Gamma-ray and particle spectroscopy activities at FRIB (GASPEC)

Andrea Gottardo (LNL-INFN), for the GAMMA collaboration

NUSDAF Collaboration Meeting, Catania, 21-24 October 2025

Outline

- GAMMA group: physics motivation

- GAMMA group: experience and know-how

 (AGATA campaigns)

- GASPEC: N=Z, direct reactions, Coulomb excitations

FRIB NUSDAF INFN

Scope of the talk:

- **Provide an overview of the GAMMA group activities related to what can be proposed for FRIB**
- **Possible ideas for activities at FRIB**

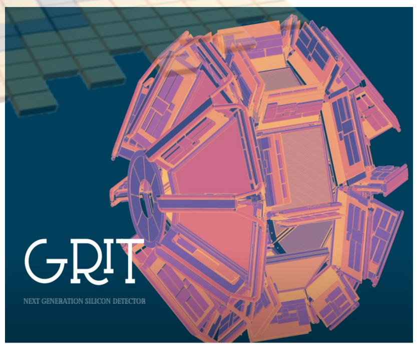
GAMMA: Nuclear structure with γ–ray spectroscopy

GAMMA group

FTE: 52.63 *+ 6 from ext. fundings*
People: 75+4 technicians
5 Sections: FI,LNL,MI,PD,PG

In 2024:
76 publications
151 Talks
25 thesis

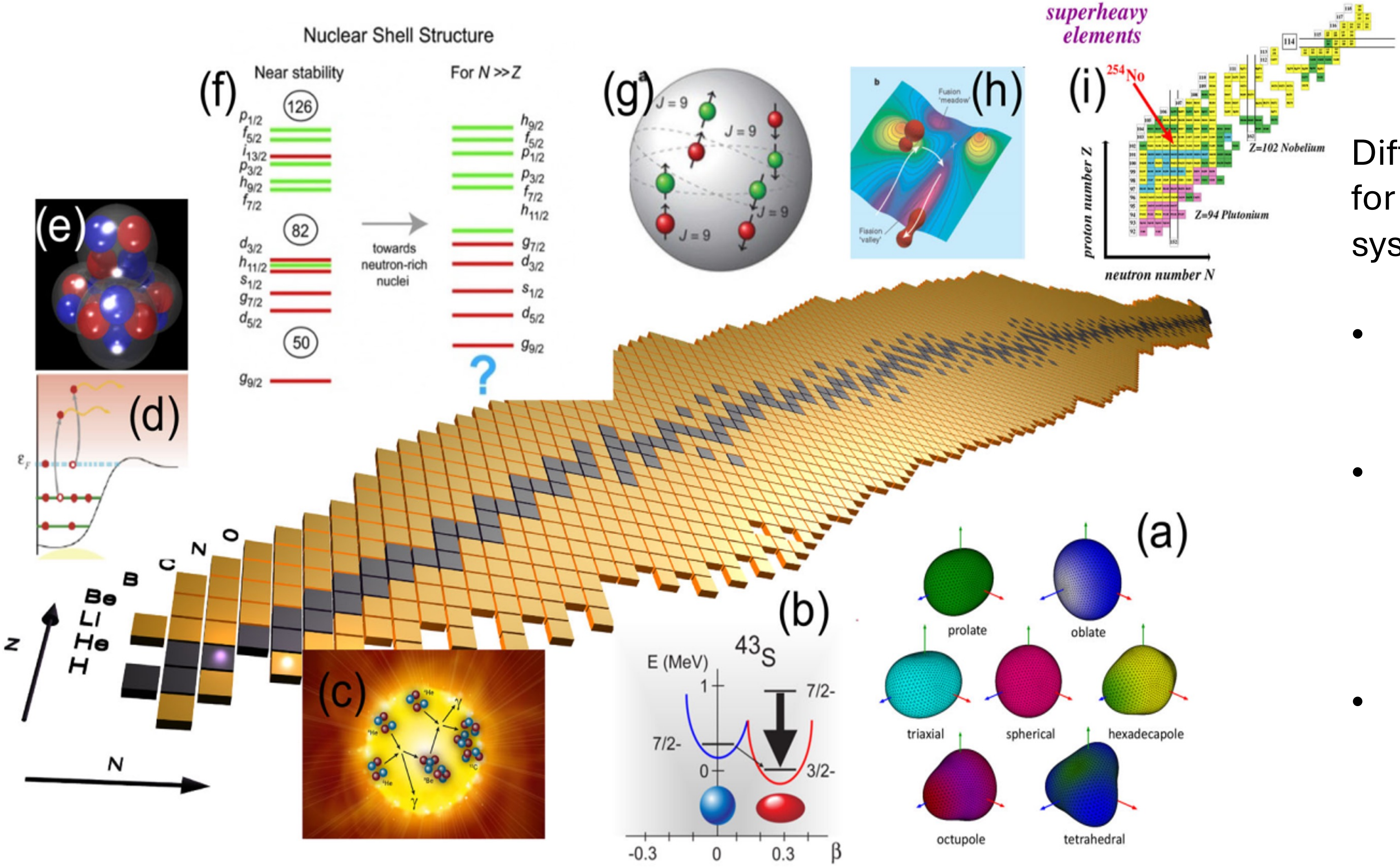
National coordinators:
Benzoni, Gottardo
Local: Galtarossa, Giaz, Goasduff, Rocchini, Simonucci



