The AGATA campaign at LNL: nuclear structure from high-resolution γ-ray spectroscopy

Andrea Gottardo, AGATA collaboration

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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

gamma

AGATA
ADVANCED GAMMA TRACKING ARRAY

Outline

- AGATA installation at LNL

- Physics campaign: selected examples
    - lifetimes near N=20
    - lifetimes near N=28
    - lifetimes in heavy nuclei via reverse plunger
    - search for a double octupole phonon in ^{96}Zr
    - fusion fission

- Plans for 25-26

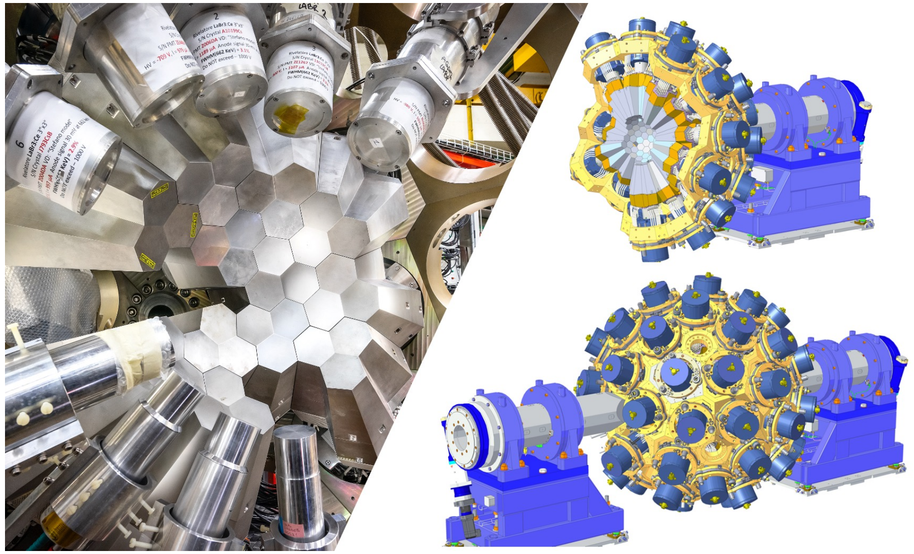
- AGATA zero-degree configurations

AGATA ADVANCED GAMMA TRACKING ARRAY

14th International Spring Seminar on Nuclear Physics: "Cutting-edge developments in nuclear structure physics"

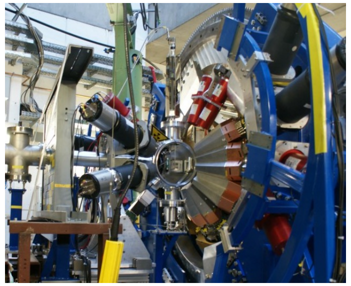
The AGATA γ-ray tracking array

- European collaboration towards a 4π array
- Travelling detector array

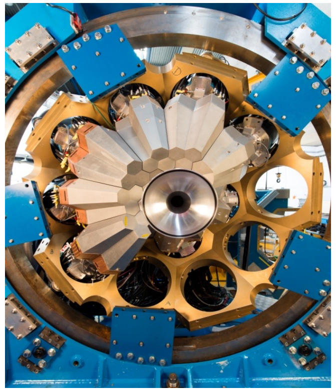


AGATA@LNL

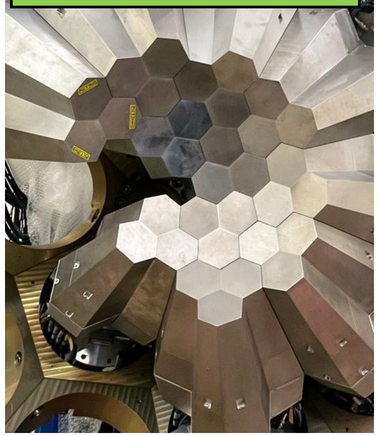
AGATA@GSI



AGATA@GANIL



AGATA@LNL



M. Zielinska physics coordinator

2009 → 2011 → 2014 → 2021-mid **2028**

Phase 1 ⟷

Phase 2 ⟷

Celebration 10(+2) years

Legnaro National Laboratories

- Stable beams from ^{1}H to ^{238}U
- Energies up to 7-20 MeV/u
- Tandem accelerator
- PIAVE superconducting RFQ
- ALPI superconducting LINAC
- ADIGE normoconducting RFQ
- SPES ISOL beams: 70 MeV proton cyclotron (40 MeV, ~300 μA on UCx), UCx ISOL source, ADIGE post acceleration

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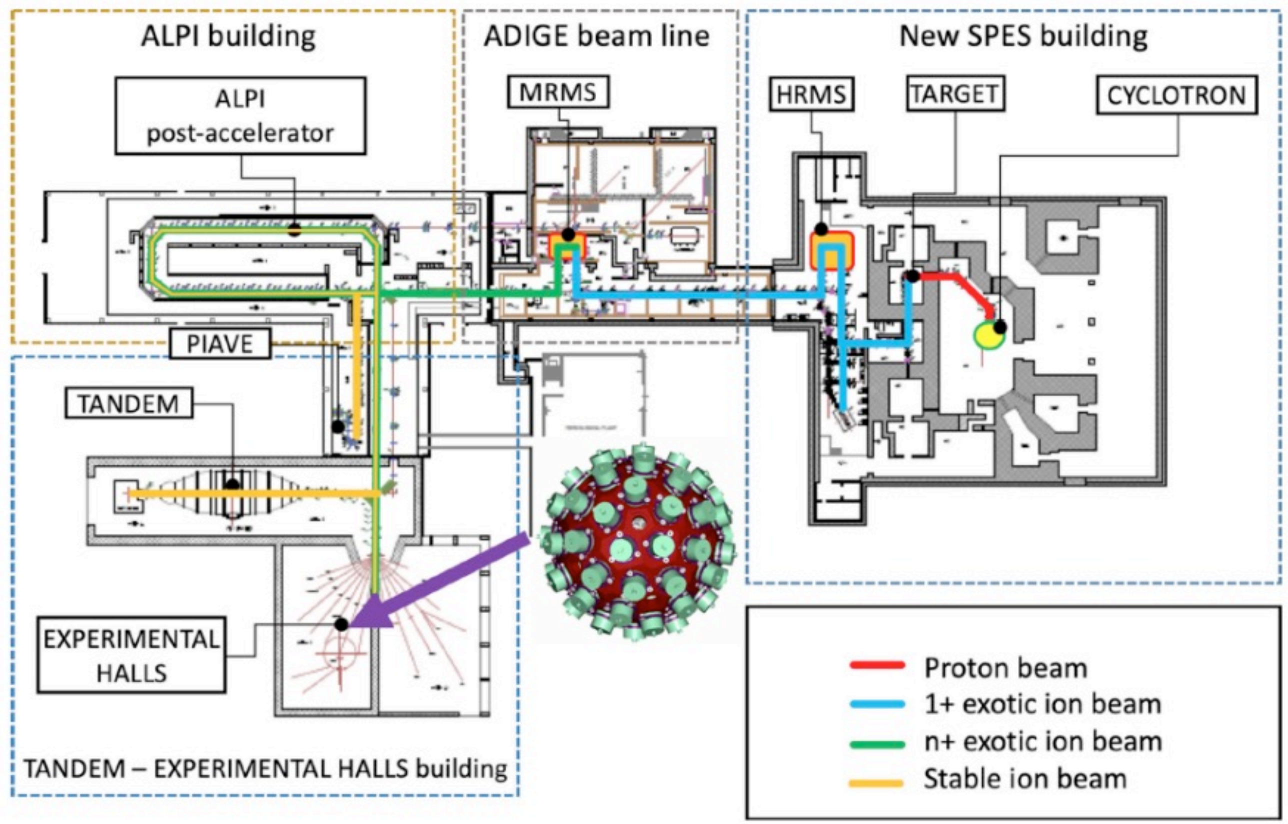
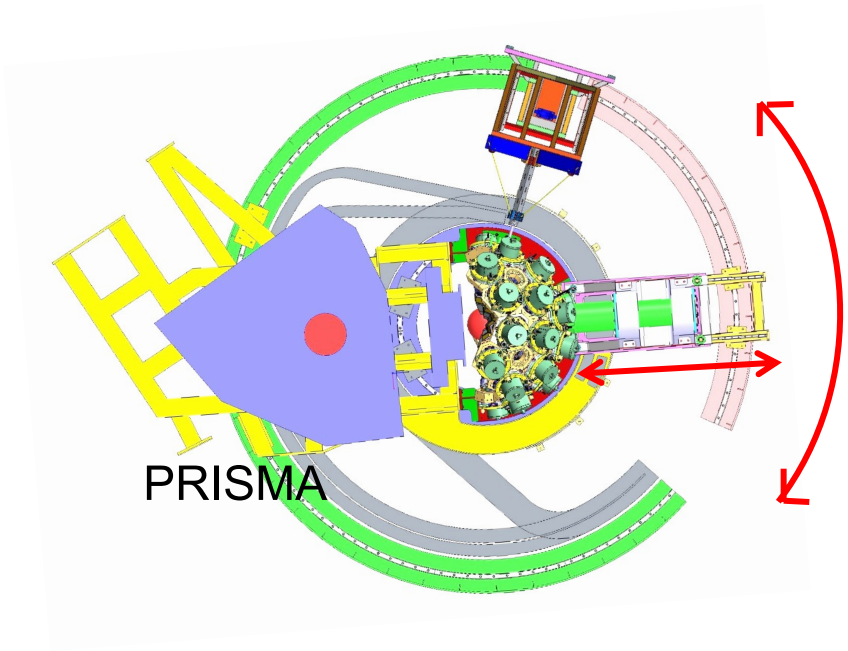


Installation at LNL

AGATA coupled with PRISMA

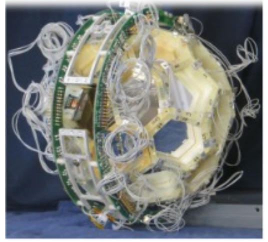


Current configuration

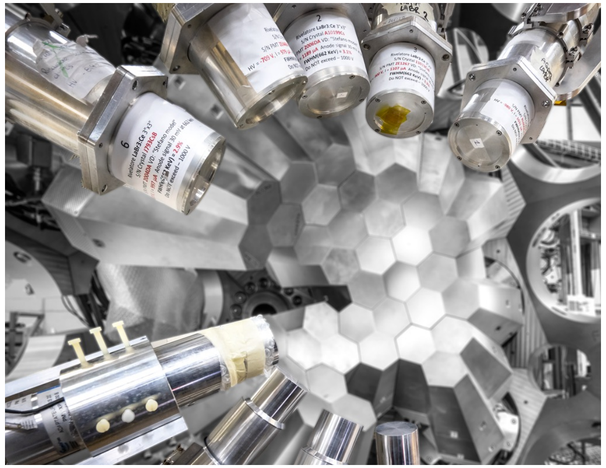
Complementary detectors for AGATA in coupling with PRISMA configuration

PRISMA
heavy ions

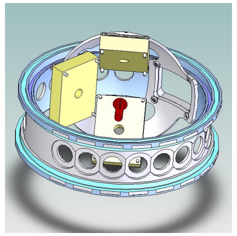
EUCLIDES
light charged particles

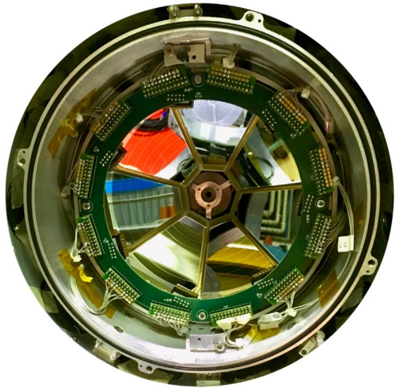


LaBr
γ-rays, fast timing



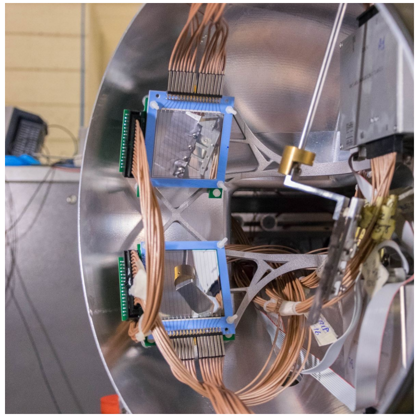
DANTE
heavy ions

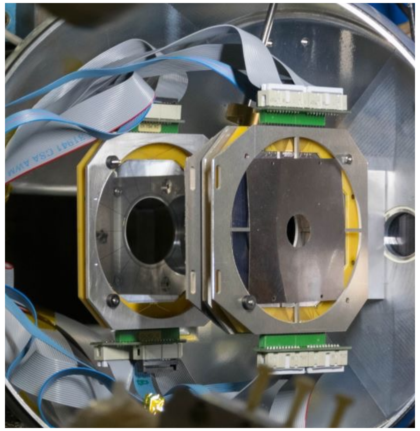




SPIDER
light and heavy ions

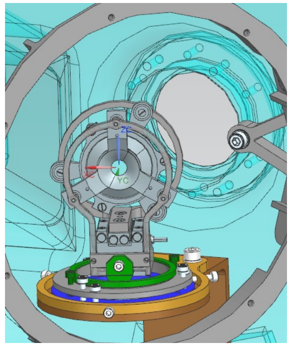
OSCAR
light charged particles





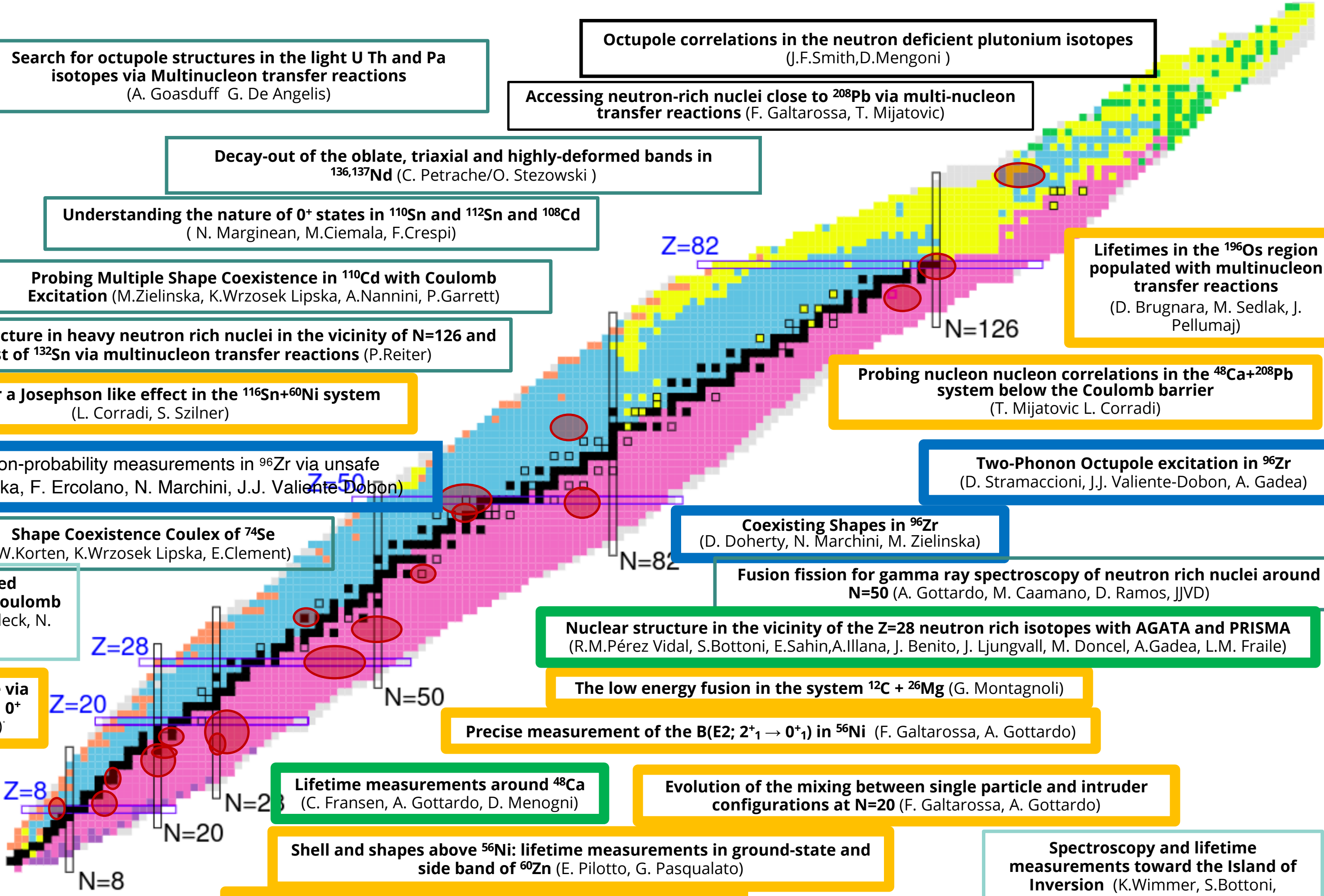
SAURON
light charged particles

PLUNGER
Lifetime measurements



The 2nd LNL AGATA campaign until now

AGATA ADVANCED GAMMA TRACKING ARRAY



Search for octupole structures in the light U Th and Pa isotopes via Multinucleon transfer reactions (A. Goasduff G. De Angelis)

