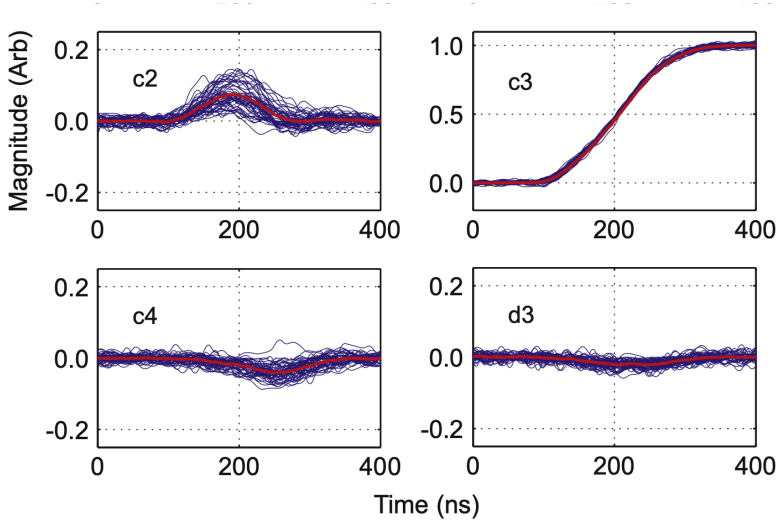
Pulse shape and tracking



γ-ray energy and direction after Compton scattering



~ 5 mm (FWHM) position resolution

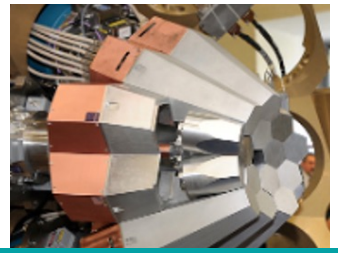
Improved resolving power and Doppler correction

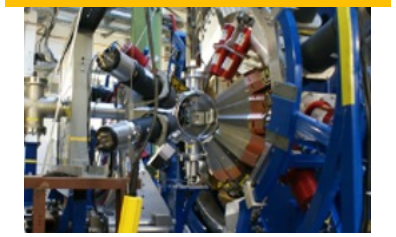
AGATA timeline

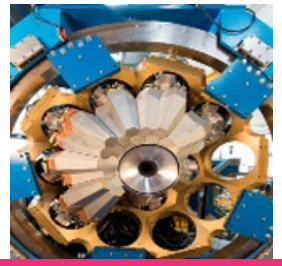
TANDEM
PIAVE
ALPI

Local project manager
J.J. Valiente-Dobón

Scientific coordinator
M. Zielinska

2009
PHASE 1

AGATA@LNL

2011

AGATA@GSI

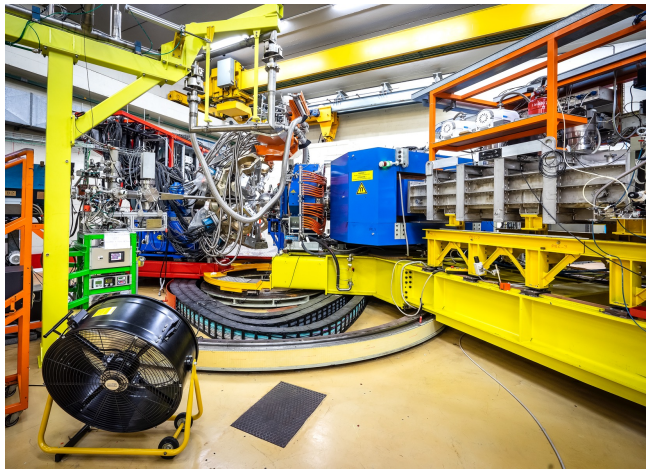
2014

AGATA@GANIL

2021 - 2026
PHASE 2

AGATA@LNL

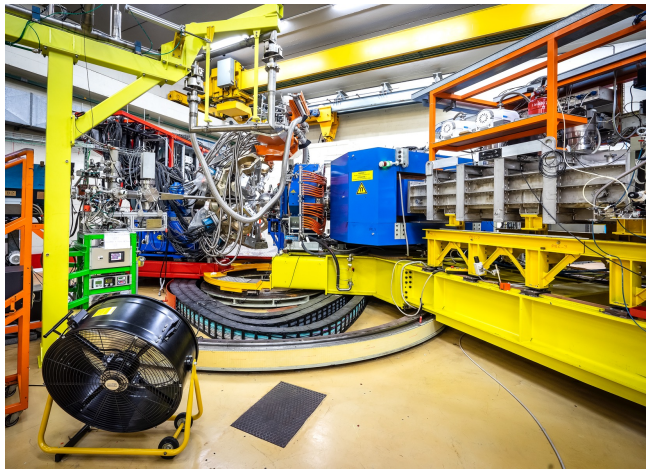
CELEBRATION 10(+2) YEARS


Installation: 2021-2022



Commissioning: April 2022

Installation: 2021-2022



Commissioning: April 2022

Nuclear Inst. and Methods in Physics Research, A 1049 (2023) 168040

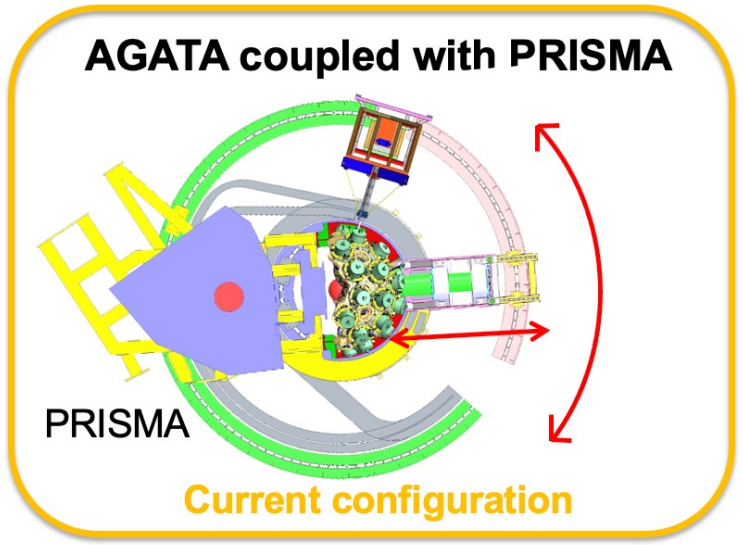
Contents lists available at ScienceDirect