AGATA ADVANCED GAMMA TRACKING ARRAY

PARIS

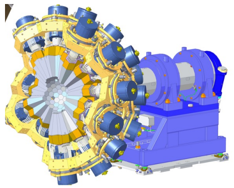
Our playground: the nucleus, a mischievous object



Different observables needed for a complete description of the system at low energy

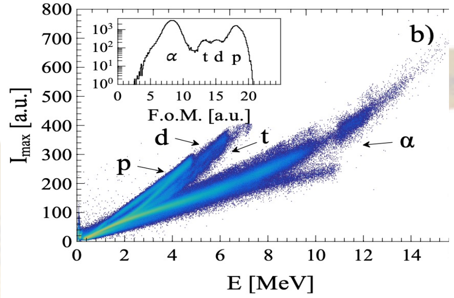
- Electromagnetic probes: γ-ray emission, electron scattering
- Hadronic probes: periferic («direct») nuclear reactions, deep inelastic reactions, compound nucleus reactions
- Impact on astrophysics (nucleosyntheis), on weak-sector physics (CKM unitarity, EDM)

Main lines of the GAMMA collaboration

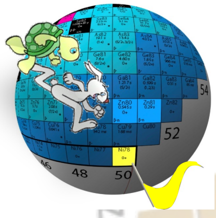


Development and operativity of large arrays:
AGATA
PARIS
GRIT

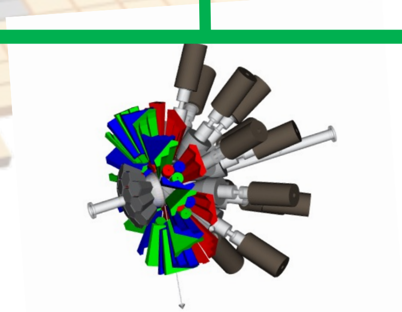
Next generation training



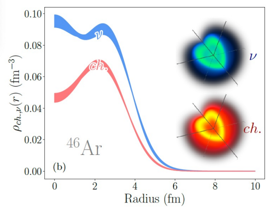
Technological development for detectors
Electronics
DAQ