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

Accessing neutron-rich nuclei close to ^{208}Pb via multi-nucleon transfer reactions (F. Galtarossa, T. Mijatovic)

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)

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

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)

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

Combined lifetime and transition-probability measurements in ^{96}Zr via unsafe Coulomb excitation (M. Zielinska, F. Ercolano, N. Marchini, J.J. Valiente-Dobon)

Shape Coexistence Coulex of ^{74}Se (W.Korten, K.Wrzosek Lipska, E.Clement)

The emergence of enhanced collectivity near magic nuclei: Coulomb excitation of ^{60}Ni (K. HadinskaKleck, N. Marchini, M. Rocchini,)

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

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)

Lifetimes in the ^{196}Os region populated with multinucleon transfer reactions (D. Brugnara, M. Sedlak, J. Pellumaj)

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

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

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

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

Nuclear structure in the vicinity of the Z=28 neutron rich isotopes with AGATA and PRISMA (R.M.Pérez Vidal, S.Bottoni, E.Sahin,A.Illana, J. Benito, J. Ljungvall, M. Doncel, A.Gadea, L.M. Fraile)

The low energy fusion in the system ^{12}C + ^{26}Mg (G. Montagnoli)

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

Lifetime measurements around ^{48}Ca (C. Fransen, A. Gottardo, D. Menogni)

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

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

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

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

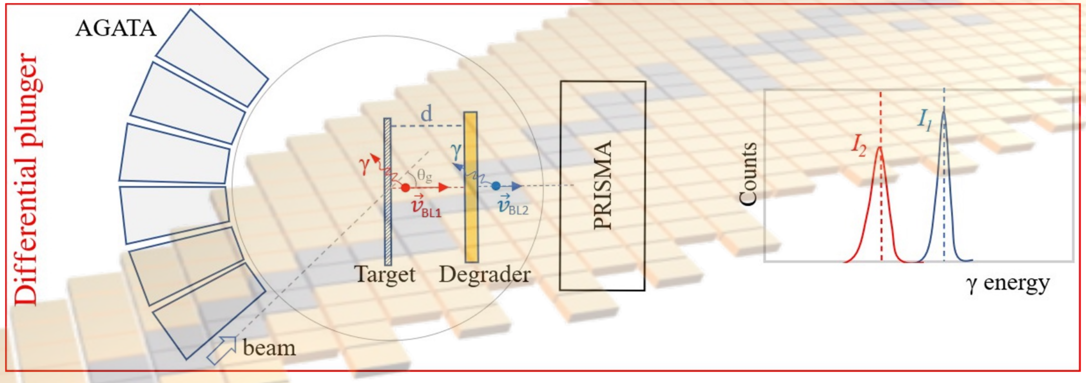
Lifetime measurements intruder states towards the island of inversion along the N=20 shell closure (Z. Irene, D. Brugnara)

- 46 experiments performed
- **2022-2024: ~7000 hours of beam on target !**
- **2025: already 750 hours of beam on target**
- Wide user community: EU, UK, USA, Canada, South Korea, China

The campaign: main physics subjects

- Nuclear Structure: - Excited level lifetimes measurement in key regions: N=20 (^{36}S, ^{26}Mg) , N=28 (^{48}Ca, ^{56}Ni...), towards N=126 (^{198}Pt) using direct and MNT reactions

  - Spectroscopy of N=50 nuclei towards ^{78}Ni with fusion-fission reactions



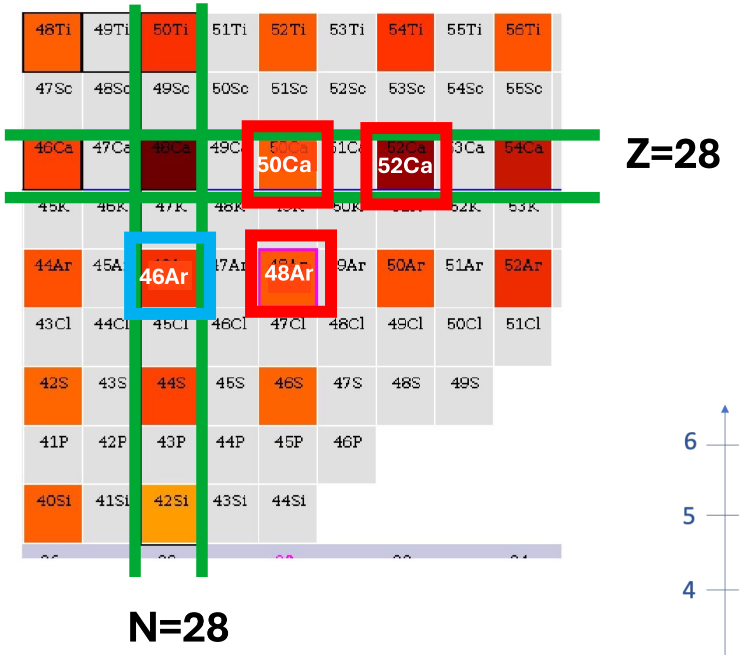
The campaign: main physics subjects

- Nuclear Structure: - Excited level lifetimes measurement in key regions: N=20 (^{36}S, ^{26}Mg) , N=28 (^{48}Ca,^{56}Ni…), towards N=126 (^{198}Pt) using direct and MNT reactions
  - Spectroscopy of N=50 nuclei towards ^{78}Ni with fusion-fission reactions
- Safe and unsafe Coulex measurements in the ^{60}Ni, ^{74}Se, ^{82}Se, $^{110\text{-}112}$Cd, ^{122}Te, ^{96}Zr, ^{162}Dy, ^{232}Th for quadrupole/octupole deformation
- Inelastic scattering on ^{96}Zr and MNT on actinides for octupole structures
- Nuclear Reactions: - Nuclear Josephson effect in near-barrier neutron pair transfer reactions between heavy ions
  - Increasing the cross-section sensitivity of sub-barrier reactions to the nbarn using γ-ray tagging
- Nuclear Astrophysics/fundamental physics

1. Multi-nucleon transfer around ^{48}Ca: motivation

- ^{48}Ca @ 305 MeV onto ^{238}U, Nb degrader
- AGATA-PRISMA
- RDDS and DSAM

Spokepersons: C. Fransen, A. Gottardo, D. Mengoni,



E(2^+) = 700 – 800 keV

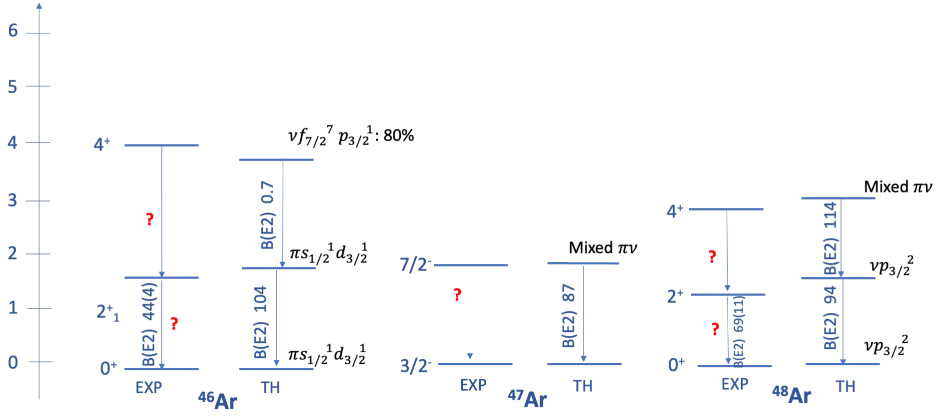
E(2^+) = 1000 – 1500 keV

E(2^+) > 2500 keV

Investigation of $^{50-52}$Ca

→ large charge and matter radii observed

→ also hints for subshell closures N=32 ($\nu p_{3/2}$), N=34 ($\nu p_{1/2}$); mass measurements



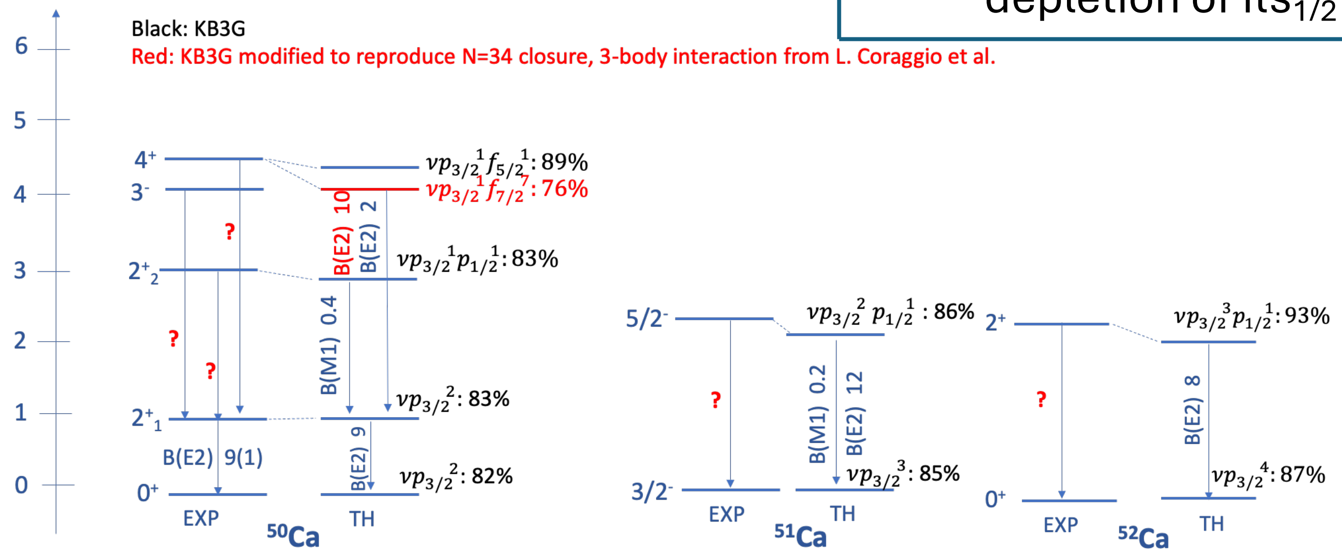
Investigation of $^{46-48}$Ar

→ Weakening of N=28 shell closure in ^{46}Ar

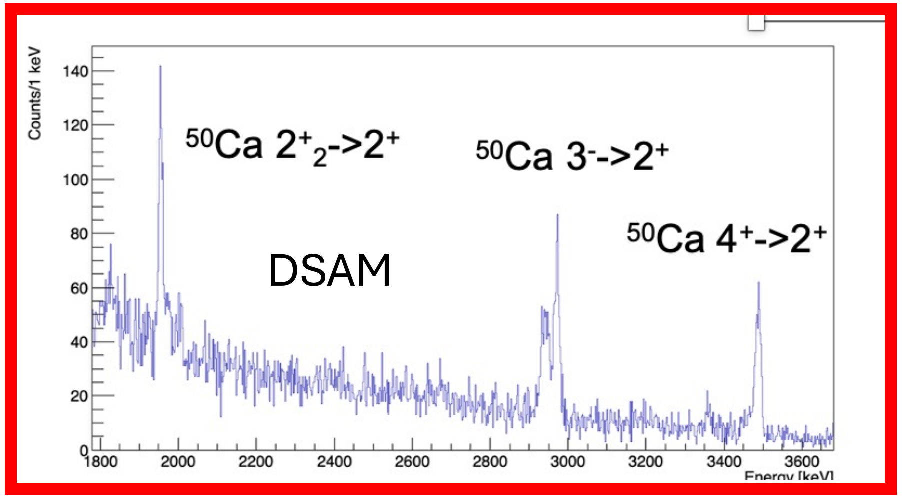
→ explanation from shell structure: depletion of $\pi s_{1/2}$?

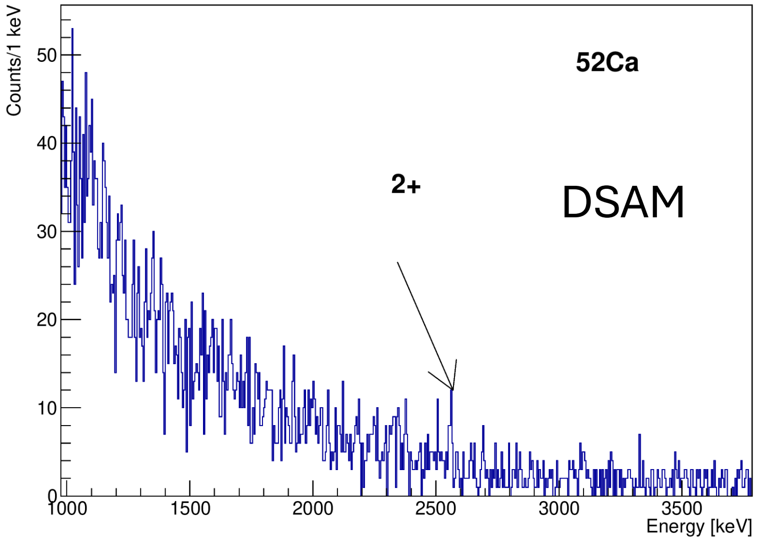
Black: KB3G

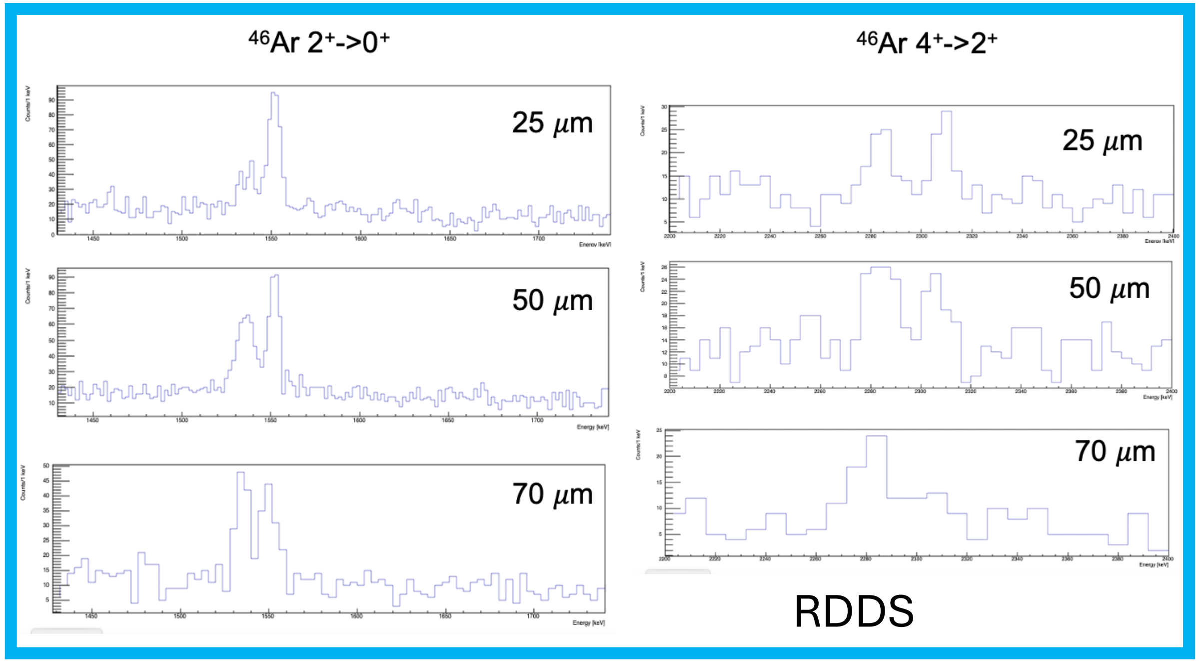
Red: KB3G modified to reproduce N=34 closure, 3-body interaction from L. Coraggio et al.