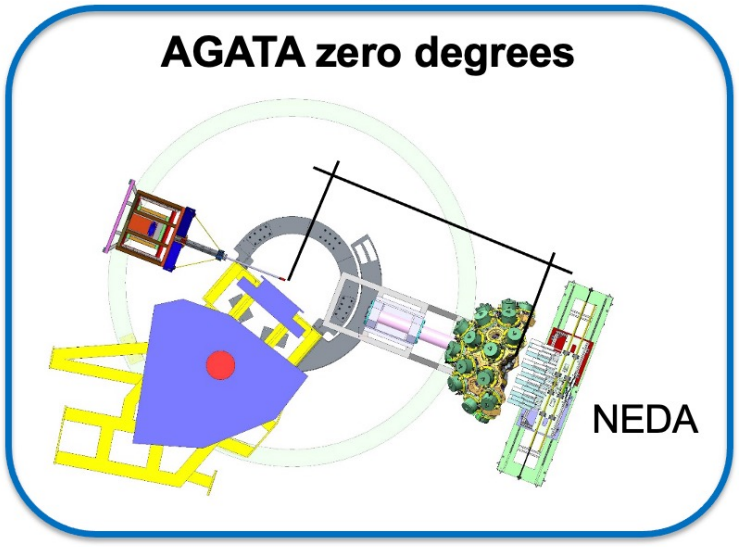
Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Full Length Article

Conceptual design of the AGATA 2π array at LNL





Many other complementary detectors

for charged particles and γ rays

The LNL physics program

PAC@LNL 21-23 February 2022

28 proposals submitted
- **10** (+3 commissioning) priority A
- **5** priority B

PAC@LNL 05-06 December 2022

24 proposals submitted
- **6** priority A
- **10** priority B

PAC@LNL 10-11-12 July 2023

15 proposals submitted
Tandem only beams:
- **8** approved priority A
- **3** approved priority B

PAC@LNL January 2024

TAP beams:
18 proposals submitted
- **7** priority A
- **5** priority B

26 + 3 experiments performed

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PAC@LNL January 2024

TAP beams:
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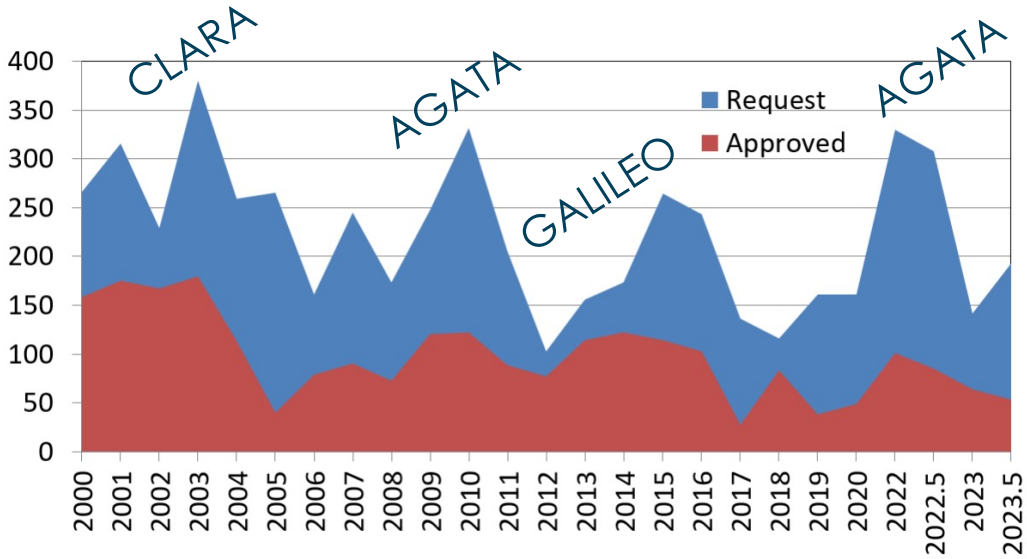
26 + 3 experiments performed

Large interest by the community

for γ-ray spectroscopy

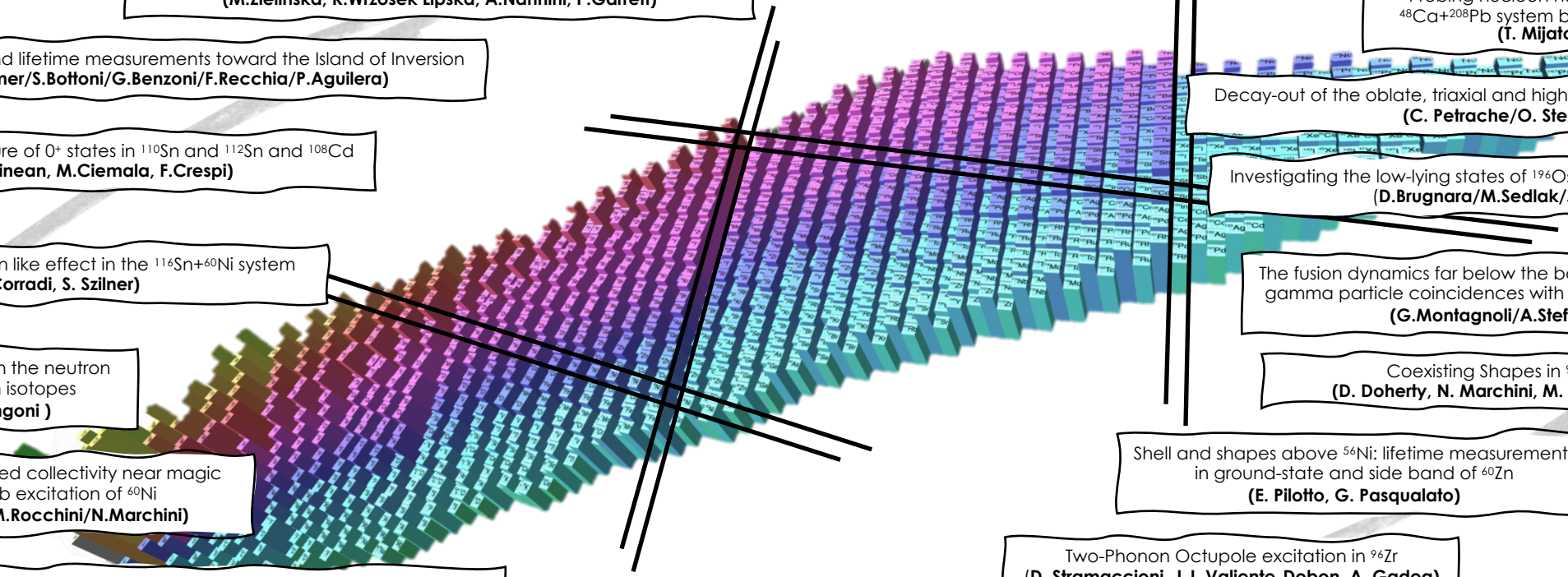


LNL is in full swing

80% of TAP beam time to AGATA

Fully-completed experiments

Simone Bottoni



Pathway to nuclear structure in heavy neutron rich nuclei in the vicinity of N=126 and nuclei northwest of ^{132}Sn via multinucleon transfer reactions
(P.Reiter)