Measurements campaigns in national and international laboratories



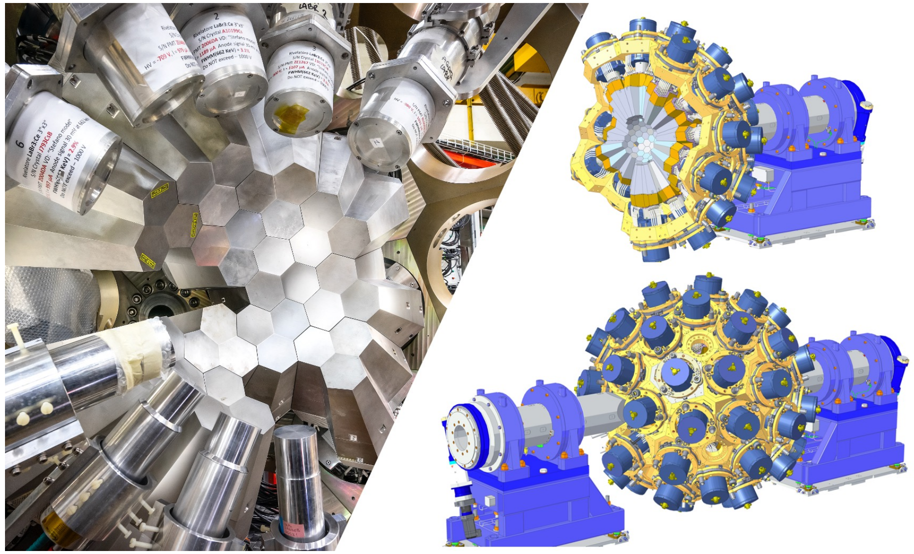
New resident arrays for INFN national laboratories



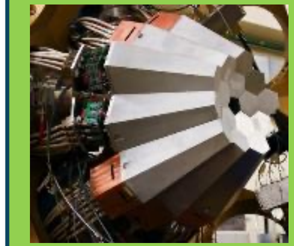
Synergies with other research lines and theoretical groups

AGATA development and campaigns

- Experience in operating γ-ray tracking arrays
- Collaboration AGATA-GRETA on tracking algorithms
- Development of physics cases adapted to γ-ray tracking arrays with both <u>stable</u> and <u>radioactive</u> beams



2010-2012
Legnaro, Italy
Intense stable beams
15 detectors

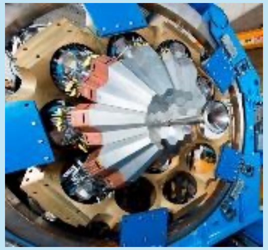


AGATA Demonstrator + PRISMA at LNL

2012-2014
GSI, Germany
Fast fragmentation beams
25 detectors

AGATA at GSI

2014- 2021
GANIL, France
ISOL and stable beams
approaching 1π (45)



AGATA at GANIL

2021-- 2028
LNL, Italy
Stable beams
SPES radioactive beams

AGATA at LNL 2.0

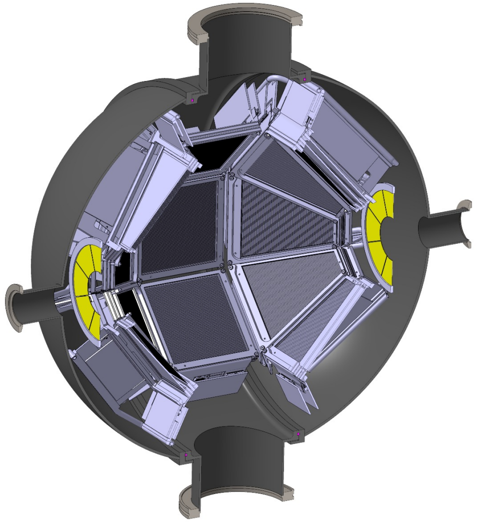
2028- 2030 (?)
GANIL, France
ISOL SPIRAL 1 Beams