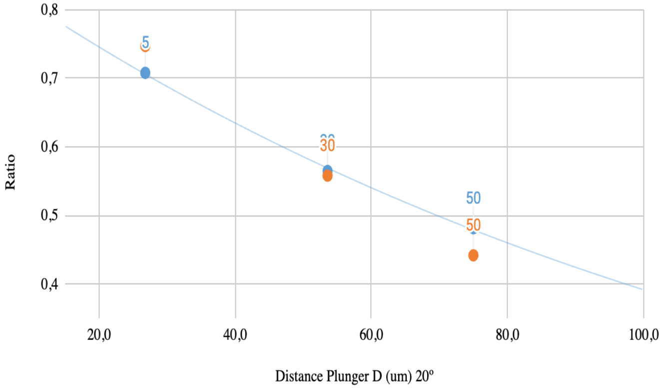


1. Multi-nucleon transfer around ^{48}Ca: results



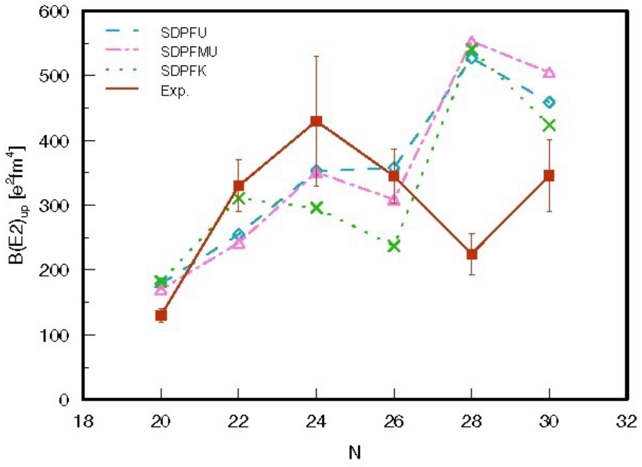






$t_{1/2}$~2 ps,
B(E2) in line with i.e. Coulex

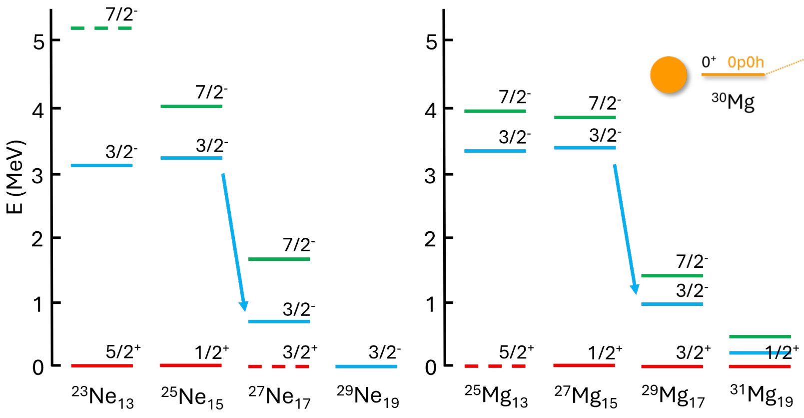
A. Gade et al., PRC 68, 014302 (2003)
S. Calinescu et al., PRC 93, 044333 (2016)

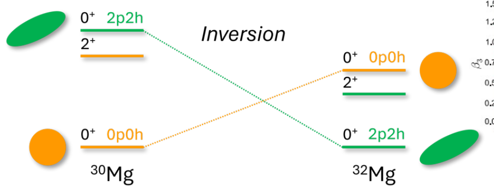


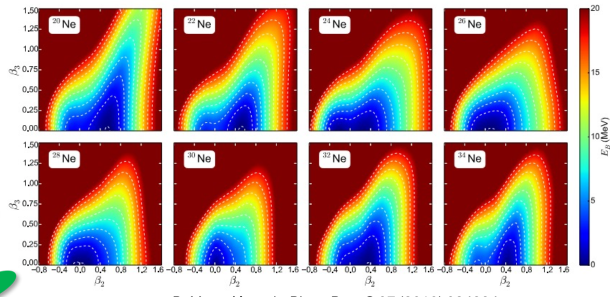
2. Towards the N=20 IoI

Intruder configurations towards N=20

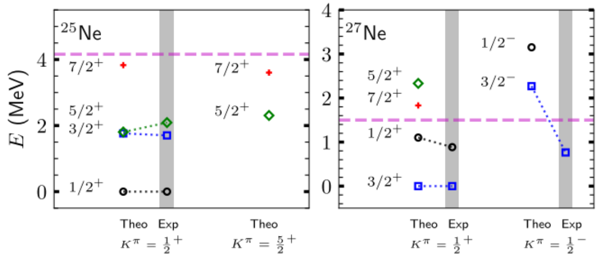
evolution of negative-parity states







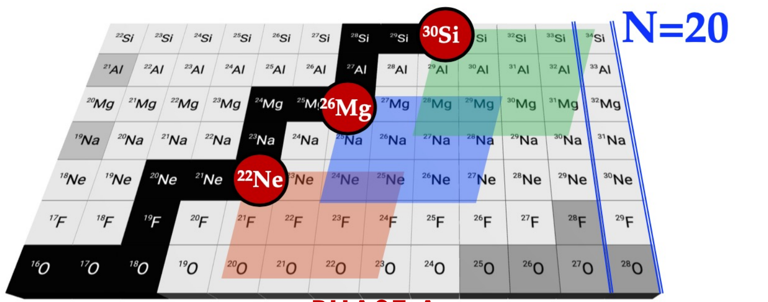
P. Marević et al., Phys. Rev. C 97 (2018) 024334



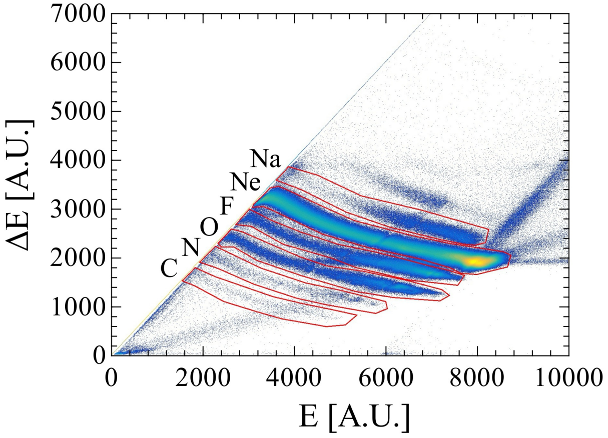
Z. H. Sun et al., Phys. Rev. C 111, 044304 – 2025

Multi-nucleon transfer reactions

AGATA+PRISMA and ^{238}U target

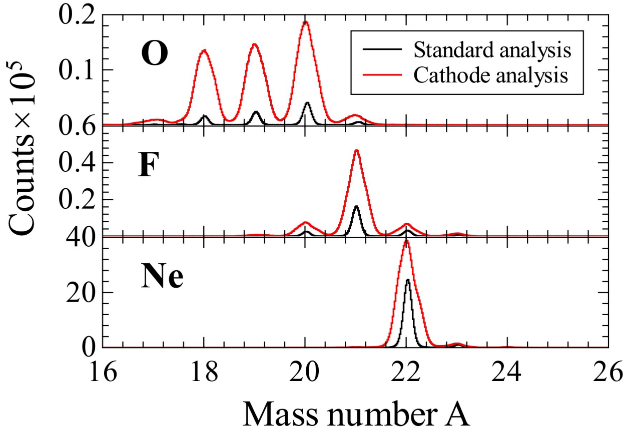


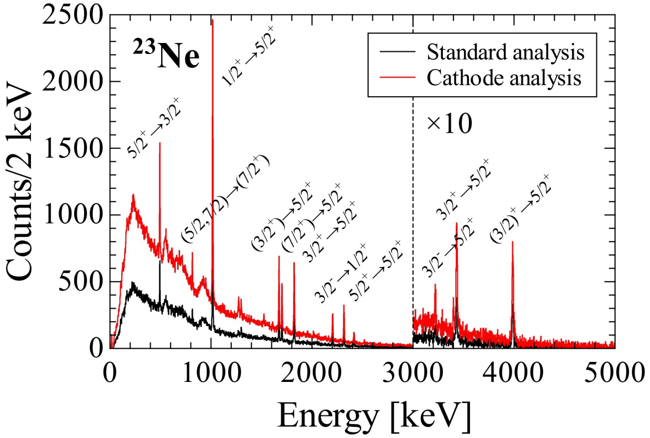
$^{22}Ne + ^{238}U$ @160 MeV



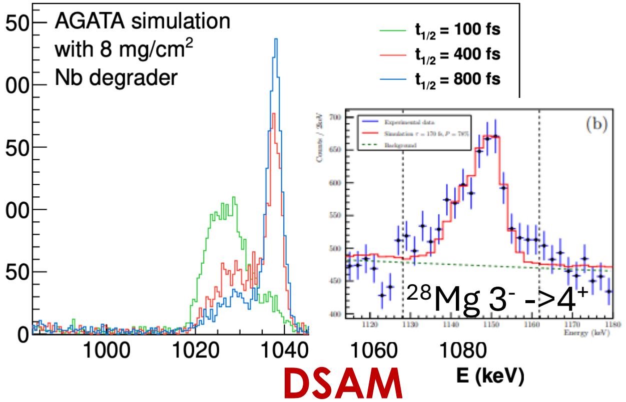
PRISMA optimization and lifetime measurements

assessing fs lifetimes of excited states





$^{26}Mg + ^{238}U$ @200 MeV

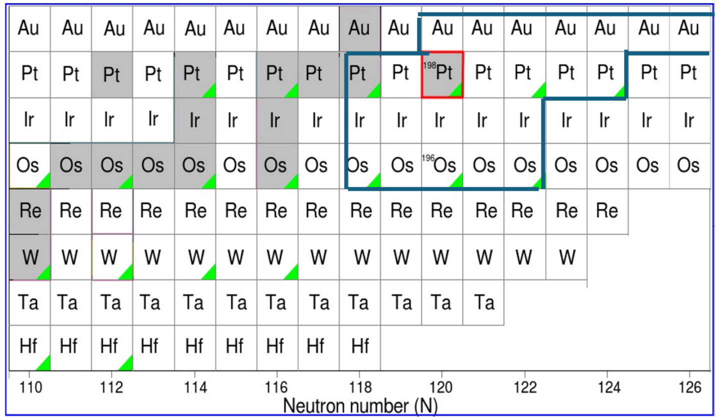


D. Genna(Milano), S. Bottoni(Milano), G. Benzoni(Milano), K. Wimmer(GSI), P. Aguilera(Padova), F. Drent(GSI), F. Recchia(Padova).

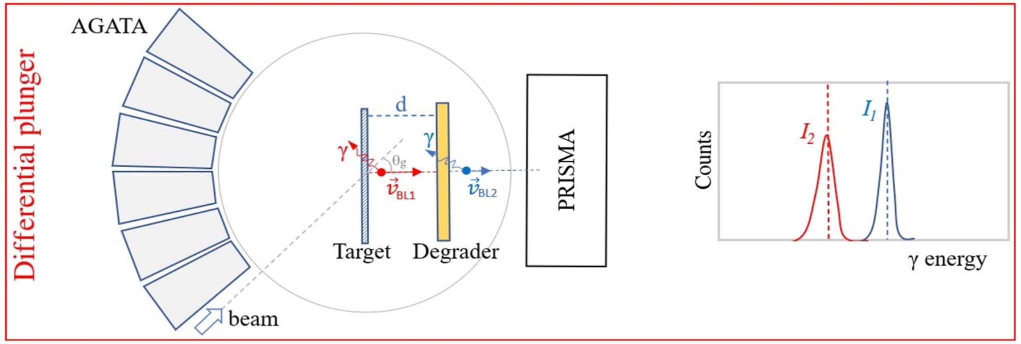
3. Reverse plunger technique: motivation

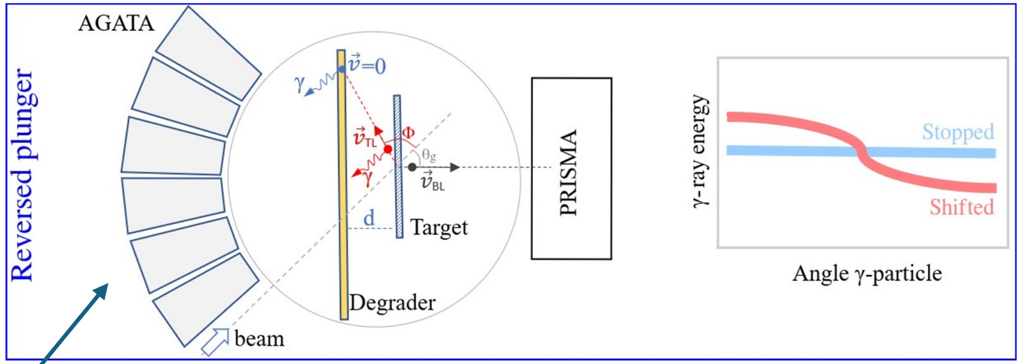
- At 7-10 MeV/u, no Z discrimination for Z>54 in PRISMA
- Kinematics reconstruction of heavy partner in typical binary reaction with AGATA-PRISMA
- No lifetime measurement for heavy reaction residues

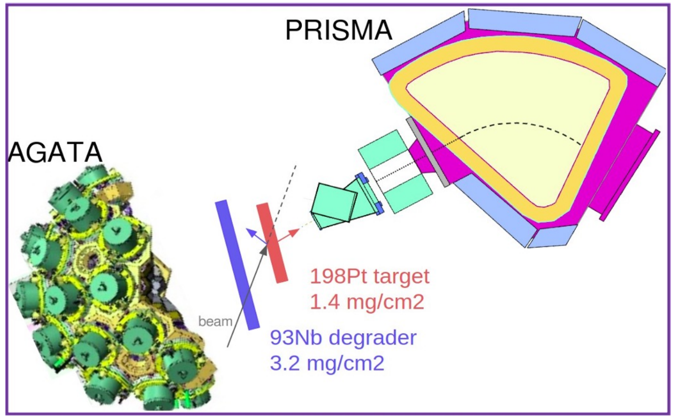
Shape transitions from prolate to oblate and spherical at N=126