Study of shape coexistence in ^{60}Fe via lifetime measurement of excited 0^+ states
(G.Pasqualato/J.Ljungvall)

Probing Multiple Shape Coexistence in ^{110}Cd with Coulomb Excitation
(M.Zielinska, K.Wrzosek Lipska, A.Nannini, P.Garrett)

Probing nucleon nucleon correlations in the ^{48}Ca+^{208}Pb system below the Coulomb barrier
(T. Mijatovic L. Corradi)

Spectroscopy and lifetime measurements toward the Island of Inversion
(K.Wimmer/S.Bottoni/G.Benzoni/F.Recchia/P.Aguilera)

Decay-out of the oblate, triaxial and highly-deformed bands in ^{136,137}Nd
(C. Petrache/O. Stezowski)

Understanding the nature of 0^+ states in ^{110}Sn and ^{112}Sn and ^{108}Cd
(N. Marginean, M.Ciemala, F.Crespi)

Investigating the low-lying states of ^{196}Os via lifetime measurements
(D.Brugnara/M.Sedlak/J.Pellumaj)

Search for a Josephson like effect in the ^{116}Sn+^{60}Ni system
(L. Corradi, S. Szilner)

The fusion dynamics far below the barrier for ^{12}C+^{24}Mg by gamma particle coincidences with AGATA+Si detectors
(G.Montagnoli/A.Stefanini)

Octupole correlations in the neutron deficient plutonium isotopes
(J.F.Smith/D.Mengoni)

Coexisting Shapes in ^{96}Zr
(D. Doherty, N. Marchini, M. Zielinska)

Emergence of enhanced collectivity near magic nuclei: Coulomb excitation of ^{60}Ni
(K.HadynskaKlek/M.Rocchini/N.Marchini)

Shell and shapes above ^{56}Ni: lifetime measurements in ground-state and side band of ^{60}Zn
(E. Pilotto, G. Pasqualato)

Two-Phonon Octupole excitation in ^{96}Zr
(D. Stramaccioni, J.J. Valiente-Dobon, A. Gadea)

Fusion fission for gamma ray spectroscopy of neutron rich nuclei around N=50
(A. Gottardo, M. Caamano, JJVD)

Test of the CKM unitarity and the existence of Fierz interference through the measurement of superallowed beta decay of light nuclei
(J.Ha/F.Recchia)

Evolution of the mixing between single particle and intruder configurations at N=20
(F. Galtarossa, A. Gottardo)

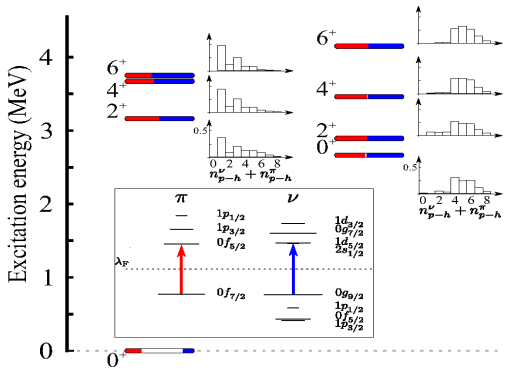
Precise measurement of the B(E2; $2^+_1 \rightarrow 0^+_1$) in ^{56}Ni
(F. Galtarossa, A. Gottardo)

Lifetime of the 6793 keV state in ^{15}O
(J.Skowronski)

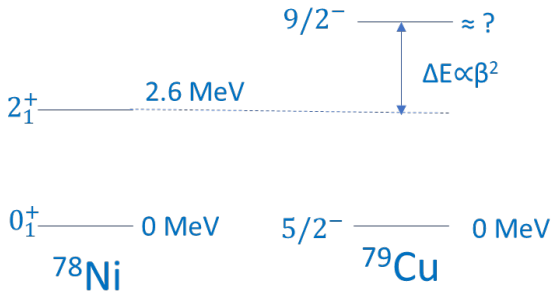
Shell evolution along N=50

shape coexistence at low excitation energy

A. Gottardo (LNL) et al.

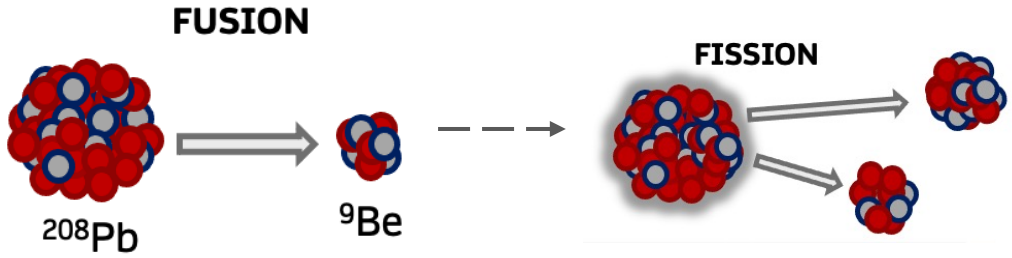


F. Nowacki et al., PRL 117, 272501 (2016)



Fusion-fission reactions

AGATA+PRISMA



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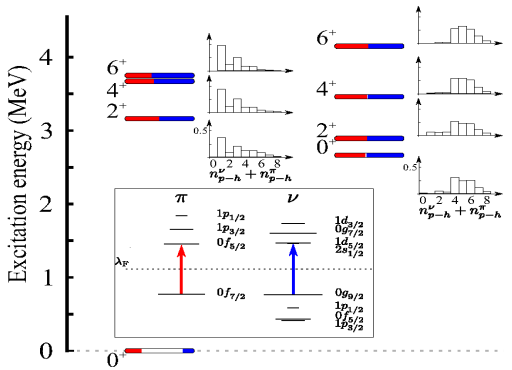

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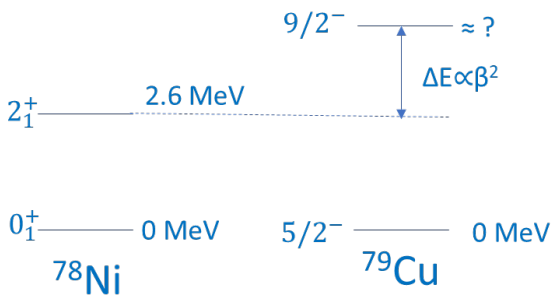