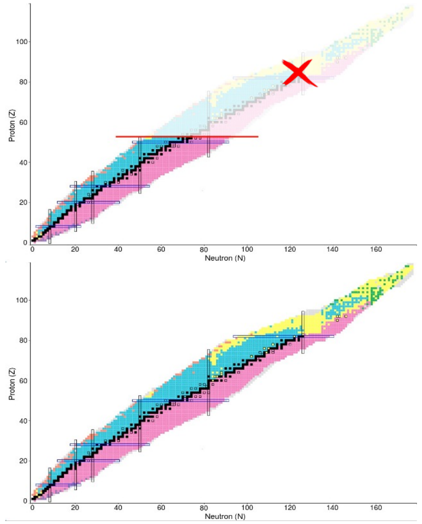


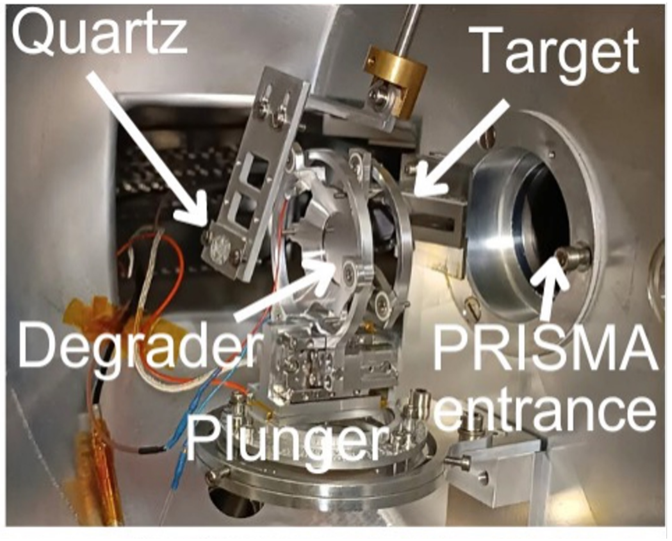
Spokepersons: D. Brugnara, J. Pellumaj







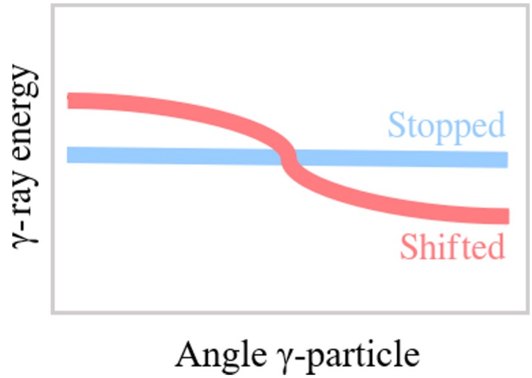




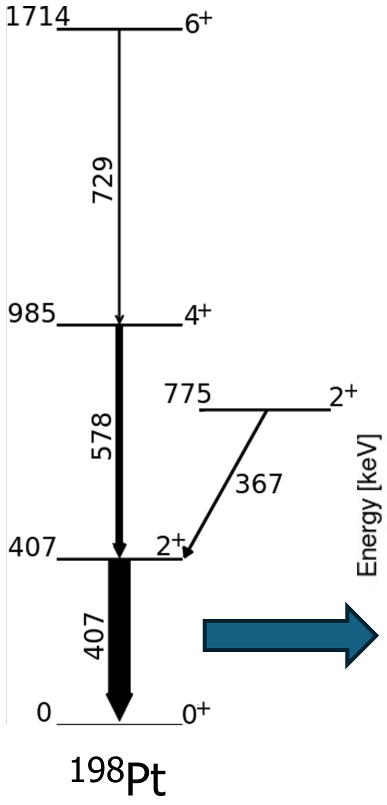
Collaboration with Univ. Cologne

3. Reverse plunger technique: results

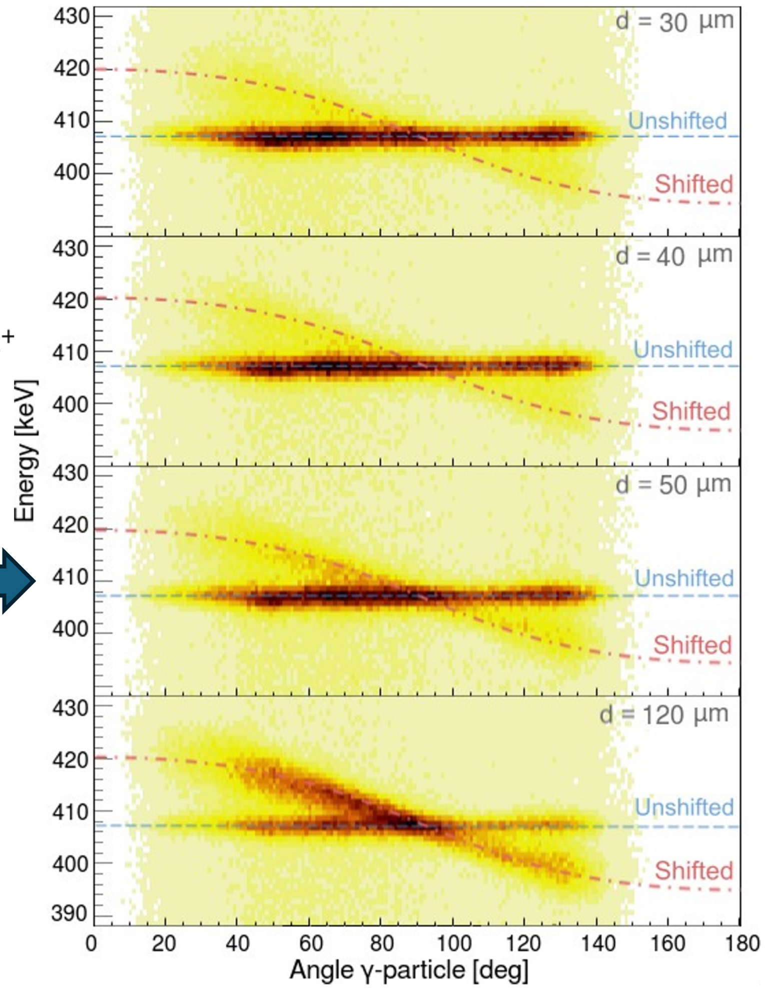
Beam: ^{136}Xe@1134 MeV Target: ^{198}Pt
Degrader: ^{93}Nb PRISMA set at 39°
Plunger (in collaboration with Koln) distances:
30, 40, 50 and 120 μm



E_{lev} [keV]	J_i^π	$t_{1/2}^{DDCM}$ [ps]	$t_{1/2}^{Lit}$ [ps]
407	2_1^+	19.3(3)	22.25(15)
775	2_2^+	30.3(4)	27(4)
985	4^+	4.7(4)	3.3(3)



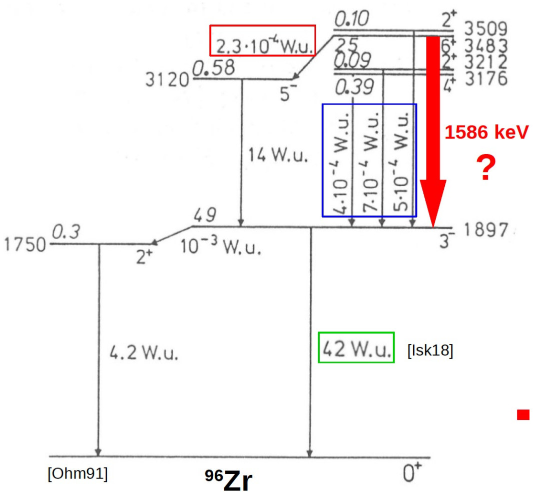
J. Pellumaj PhD thesis



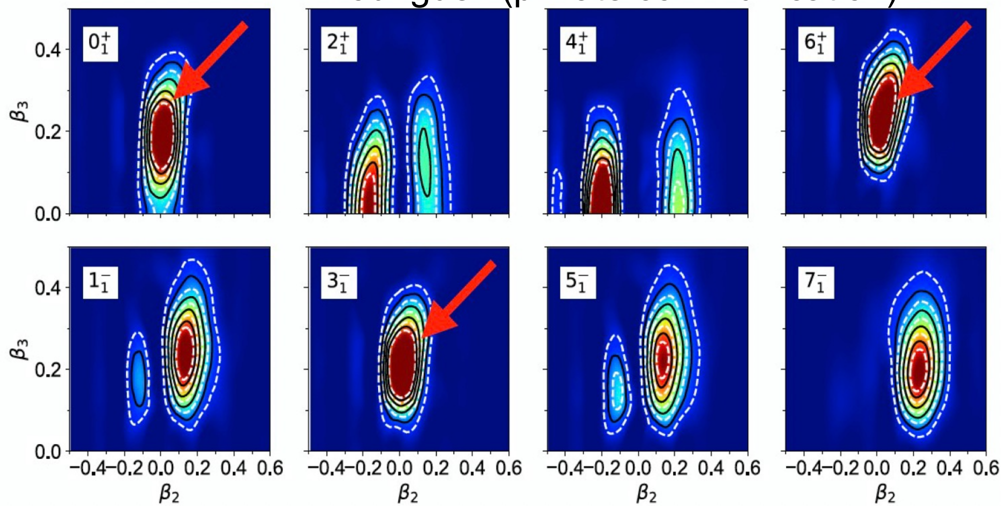
- The technique works and is being applied to measure lifetimes in neutron-rich Pt, Os isotopes !

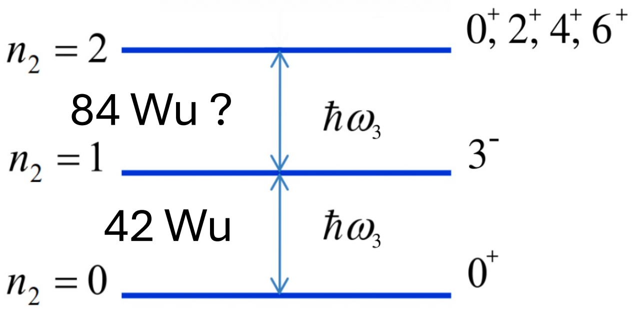
4. Octupole phonons in ^{96}Zr: motivation

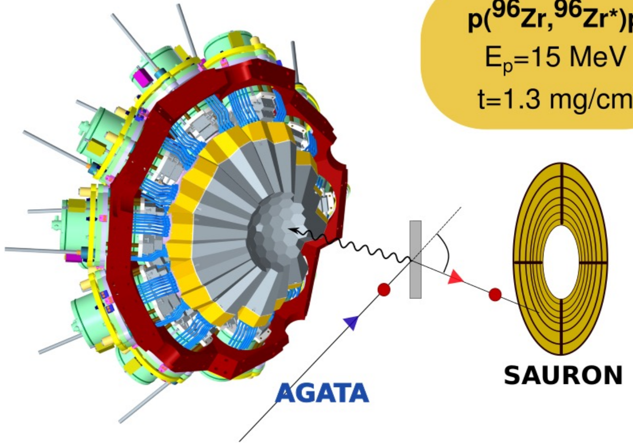
Gogny EDF calculations show strong octupole deformation for 0^+, 3^- and 6^+ collective wf, which indeed present very similar features



T. Rodriguez (private communication)

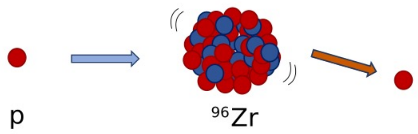






p(^{96}Zr,^{96}Zr*)p'
E_p=15 MeV
t=1.3 mg/cm^2

PROTON INELASTIC SCATTERING



- **γ rays** measured in **AGATA** and light products in the **SAURON annular DSSD**
- **Protons** discriminated via PSA

Measurement by safe Coulex of the B(E3)

D. Doherty, N. Marchini, M. Zielinska

F. Ercolano Master thesis

Unsafe ^{96}Zr Coulex

Spokepersons: D. Stramaccioni/J.J. Valiente-Dobon

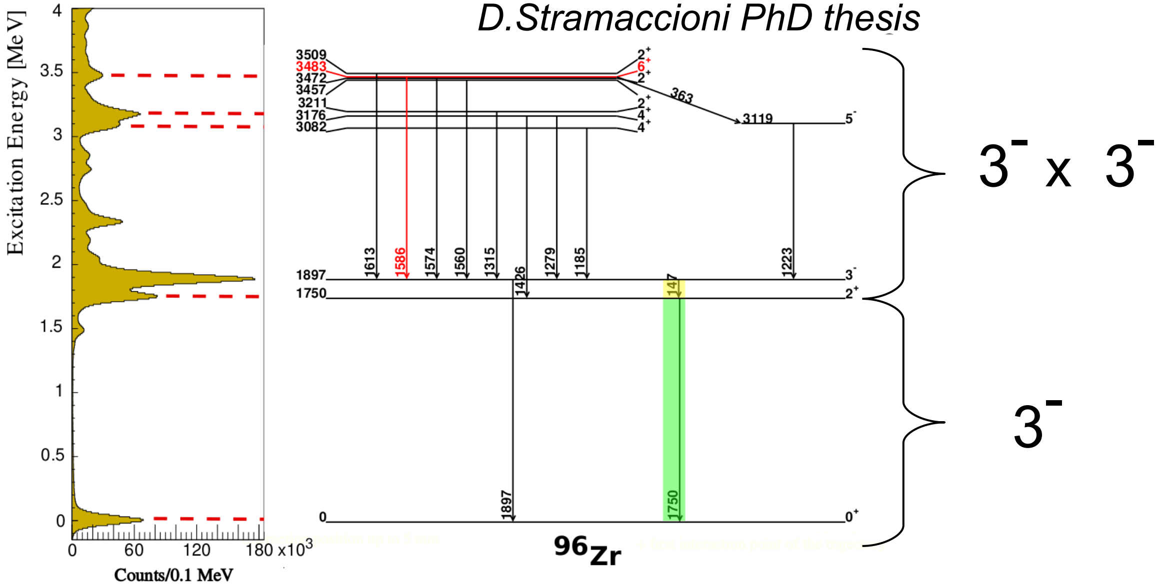
D.Stramaccioni PhD thesis

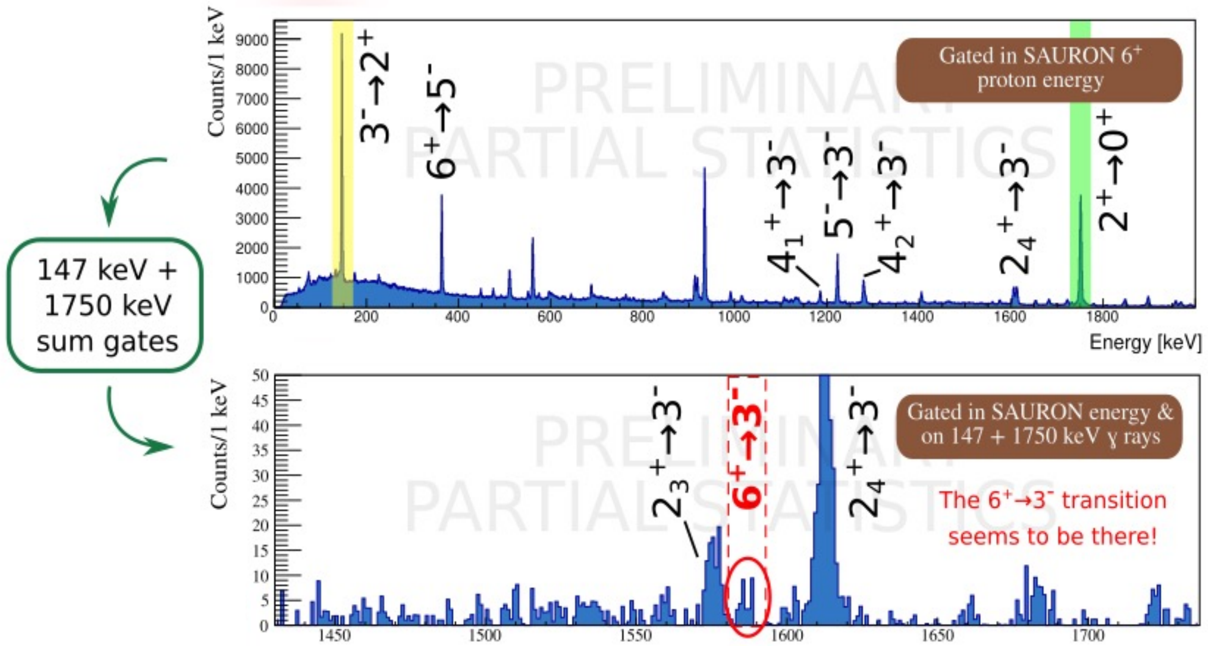
4. Octupole phonons in ^{96}Zr: results

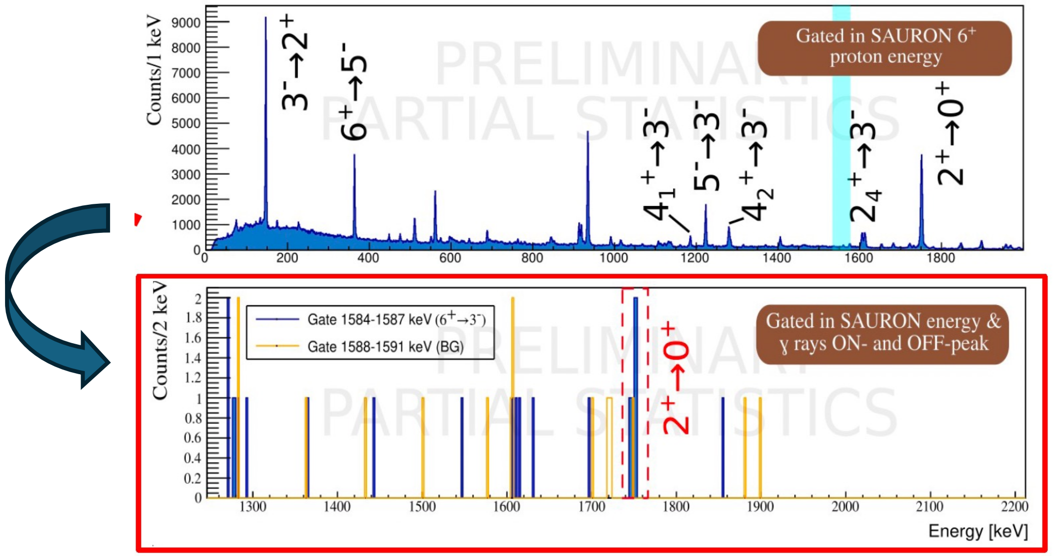
Spokepersons: D. Stramaccioni/J.J. Valiente-Dobon

- The reconstructed ^{96}**Zr excitation energy** spectrum shows that the **6$^+$ state**, along with a few candidates for the other **two-phonon multiplet members**, was strongly populated

- Tentative evidence of an E3 branch connecting 6+ and 3- states. Searching for other members (0$^+$, 2$^+$, 4$^+$) of the double octupole phonon.



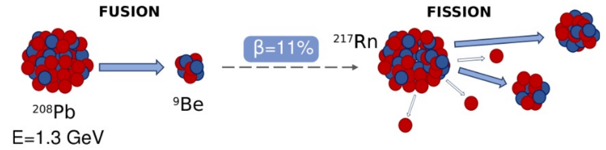


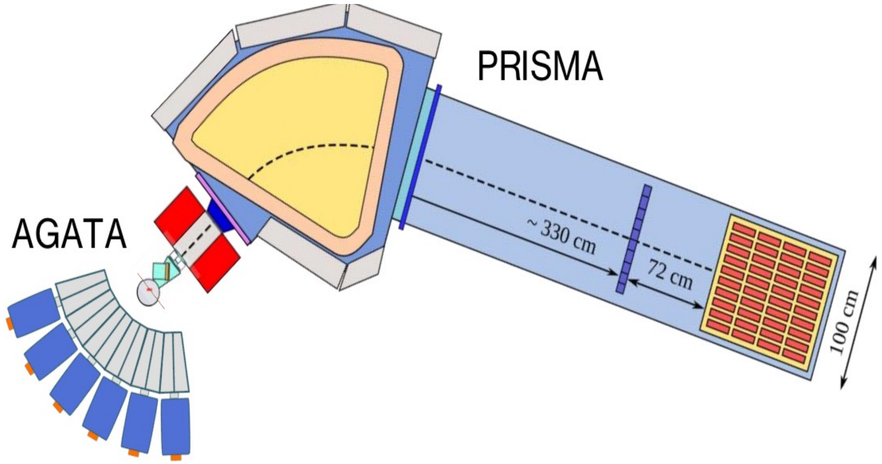


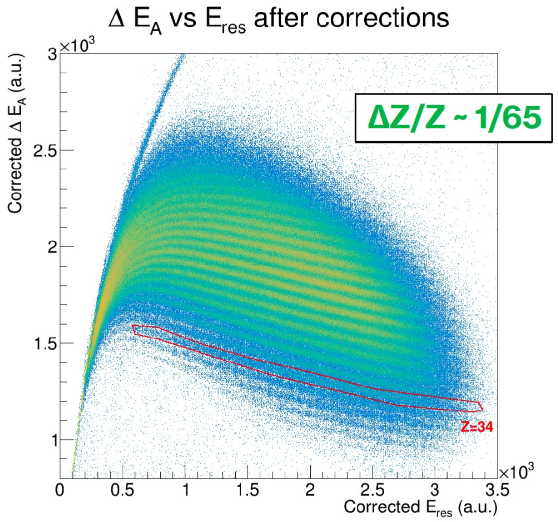
5. Fusion-fission $^{208}Pb+^{9}Be$

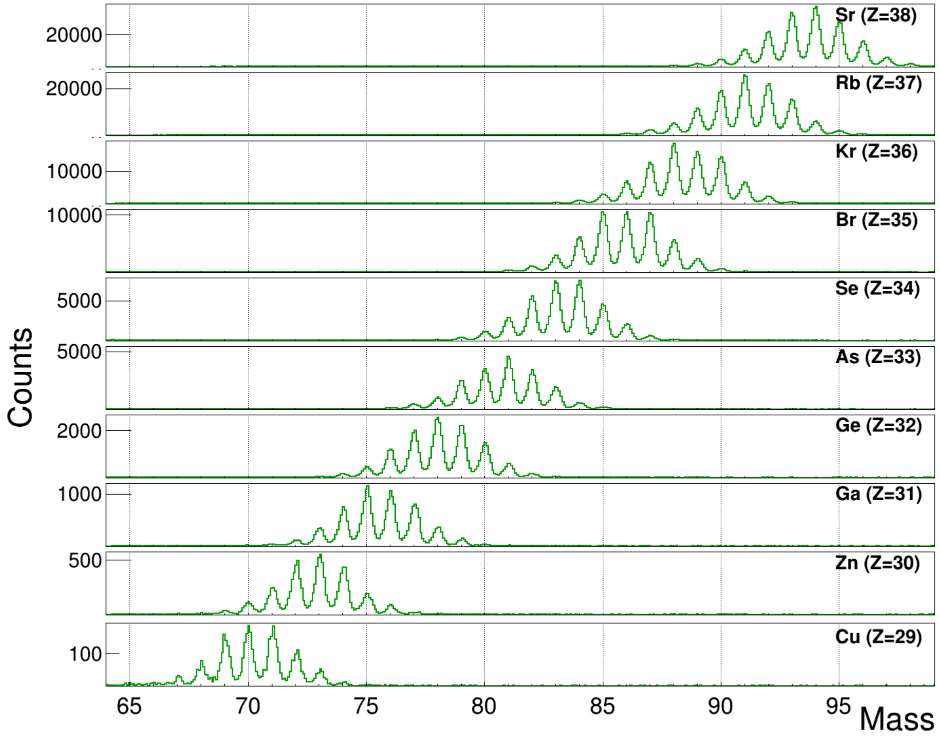
Spokepersons: M. Caamano, A. Gottardo, J.J. Valiente-Dobon

^{208}Pb beam, 6 MeV/u

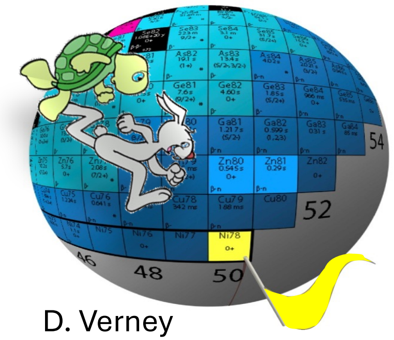








Filippo Angelini PhD thesis (2nd year) UNIPD

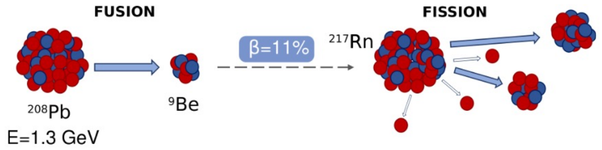


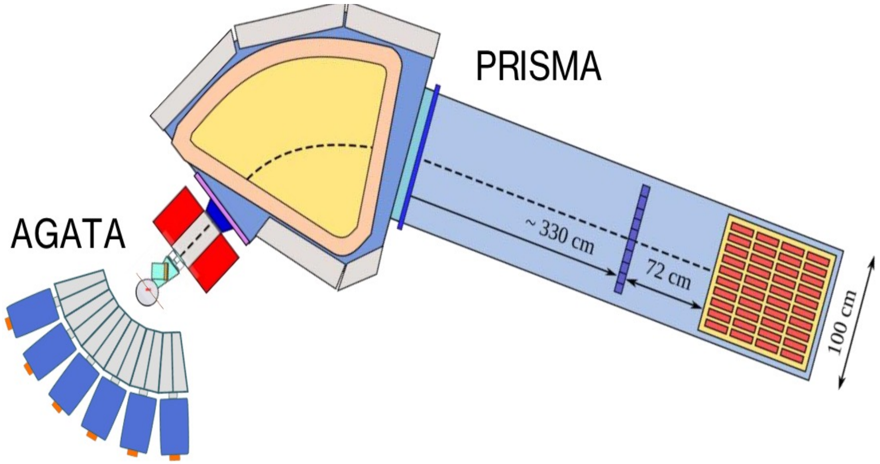
D. Verney

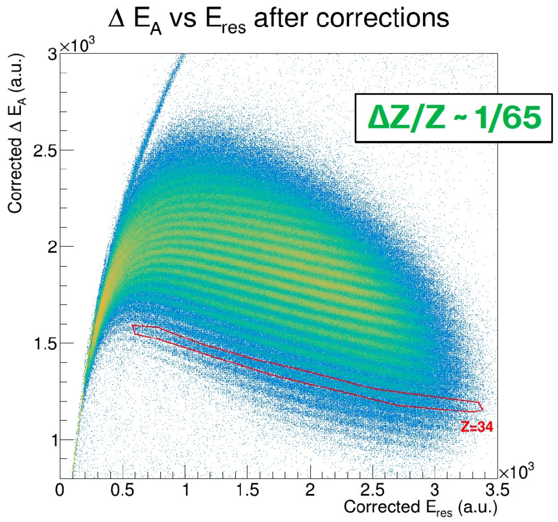
5. Fusion-fission $^{208}Pb+^{9}Be$

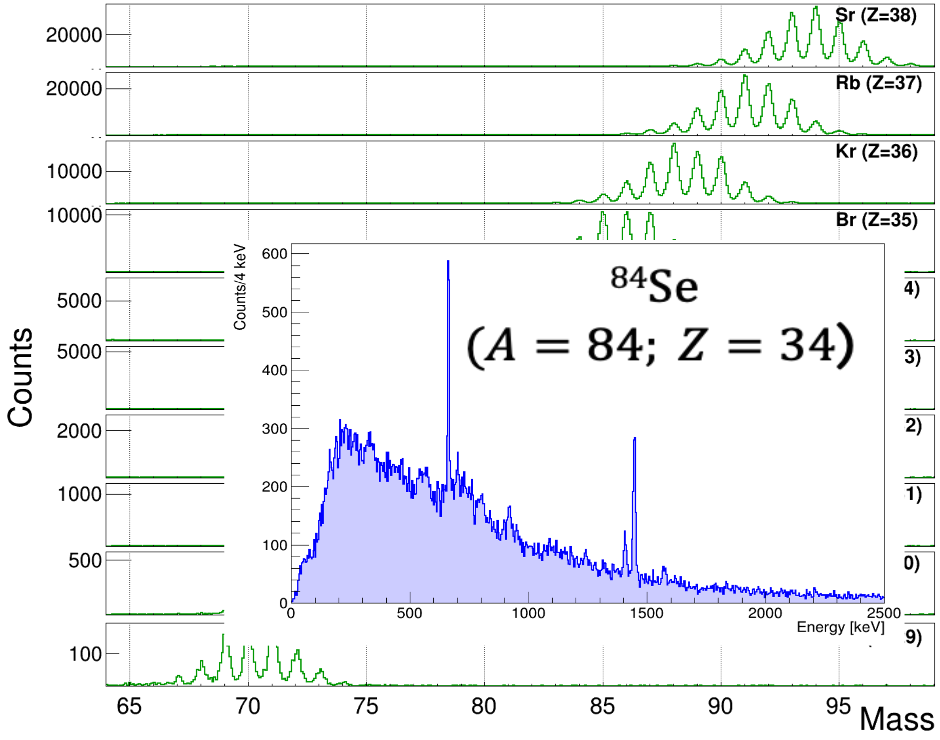
Spokepersons: M. Caamano, A. Gottardo, J.J. Valiente-Dobon

^{208}Pb beam, 6 MeV/u

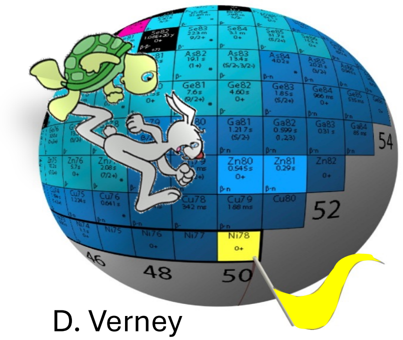








Filippo Angelini PhD thesis (2nd year) UNIPD

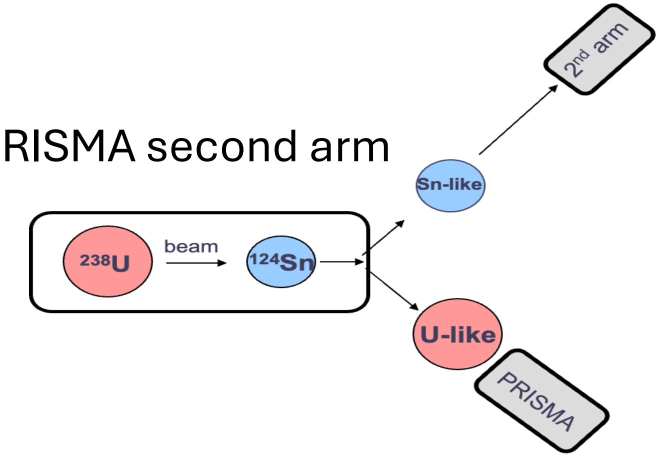


D. Verney

First half 2026: AGATA –PRISMA campaign with ^{238}U beams at 7 MeV/u from PIAVE-ALPI for fusion-fission and MNT reactions

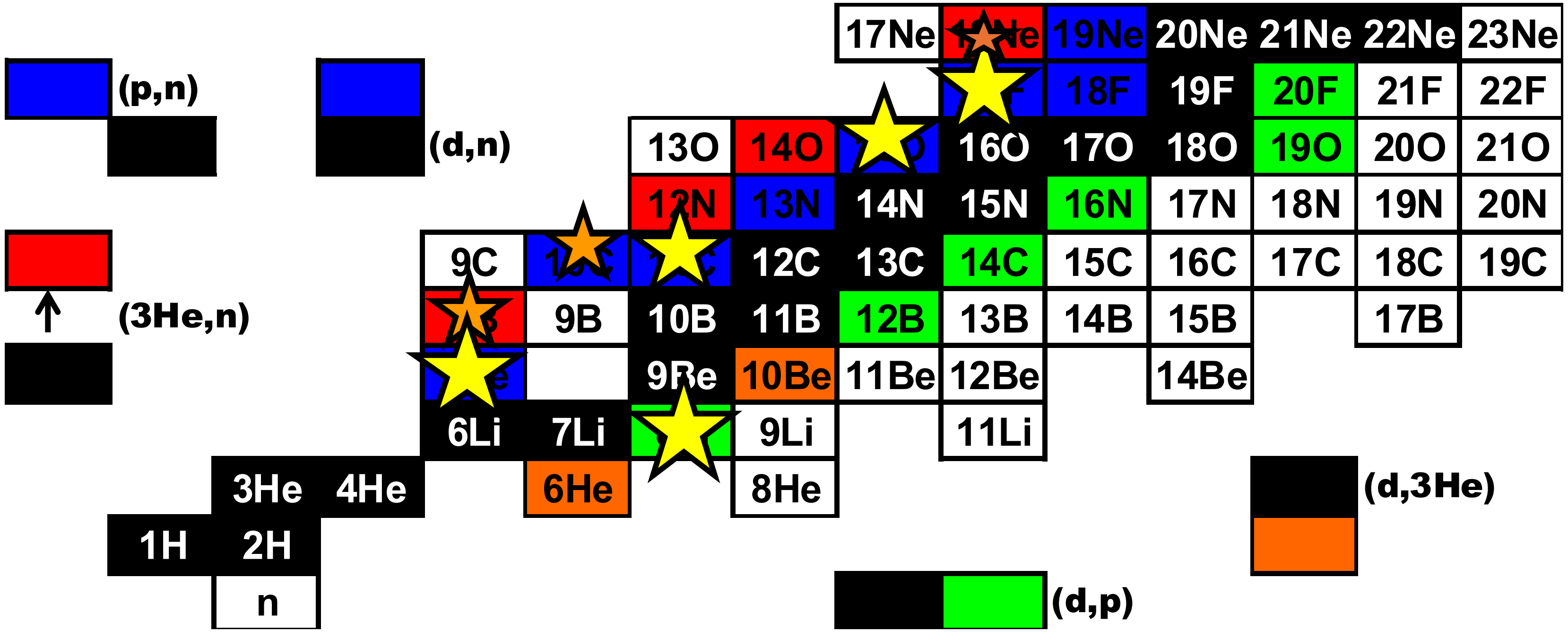
- spectroscopy of medium-spin states
- lifetimes of excited states

PRISMA second arm



Plans for 2025-26

- ^{238}U beams at 7 MeV/u from PIAVE-ALPI for fusion-fission and MNT reactions
- In-flight light exotic beams from EXOTIC facility



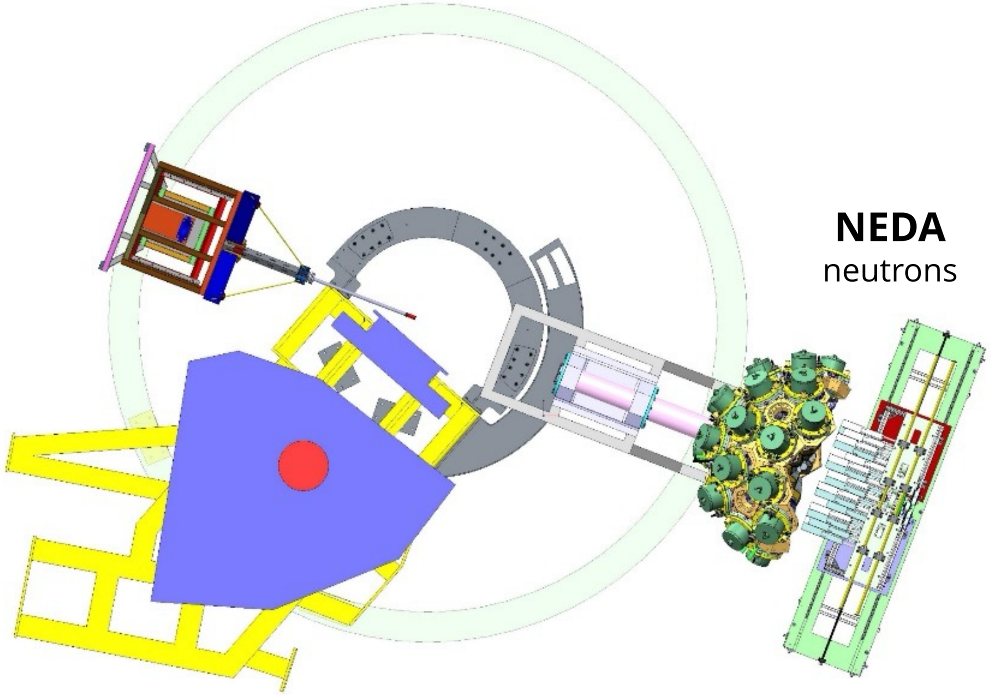
^{17}F	E = 3–5 MeV/u	Purity: **93-96 %**	Intensity: **10^5 pps**
^{8}B	E = 3–5 MeV/u	Purity: **30-43 %**	Intensity: **~ 10^3 pps**
^{7}Be	E = 2.5–6 MeV/u	Purity: **99 %**	Intensity: **10^6 pps**
^{15}O	E = 1.3 MeV/u	Purity: **97-98 %**	Intensity: **$4*10^4$ pps**
^{8}Li	E = 2–2.5 MeV/u	Purity: **99 %**	Intensity: **10^5 pps**
^{10}C	E = 4 MeV/u	Purity: **99 %**	Intensity: **$5*10^3$ pps**
^{11}C	E = 5 MeV/u	Purity: **99 %**	Intensity: **$2*10^5$ pps**
^{18}Ne	E = 1.3 MeV/u	Purity: **95 %**	Intensity: **$6*10^3$ pps (under dev.)**

Soon to be commissioned on AGATA target point

$1.5*10^5$ pps on AGATA target point (150 enA ^{11}B primary beam) !