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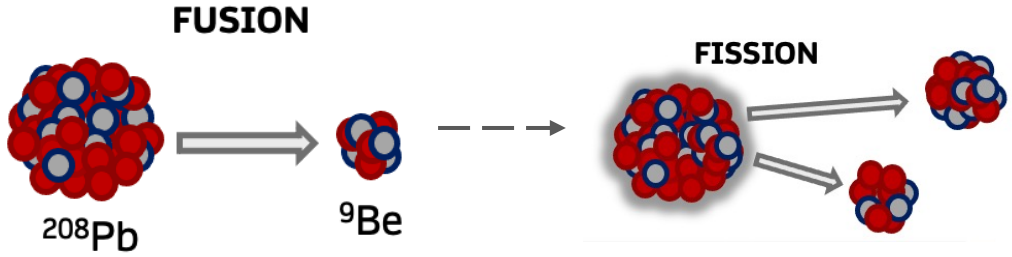
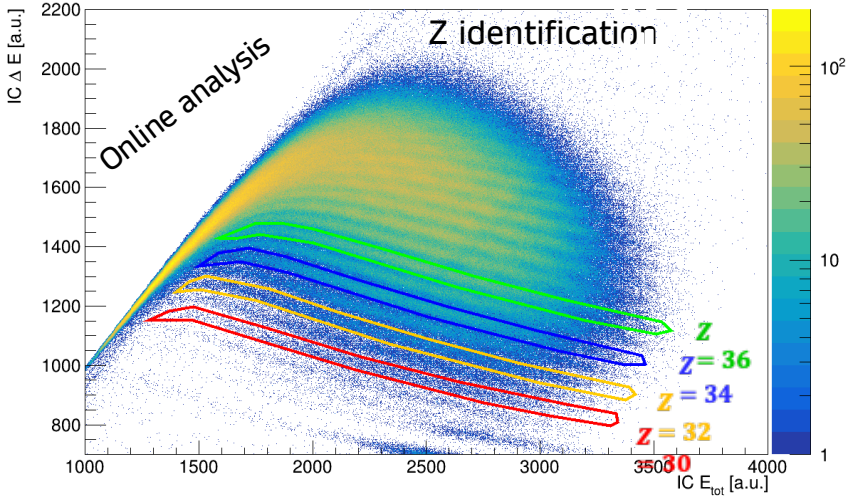
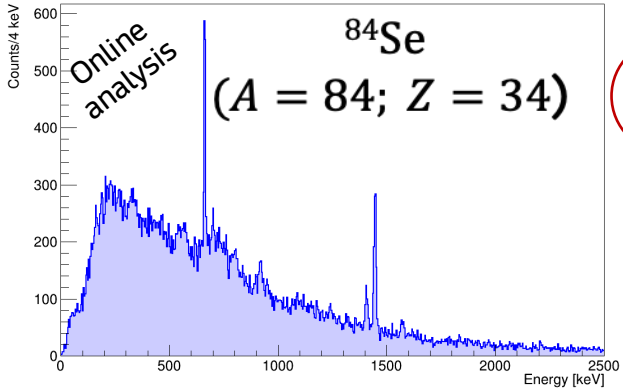
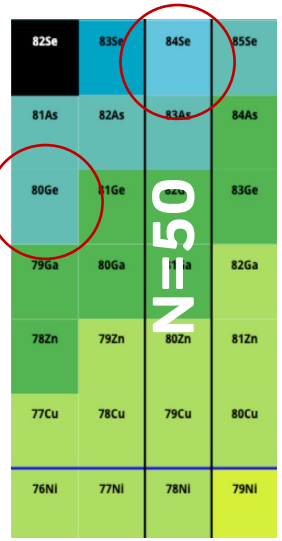


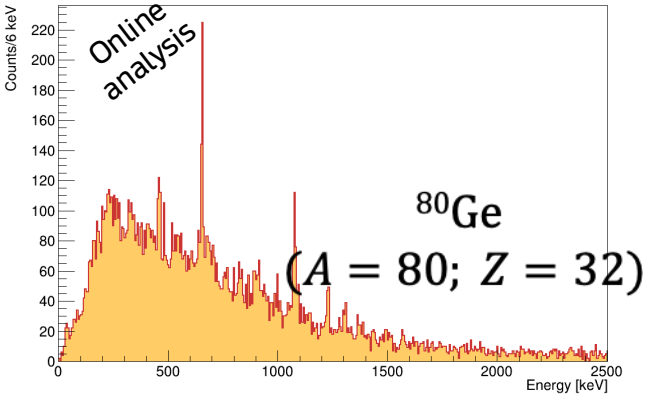
Spectroscopy of low-Z fission fragments

towards doubly-magic ^{78}Ni







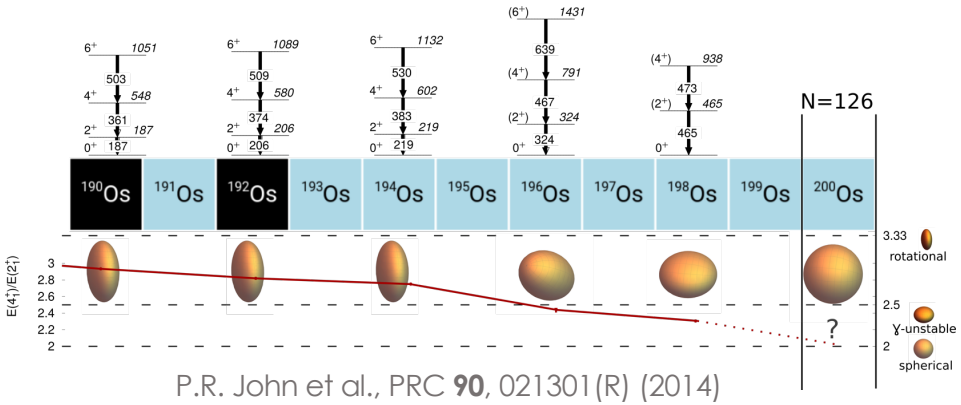


Analysis by F. Angelini (UNIPD)