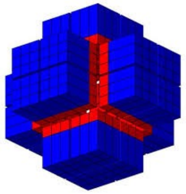
Agata @ zero degree (~ mid '26)

To be implemented in 2026 after the Uranium campaign

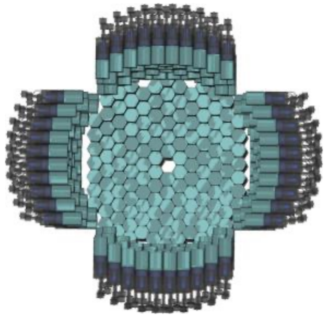


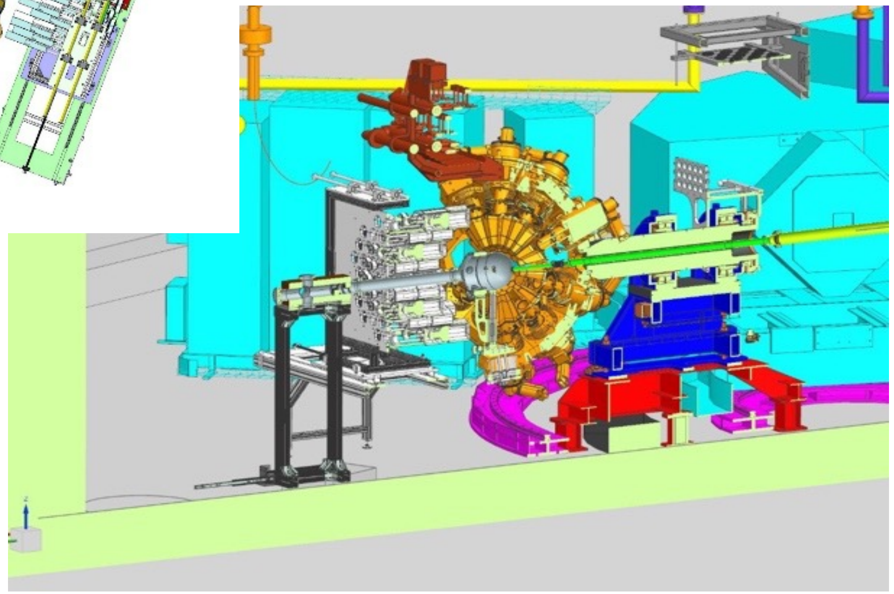
NEDA
neutrons

PARIS
γ-rays

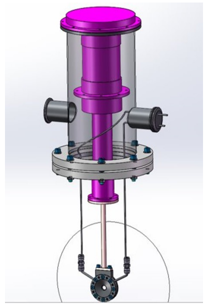


NEDA
neutrons





CTADIR
cryogenic
target



The young strength of AGATA@LNL: PhD, Postdocs

9 nationalities !

INFN
LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

INFN

UNIVERSITAS STUDII PADUANI
MCCXXII

UNIVERSITAS STUDIORUM MEDIOLANENSIS

FLORENTINA STUDIORUM UNIVERSITAS

FERRARIAE UNIVERSITAS
13 91
EX LABORE FRUCTUS

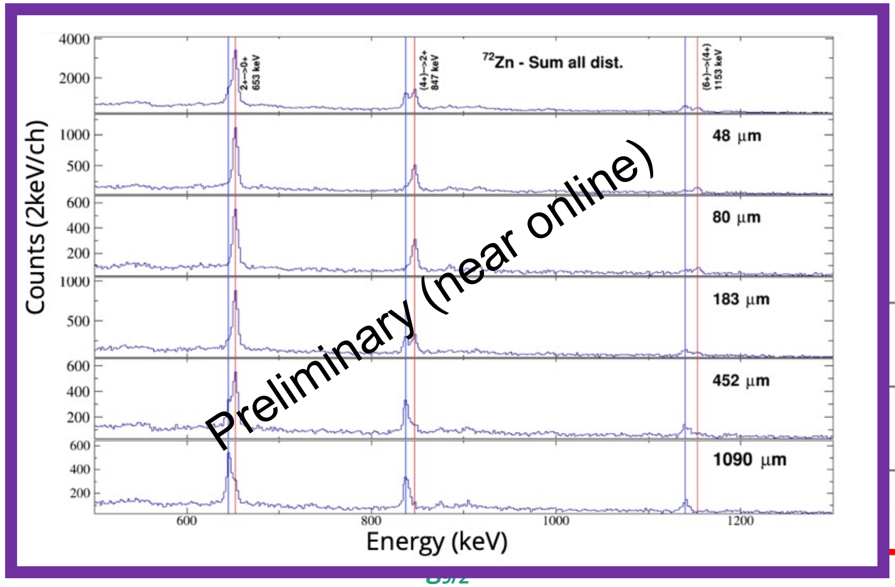
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Thanks for the attention !

Backup

1. Physics of the $\nu g_{9/2}$ shell beyond N=40

- ^{70}Zn @ 470 MeV onto ^{238}U, Nb degrader, AGATA- PRISMA, RDDS

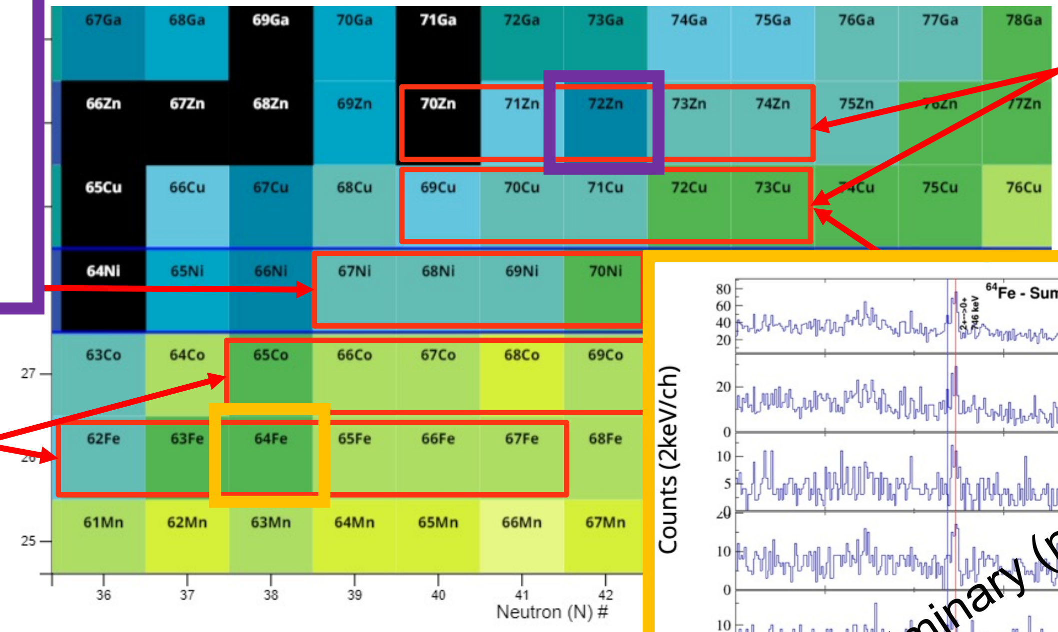


Joint proposal aiming to study the physics of the $\nu g_{9/2}$ beyond N=40:

- Collectivity and seniority conservation in $\nu g_{9/2}$ orbital
- Shape coexistence and octupole vibrations in ^{68}Ni
- Island of inversion and the role of intruders at N~40

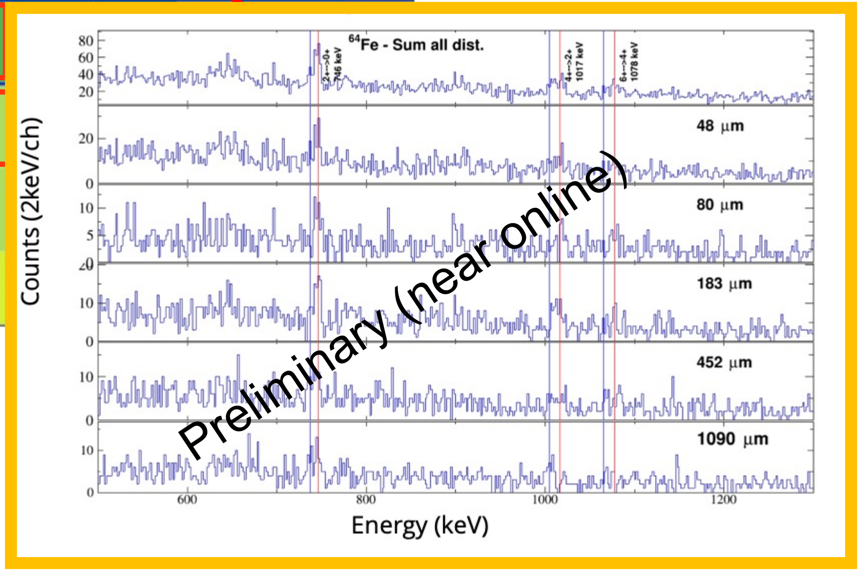
AGATA measurement conditions:

- 50-60 kHz/core
- 100 validations/core



C. Lifetime measurements in neutron-rich $^{67-73}$Cu and $^{70-74}$Zn nuclei above N=40

D. Spectroscopy and lifetime measurements neutron-rich Co and Fe isotopes

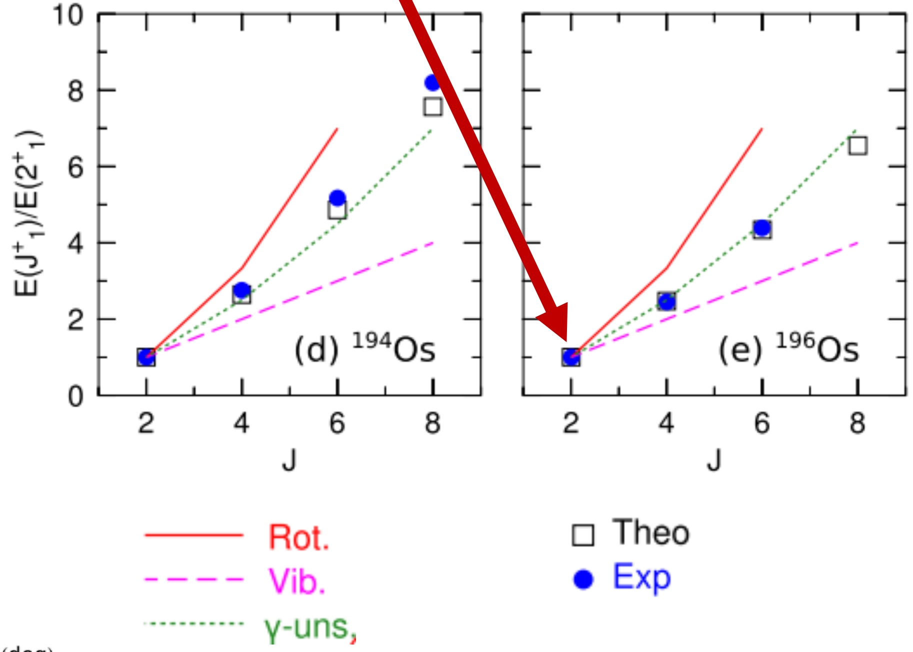


Spokepersons: R.M.Pérez Vidal, S.Bottoni, E.Sahin, A.Illana, J. Benito, J. Ljungvall, M. Doncel, A.Gadea, L.M. Fraile

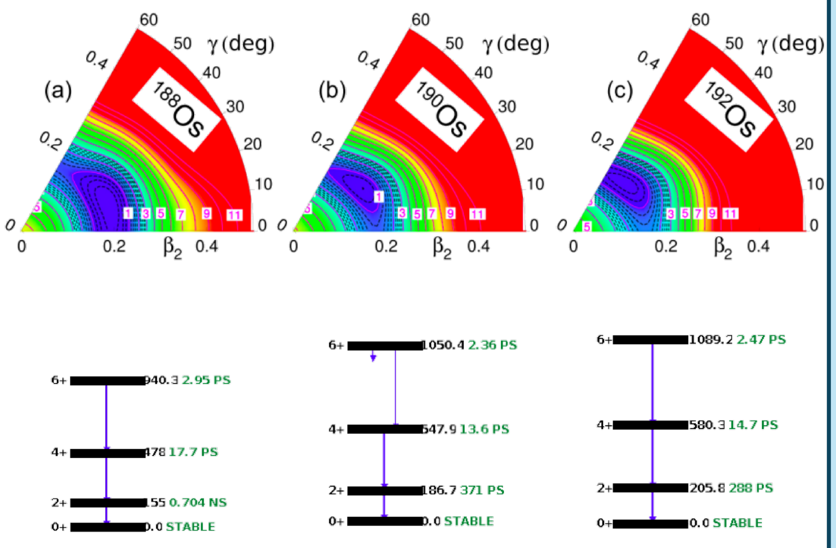
A playground for nuclear models

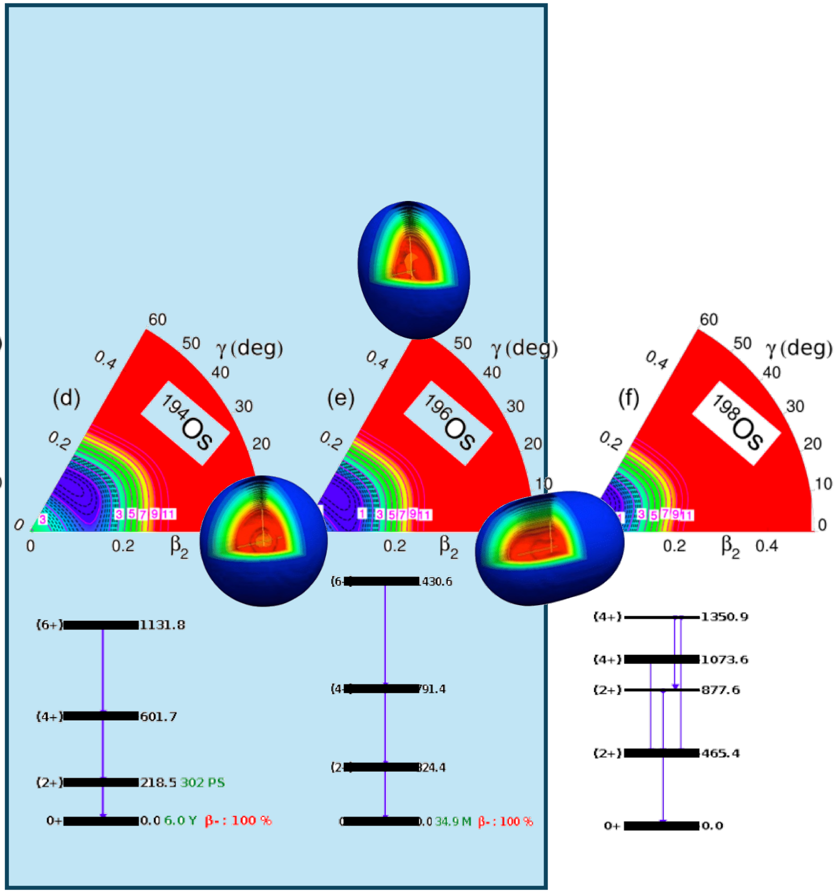
The Os-Pt region shows a unique set of prolate, oblate, axially asymmetric, and co-existing shapes.