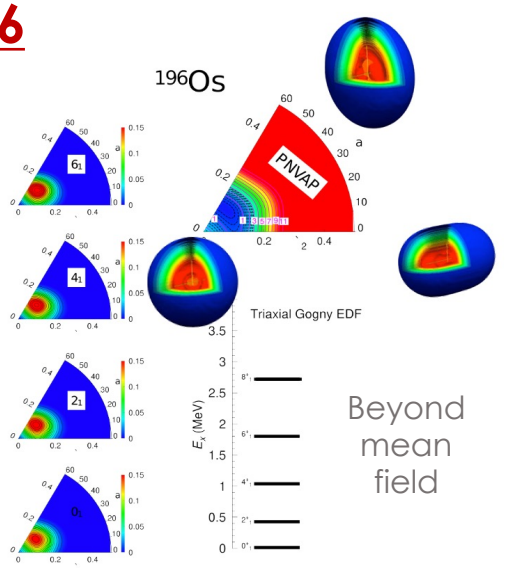
From deformation to sphericity at N=126

triaxial features of ^{196}Os

D. Brugnara (LNL) et al.

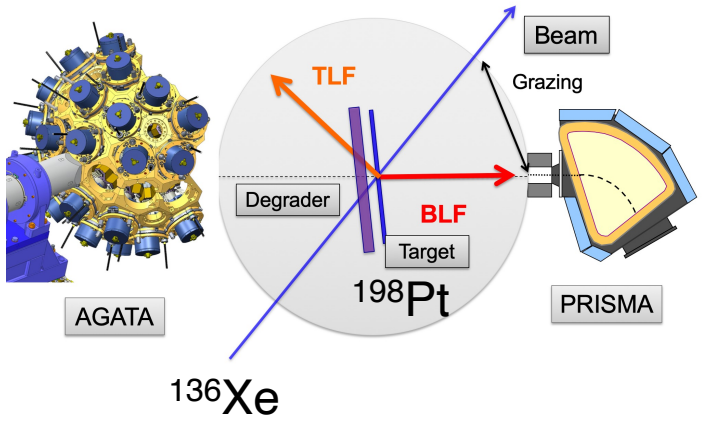


P.R. John et al., PRC **90**, 021301(R) (2014)



Multi-nucleon transfer reactions

AGATA+PRISMA



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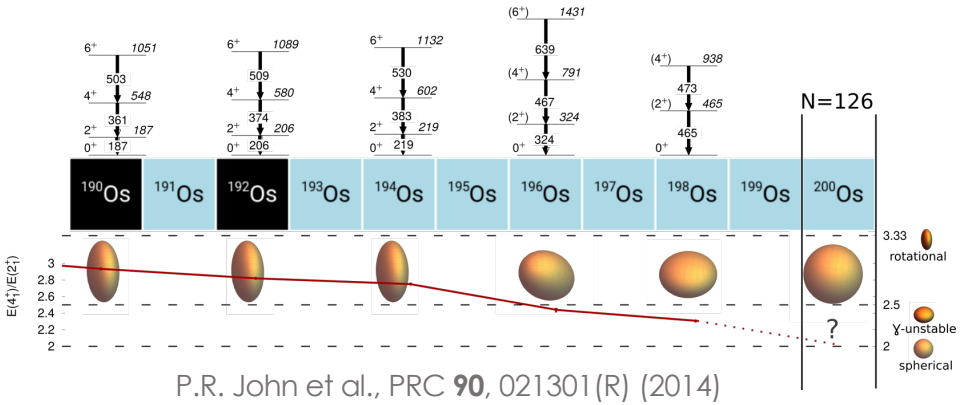

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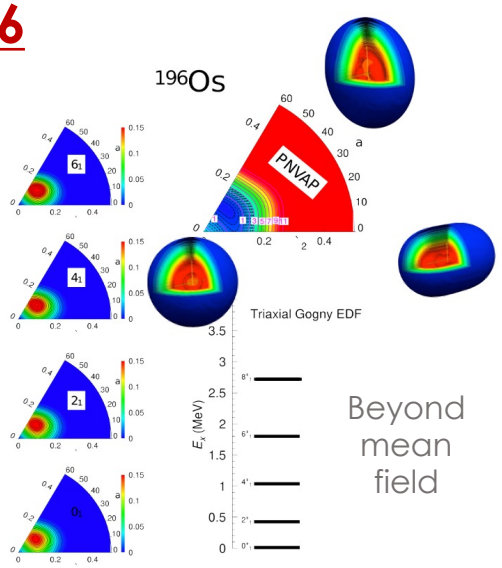

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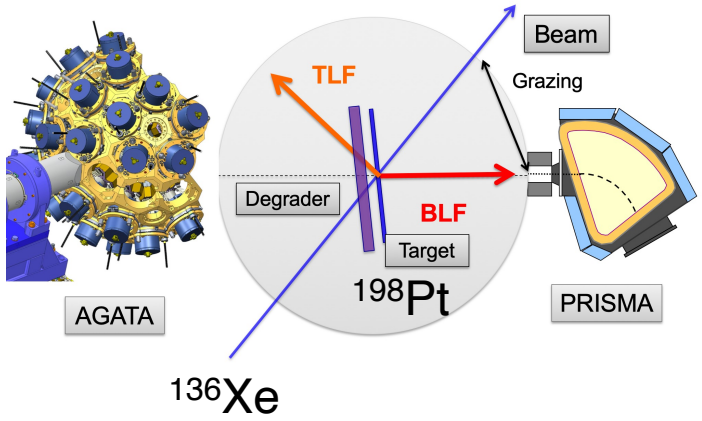
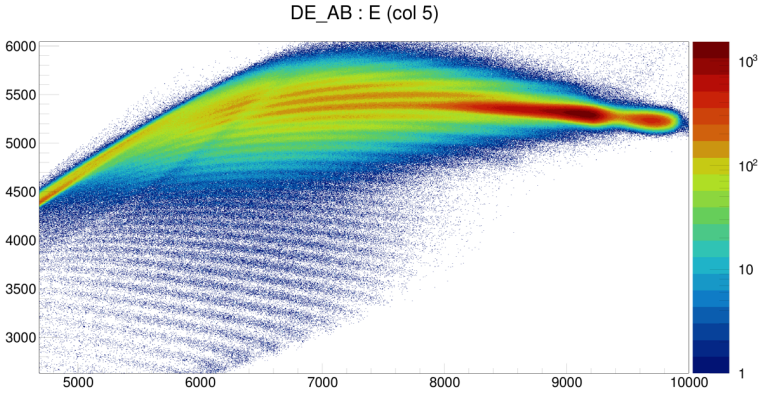
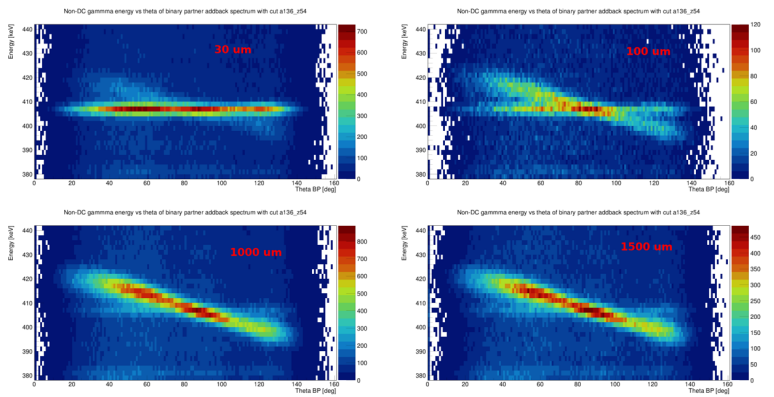