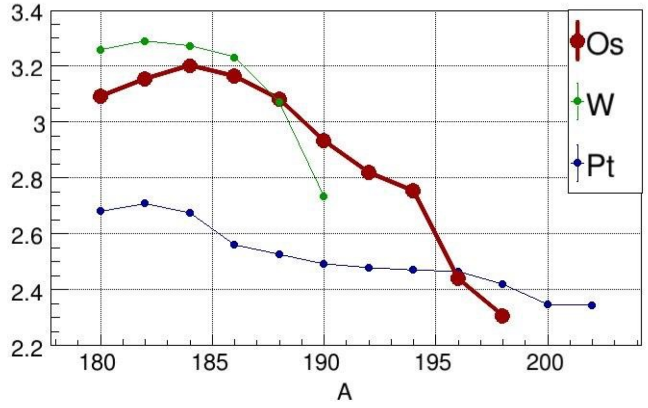
"An almost perfect γ-unstable/triaxial rotor yrast band is predicted for ^{196}Os"



PES calculated by beyond-mean-field with the Gogny D1S interactions + PN-VAP
T. R. Rodríguez



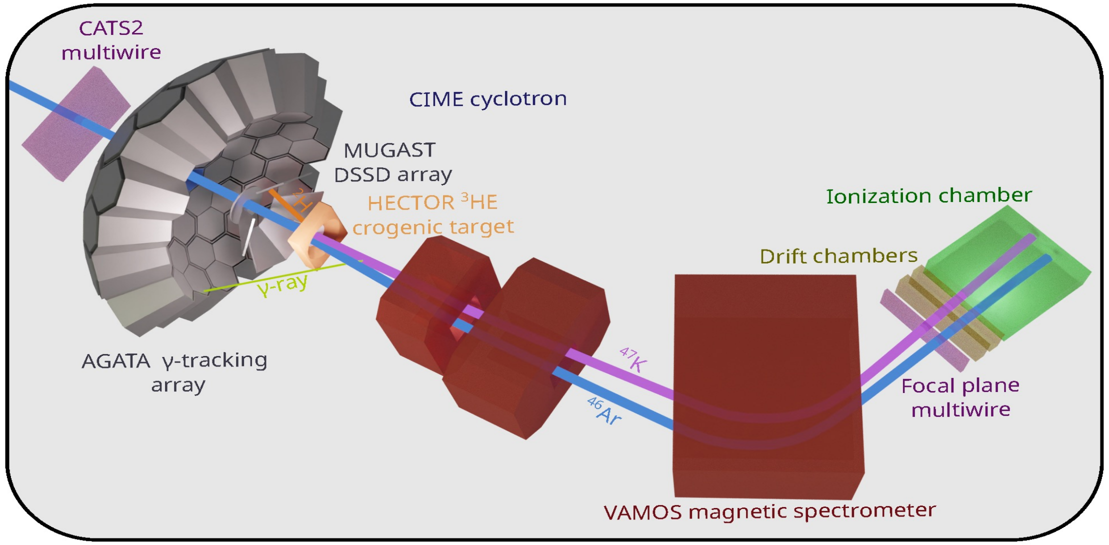


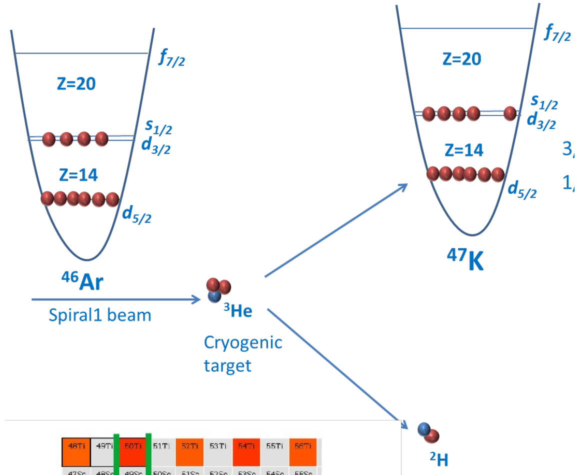


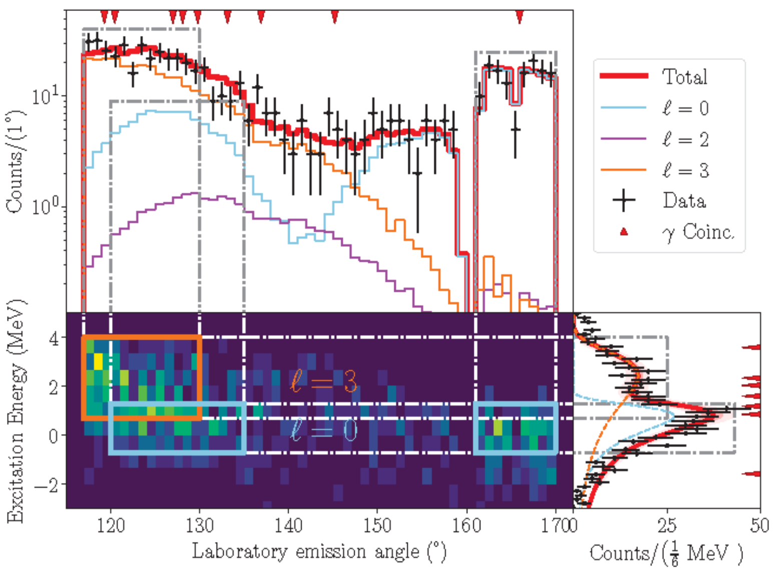
Digression. ^{46}Ar: proton closure, bubble nucleus ?

Spokepersosns: A. Gottardo, M. Assié, D. Mengoni

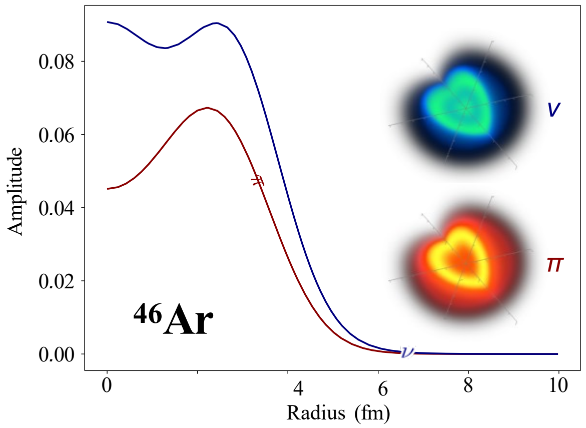
- ^{46}Ar(^{3}He,d)^{47}K experiment performed during the AGATA GANIL campaign with SPIRAL1 beams
- AGATA-MUGAST-VAMOS setup, HeCTOR cryogenic ^{3}He target
- Suppressed proton transfer to the 3/2^{+} state in ^{47}K, contrary to shell-model predictions (SDPF versions)





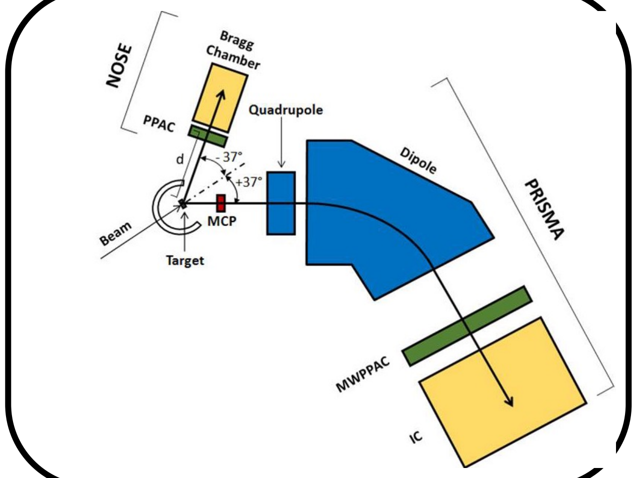


D. Brugnara PhD thesis



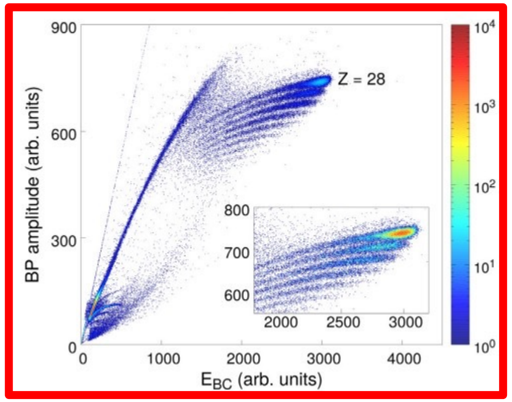
-> Ab-initio NNLO$_{sat}$ calculations predict a closed $\pi d_{3/2}$ shell , and an empty $\pi s_{1/2}$ shell, leading to a proton density bubble in ^{46}Ar

PRISMA second arm

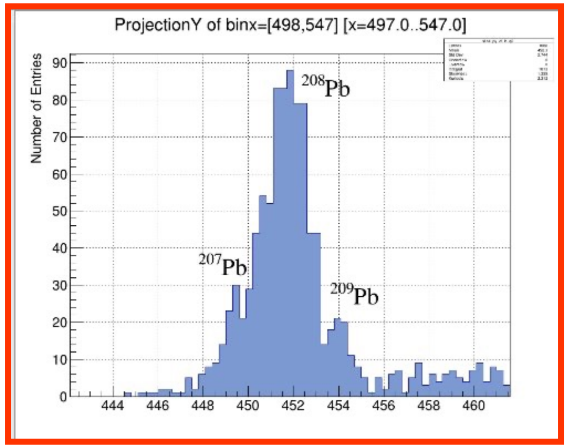


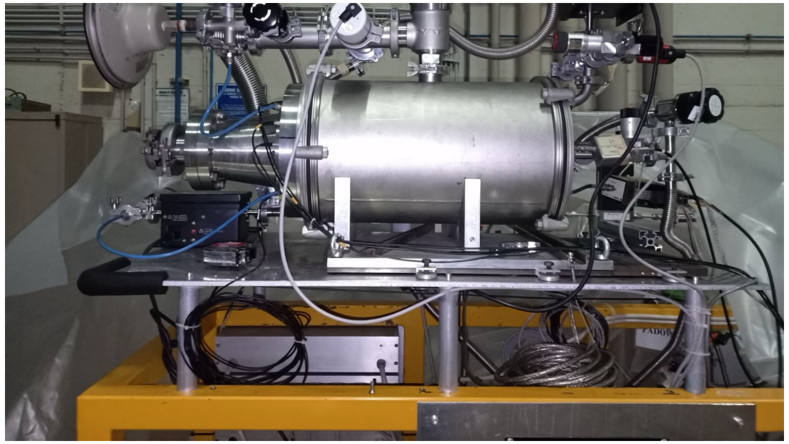
^{238}U → beam → ^{124}Sn →

Sn-like → 2nd arm

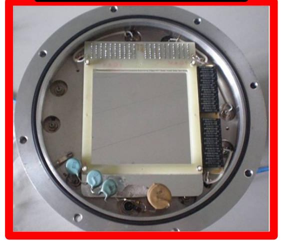


U-like → PRISMA





MWPPAC

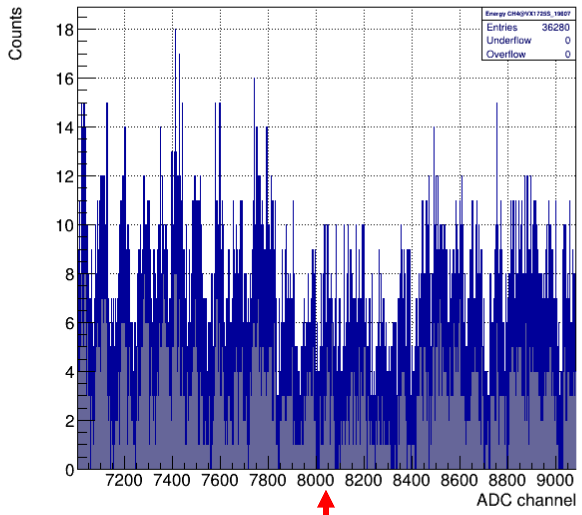


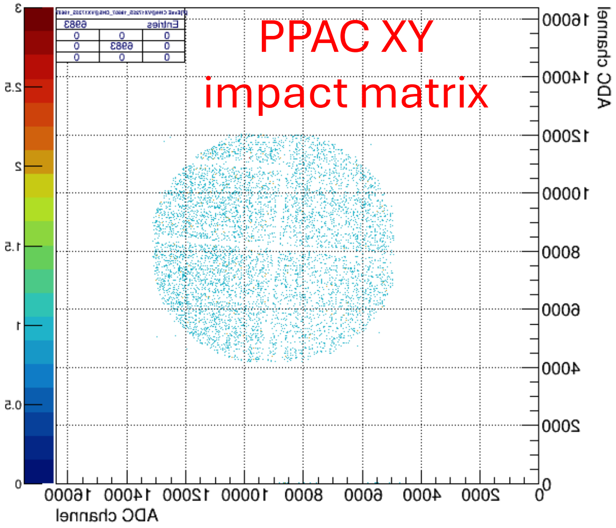
Bragg IC

ULTIMATE GOAL

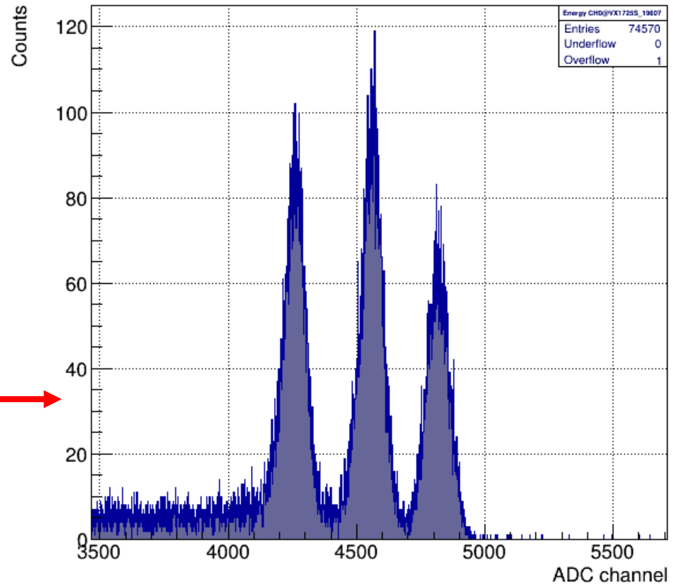
direct identification in PRISMA of ions in the mass range 200 < A < 250 by tagging target-like products selected in Z by NOSE

Prisma second arm tests (06/02/2025)



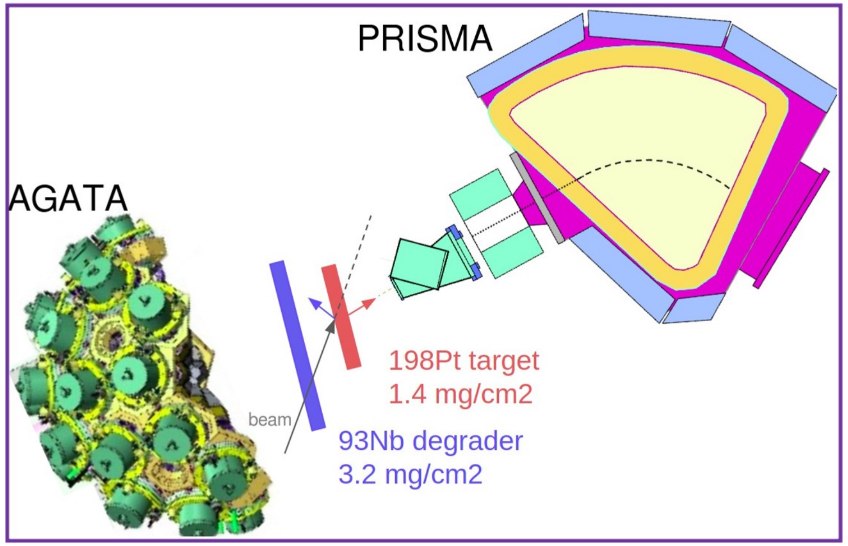


PPAC wires, separated by 1 mm, are visible

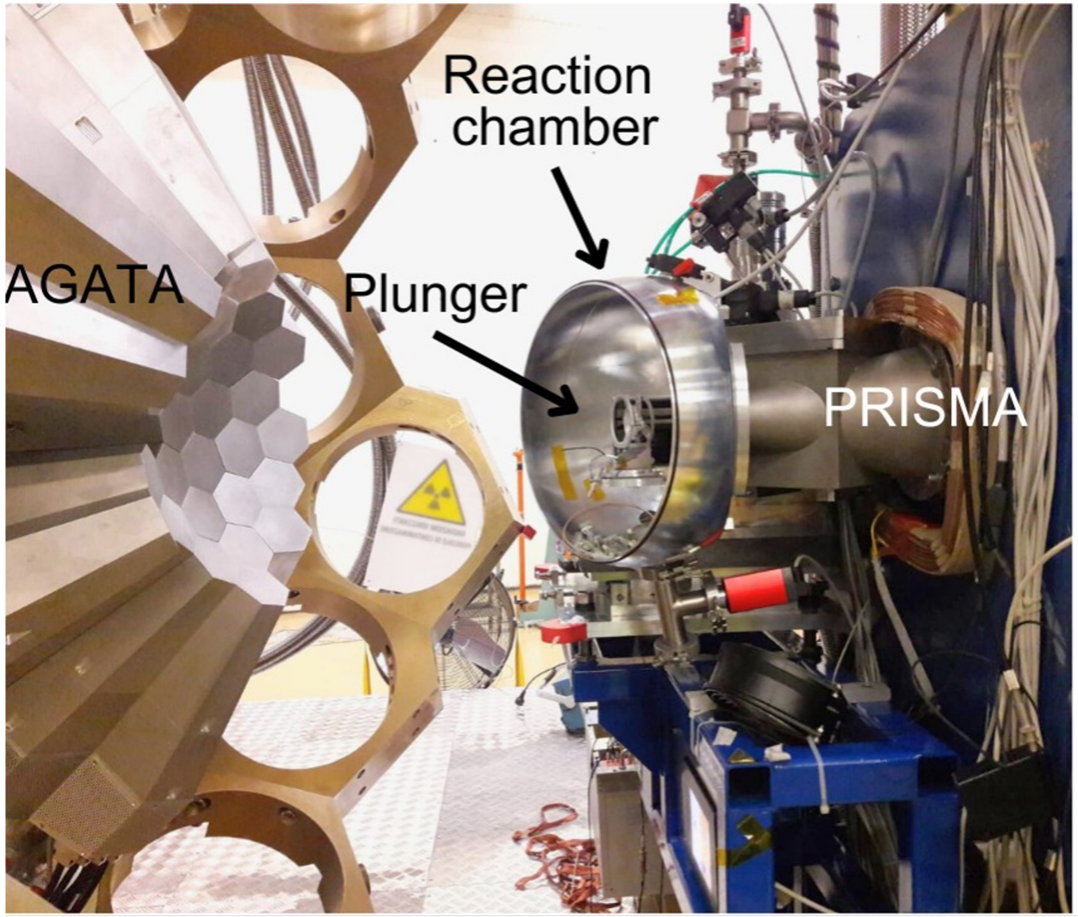


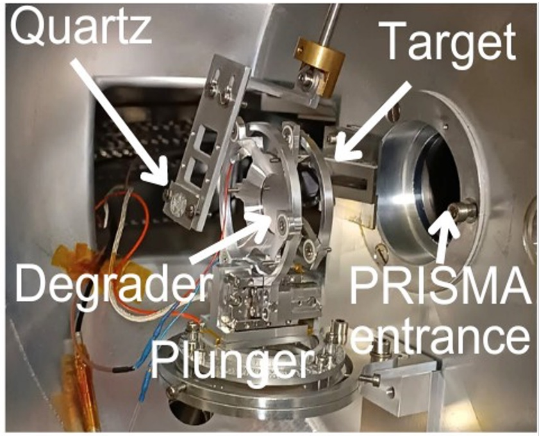
Energy in the Bragg chamber with 3-peaks α source