^{136}Xe

Lifetime measurements with the inversed plunger

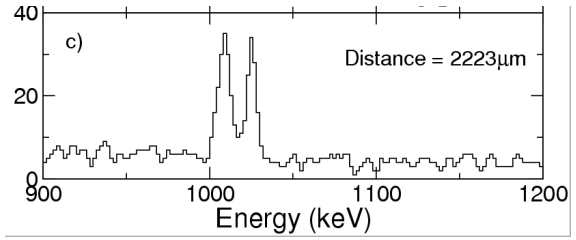
assessing ps lifetimes of excited states





2^+ of ^{198}Pt

$\tau^{-1} \sim B(E2: J_i \rightarrow J_f) = 1/(2J_i+1)\langle\psi_f ||\mathbf{E2}|| \psi_i\rangle^2$

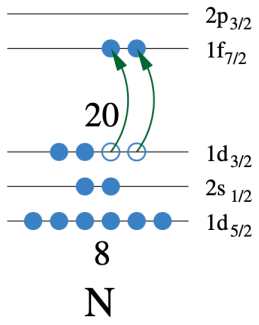


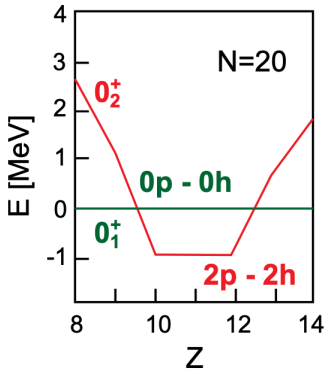
Analysis by B. Gongora and J. Pellumaj (LNL)