1. Reversed plunger techinique: setup



Spokepersons: D. Brugnara, J. Pellumaj



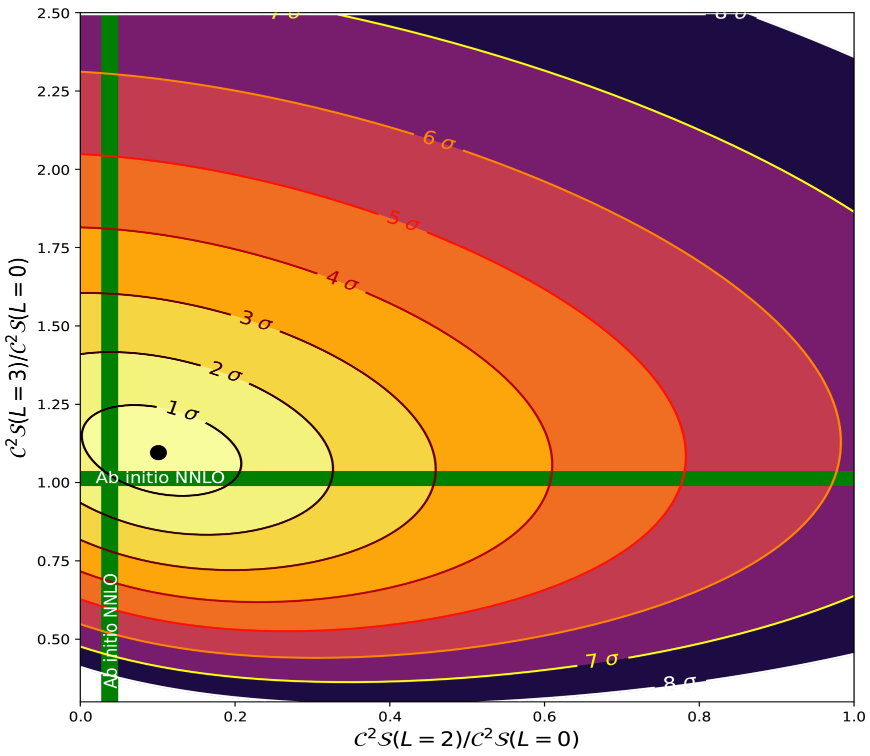


Beam: ^{136}Xe@1134 MeV Target: ^{198}Pt
Degrader: ^{93}Nb PRISMA set at 39°
Plunger (in collaboration with Koln) distances: 30, 40, 50 and 120 μm

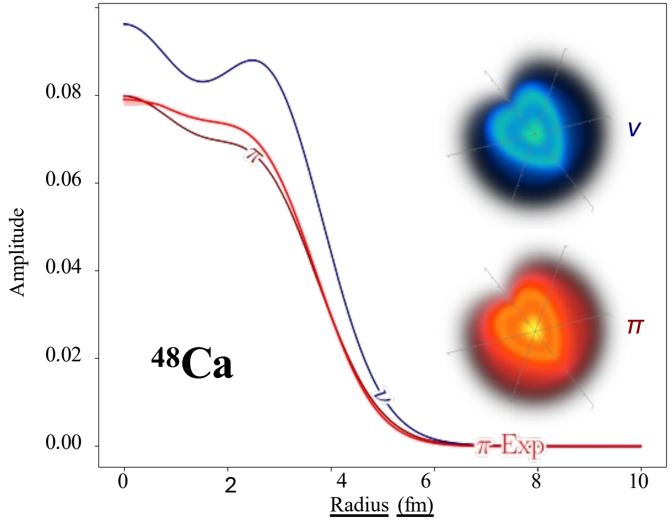
Ab-initio model NNLO$_{sat}$: shell structure

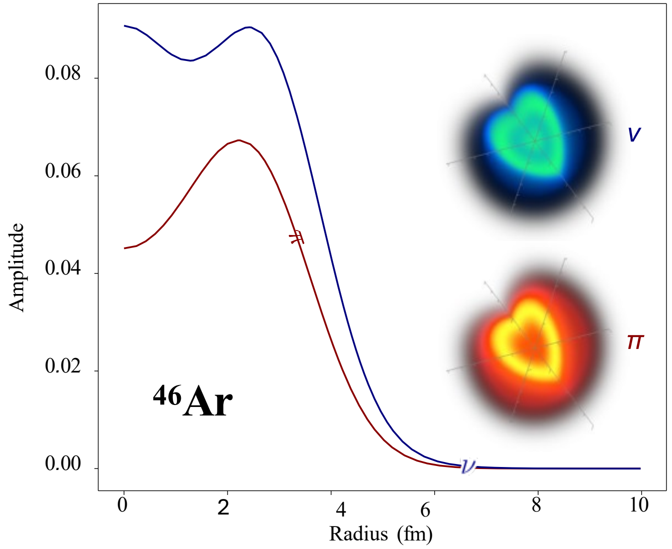
Ab-initio calculations

- Ab-initio calculations with the NNLOsat in ADC2 and ADC3 (C. Barbieri, S. Brolli, V. Somà)
- NNLO$_{SAT}$ chosen because of its capability of reproducing radii (cross check with the NNLO$_{lnl}$ in ADC2)
- 14 harmonic oscillator shells and $\hbar\Omega$=22 MeV to optimize the convergence of binding energies
- BE and charge radii well in agreement with ^{48}Ca and ^{46}Ar data
- **SF in ^{46}Ar in agreement with data**



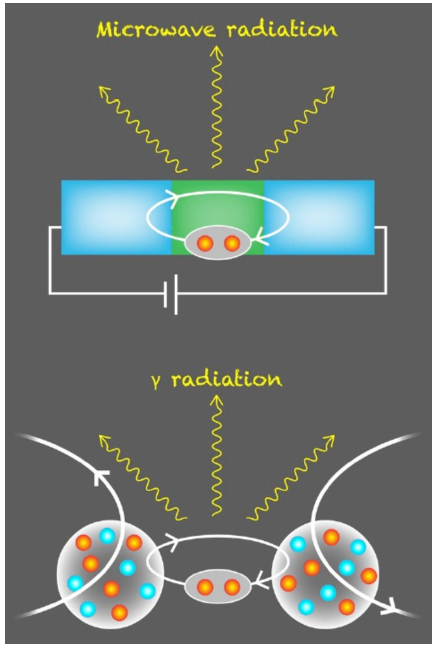
- NNLO$_{SAT}$: a $\pi d_{3/2}$ subshell closure and an empty $\pi s_{1/2}$



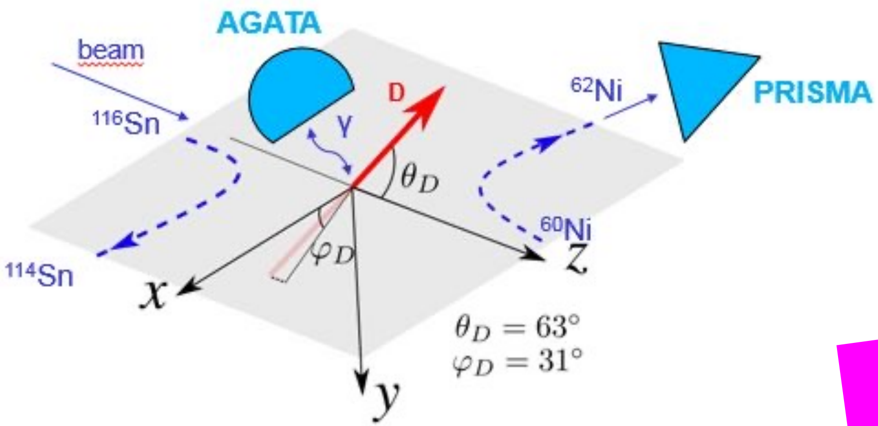


5. Search for a nuclear Josephson effect

- Search for evidence that two colliding nuclei behave like a Josephson junction, a device in which **Cooper pairs tunnel through a barrier between two superfluids**



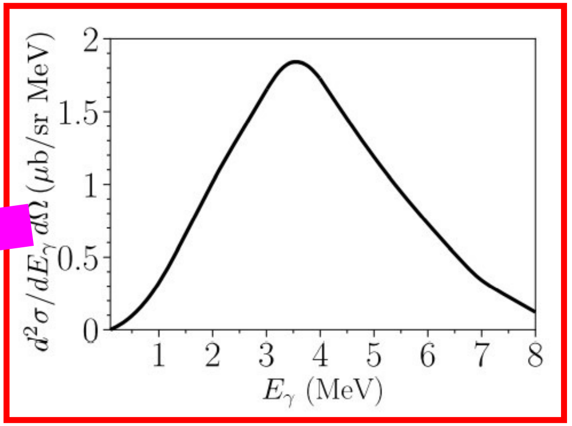
^{116}Sn beam PIAVE+ALPI, E_{lab} = 452.5 MeV, I = 2 pnA
target thickness 200 μg/cm2, Prisma θ_{lab} = 20°

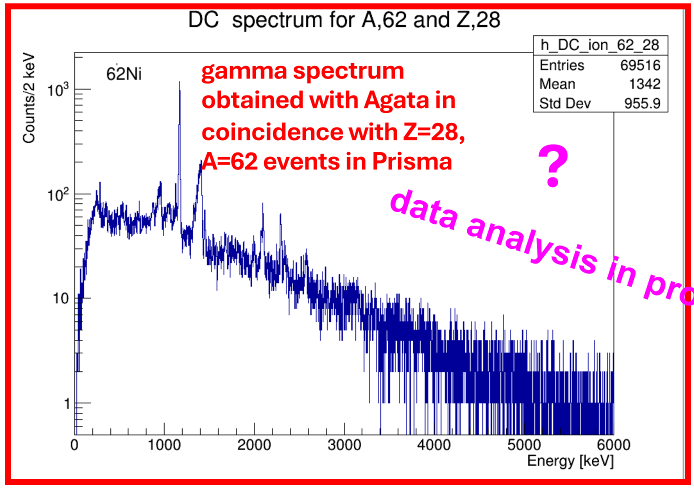


- ^{116}Sn+^{60}Ni reaction at energies below the Coulomb barrier.

- **γ**-ray radiation emitted via a **dipole oscillation D** generated by the two neutron transfer process

gamma ray strength function predicted by Broglia et al.

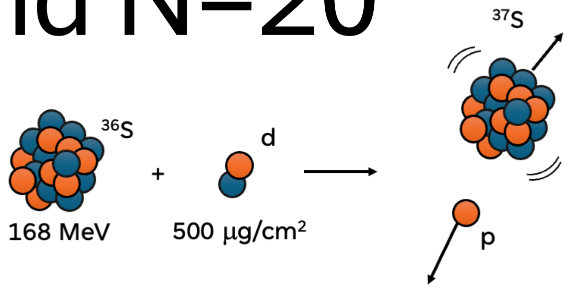




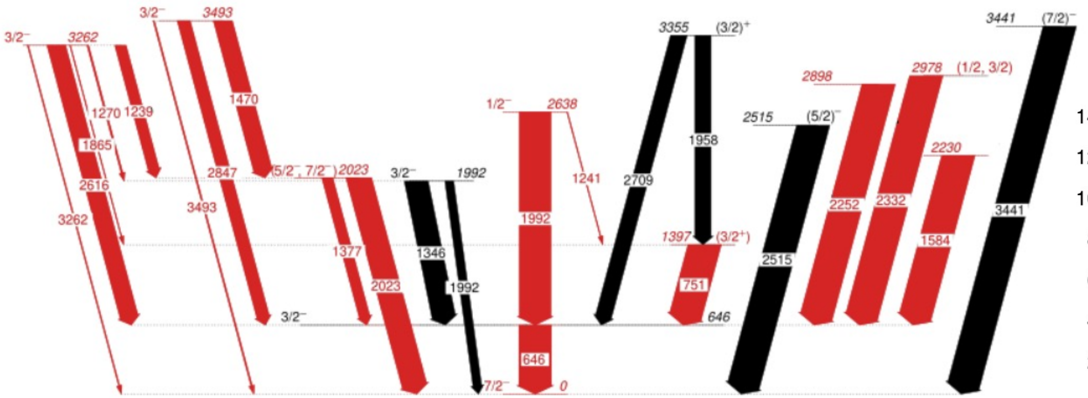
Preliminary data

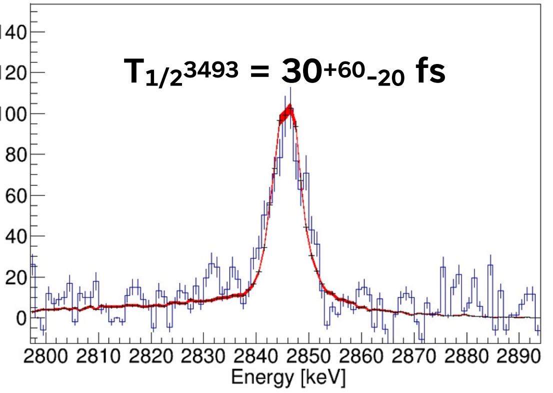
Spokespersons L.Corradi, S.Szilner

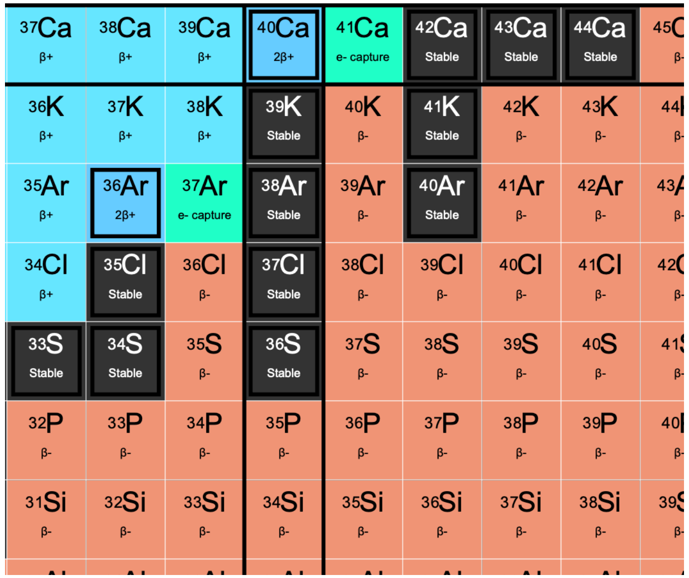
Research focus: shell structure around N=20



- **How to identify single-particle states ? Observable: particle transfer cross section vs B(E2)**
- Co-spokesperson of the first experiment of the LNL AGATA campaign: $^{36}S(d,p)^{37}S$







Results:

- lifetimes of normal and intruder states
- simultaneous test of the shell-model predictions for spectroscopic factors (single-particle dof) AND E2 collectivity (collective dof)

Luca Zago PhD thesis (t.b.d. 2024-25) UNIPD