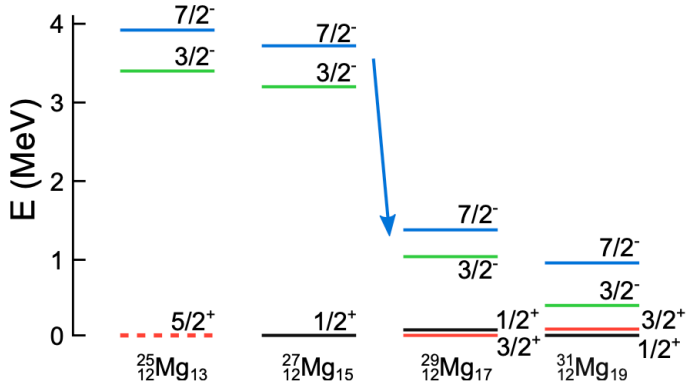
Intruder configurations towards N=20

evolution of negative-parity states

K. Wimmer (GSI) et al.

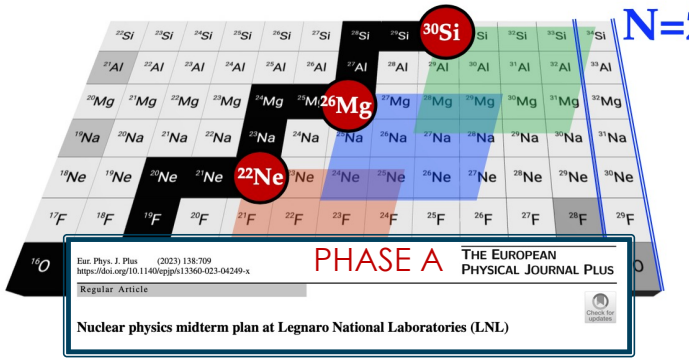






Multi-nucleon transfer reactions

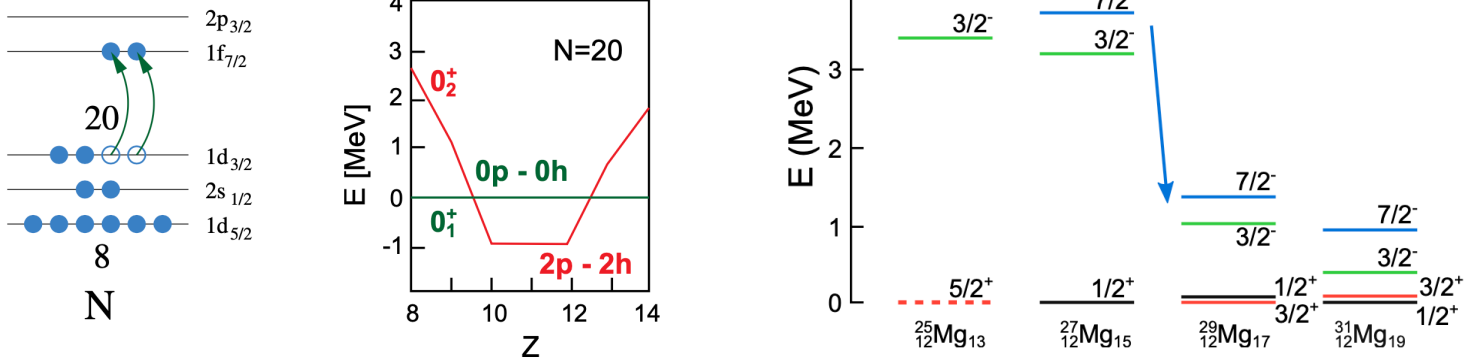
AGATA+PRISMA and ^{235}U target



Intruder configurations towards N=20

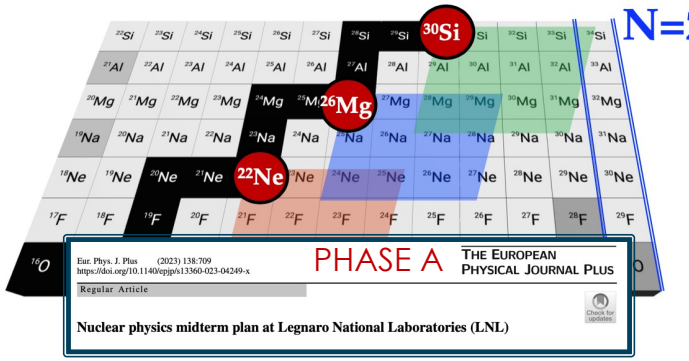
evolution of negative-parity states

K. Wimmer (GSI) et al.



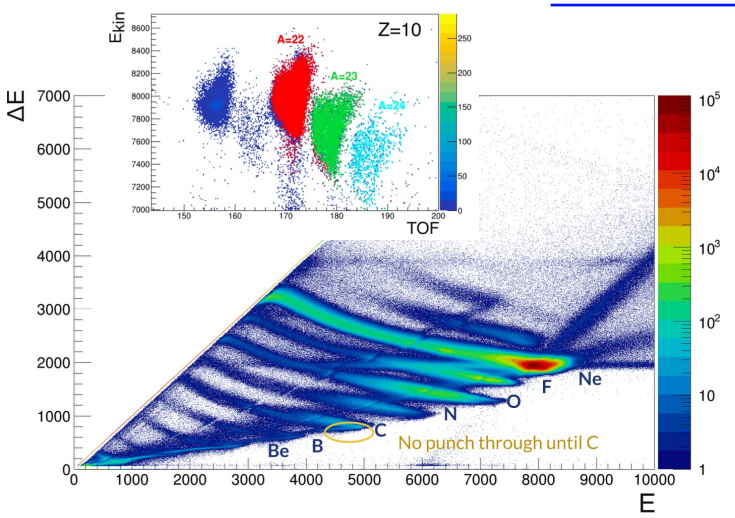
Multi-nucleon transfer reactions

AGATA+PRISMA and ^{235}U target

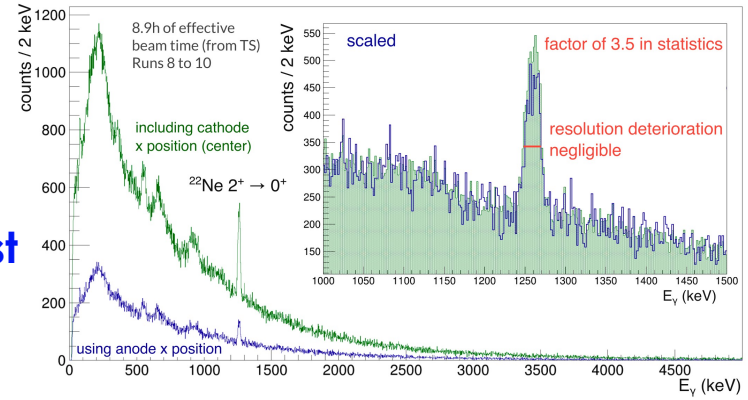


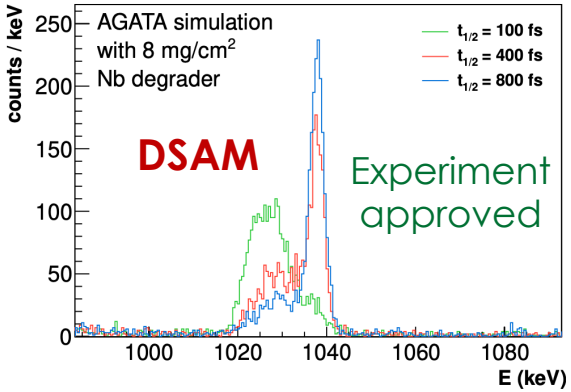
PRISMA optimization and lifetime measurements

assessing fs lifetimes of excited states



^{22}Ne beam test





Analysis by F. Drent (GSI), P. Aguilera (UNIPD), D. Genna (UNIMI)

More physics…

Simone Bottoni

Lifetime measurements for the study of intruder states towards the island of inversion along the N = 20 shell closu

R. Nicolás del Álamo[1,2], I. Zanon[3], D. Brugnara[4] and the AGATA and PRISMA collaborations
1 Università degli studi di Padova, 2 INFN Sezione di Padova, 3 Stockholm University, 4 INFN Laboratori Nazionali di Legnaro

Istituto Nazionale di Fisica Nucleare

The N=20 Island of Inversion

Aim of the experiment

The purpose of the experiment is to investigate a group of states in **³⁴Si and ³⁵P** and determine whether they are **intruder states**. By studying these states, we aim to gain insight into the **evolution** of the **shell structure** moving from the valley of stability towards the N=20 island of inversion.

Nuclear shell model Hamiltonian

$$H = \sum_i \left[\frac{\vec{p}_i^{\,2}}{2m_i} + U_i(\vec{r}_i)\right] + \sum_{i>j}^{A} V_{ij}(\vec{r}_i - \vec{r}_j) - \sum_{i=1}^{A} U_i(\vec{r})$$

H_0 H_{res}

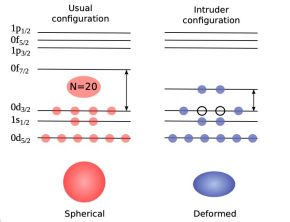
$$H_0|\psi_0\rangle = E_0|\psi_0\rangle$$

Eigenenergies and eigenstates of the system

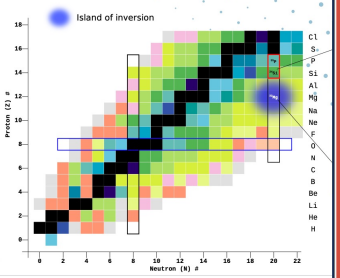
$$H|\Psi\rangle = E|\Psi\rangle \qquad |\Psi_k\rangle = \sum_i^{\infty} C_i^k|\psi_0\rangle_i \approx \sum_i^{N} C_i^k|\psi_0\rangle_i$$

Lifetime measurements provide information on the nuclear wavefunctions

$$\tau^{-1} \sim |\langle\Psi_f||\mathcal{M}(L)||\Psi_i\rangle|^2$$



A. Poves and J. Retamosa, PL B 184 (1987)
N. Fukunishi, T. Otsuka and T. Sebe, PL B 296 (1992)



PHYSICS CASE

Two-Phonon Octupole excitation in ^{96}Zr

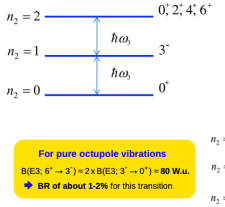
D. Stramaccioni[1,2], J.J. Valiente Dobón[1], T.R. Rodríguez[3], A. Gadea[4] and the AGATA collaboration
[1]INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy ; [2] Università degli Studi di Padova, Dipartimento di Fisica e Astronomia, Padova, Italy ; [3] Universidad Complutense de Madrid, Madrid, Spain ; [4] Instituto de Física Corpuscular, Valencia, Spain

One- and Two-Octupole vibrations

Closed (sub-)shell nuclei can show **collective excitations** built from **octupole surface vibrations**

$$H_{vibr} = \sum_{\lambda} \hbar\omega_{\lambda} \sum_{\mu} \left(b^{+}_{\lambda\mu} b_{\lambda\mu} + \frac{1}{2}\right)$$

$$b^{+}_{\lambda\mu}|0\rangle = |\lambda\mu\rangle$$



For pure octupole vibrations

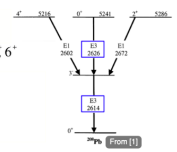
B(E3; $6^- \rightarrow 3^-$) ≈ 2 x B(E3; $3^- \rightarrow 0^+$) ≈ **80 W.u.**

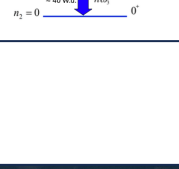
➔ **BR of about 1-2%** for this transition

Two-Phonon excitation

• $E_{2ph}/E_{1ph} \approx 2$ • Large B(E3)

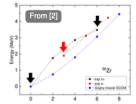
Example: ^{208}Pb

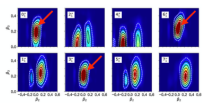




The ^{96}Zr case

In ^{96}Zr, the **E vs J** trend can be explained considering the **energy gain in 0^+, 3^- and 6^+**, possibly arising from **strong octupole correlations**





Gogny EDF calculations show strong **octupole deformation for 0_1^+, 3_1^- and 6_1^+ collective wf.** which present very **similar features**

Since the 3^- is the 6^+ a

Lifetime of the 6_1^+ state
$T_{1/2}(6_1^+) = 25(9$

First B(E3) in a c

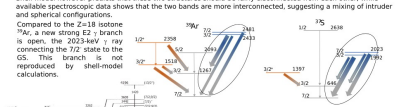
Mixing between single-particle and intruder states towards the N=20 island of inversion: lifetimes in ^{37}S

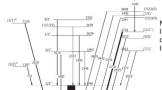
L. Zago[a,c], F. Galtarossa[b,c], A. Gottardo[c], J.J. Valiente Dobon[c], F. Angelini[a,c], M. Balogh[c], D. Brugnara[a], J. Collado Ruiz[c], G. de Angelis[c], A. Ertoprak[a], A. Goasduff[c], B. Gongora Servin[a], A. Gozzelino[c], T. Marchi[c], D. R. Napoli[c], J. Pellumaj[a], R. M. Perez Vidal[a,c], M. Sedlak[a], I. Zanon[a], A. Gadea[d], N. Mianì[c], P. A. Aguilera[b], D. Bazzacco[c], J. Benito Garcia[d], S. Carollo[a,c], Z. Huang[c], S. M. Lenzi[a,c], R. Menegazzo[a], D. Mengoni[a,c], S. Pigliapoco[a,c], E. Pilotta[a,c], M. Polettini[a], F. Recchia[a,c], K. Rezynkina[a], G. Zhang[a], G. Benzoni[e], S. Bottoni[e], G. Corbari[a], N. Marchini[e], A. Nannini[e], M. Rocchini[e], M. Beckers[g], F. Dunkel[g], C. Fransen[g], L. Kornweibel[g], C. Lakenbrink[g], F. Von Spee[g], J. Dikici[h] and AGATA collaboration
[a]INFN LNL, [b]INFN PD, [c]Università di Padova, [d]IFIC - INFN-Mi e Unimi Statale, [e]INFN-FI, [f]University of Cologne, [g]Ruder Boskovic Institute

MOTIVATION

^{37}S should be a textbook example of a N=20 magic nucleus plus 1 neutron, but correlations (quadrupole and pairing) bring intruder states lower in energy in competition with the single-particle configurations. Shell-model however predicts that these two structures should be fairly disconnected from each other, while available spectroscopic data shows that the two bands are more interconnected, suggesting a mixing of intruder and spherical configurations.

Compared to the Z=18 isotone ^{39}Ar, a new strong E2 γ branch is open, the 2023-keV γ ray connecting the 7/2⁻ state to the GS. This branch is not reproduced by shell-model calculations.





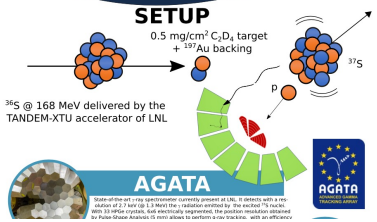
No lifetime measurement on any of these states is present in literature. They would directly give information on the collectivity of these states, and if ^{37}S lies already at the edge of the N=20 Island of Inversion.

PHYSICS AIM

first lifetime measurement of ^{37}S excited states, in particular of the intruder 1397 and 2023-keV levels.

SETUP

0.5 mg/cm² C_2D_4 target + ^{197}Au backing



^{36}S @ 168 MeV delivered by the TANDEM-XTU accelerator of LNL

Octupole Collectivity in ^{96}Zr from Low-Energy Coulomb Excitation with the AGATA+SPIDER Setup

Federica Ercolano - Università degli Studi di Napoli "FEDERICO II" & INFN Sezione di Napoli

Zirconium Isotopes

The Zirconium isotopes have been the subject of intensive experimental and theoretical work to gather insight into a variety of di phenomena. They span a wide range of masses from a mid-open-shell region (^{80}Zr$_{40}$), which is thought to be deformed, through (^{90}Zr$_{50}$), to a closed neutron subshell (^{96}Zr$_{56}$), and then to a sudden reappearance of deformation (^{100}Zr$_{60}$), which has been show another mid-open-shell region (^{110}Zr$_{70}$). This variety of behaviour is unprecedented elsewhere on the nuclear mass surface. In isotope occupies an intriguing position along the isotopic chain, corresponding to a subshell closure for both protons (Z=40) and n

Fusion dynamics far below the barrier for ^{12}C + ^{28}Si

M. Del Fabbro[1,3], G. Montagnoli[1], A.M. Stefanini[2] and PRISMA-AGATA collaboration
[1]University and INFN Padova, Italy, [2]INFN-Lab. Naz. di Legnaro, Padova, Italy, [3]Univ. of Ferrara, Italy

Heavy-ion fusion reactions are essential to investigate the fundamental problem of quantum tunnelling of many-body systems in the presence of intrinsic degrees of freedom. In addition, fusion of light systems is a base for the understanding of astrophysical reactions. The study of light systems with Q > 0, and the identification of hindrance [1] requires challenging measurements, so the investigation of slightly heavier systems allows a reliable extrapolation towards the lighter cases.

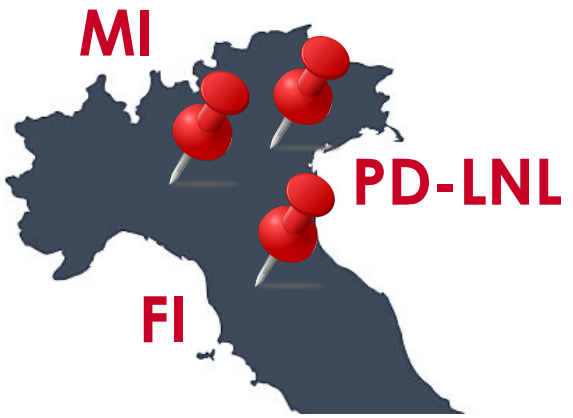
Come and see the AGATA posters

The young strenght of AGATA at LNL

Simone Bottoni

AGATA ADVANCED GAMMA TRACKING ARRAY

INFN LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro



Thank you!

on behalf of the GAMMA collaboration