AGATA at GANIL

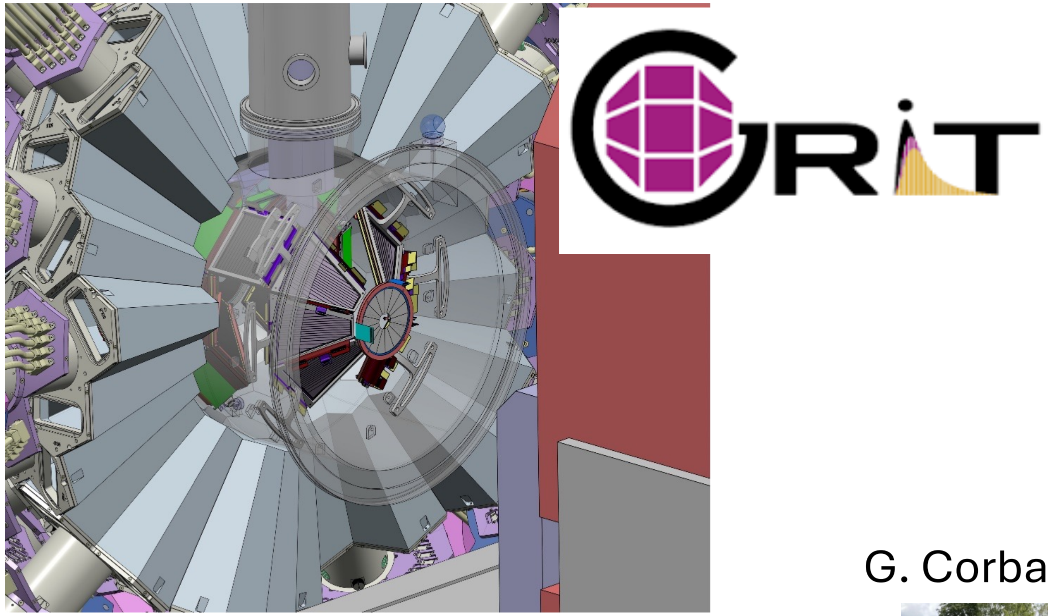
>2030
LNL, SPES, Italy
FAIR, Germany
ISOLDE, CERN
GANIL, France
JYFIL, Finland
RIB at low and high energies

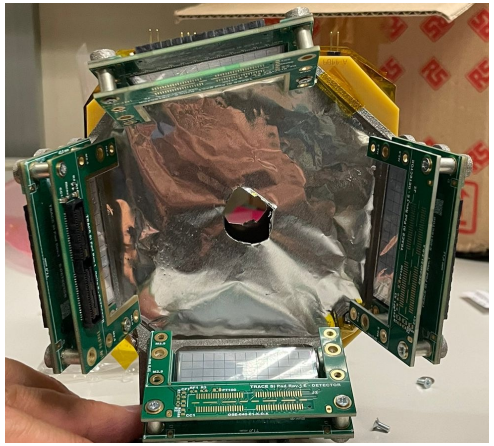
Development and operation of segmented Si arrays

- France-Italy-Spain-UK-Croatia-India, collaboration
- High-segmented Si array
- 4π angular coverage
- Particle discrimation with both E-ΔE and PSA techniques
- Fully compatible with AGATA
- Several experimental campaigns already performed with prototypes
- TRACE detector developed locally in Italy within GAMMA collab.



GRIT at the center of AGATA with the CTADIR target

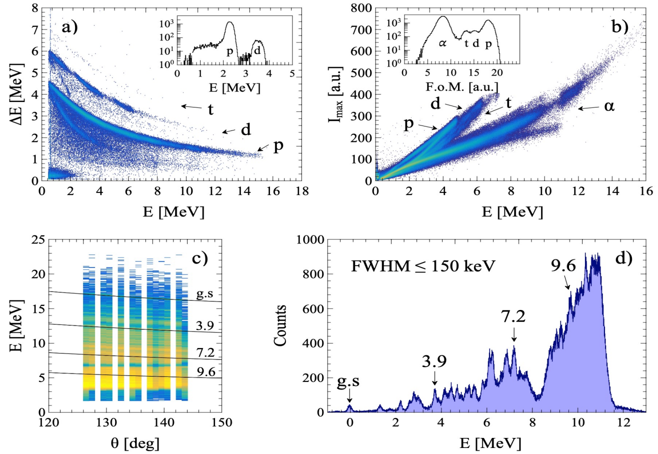




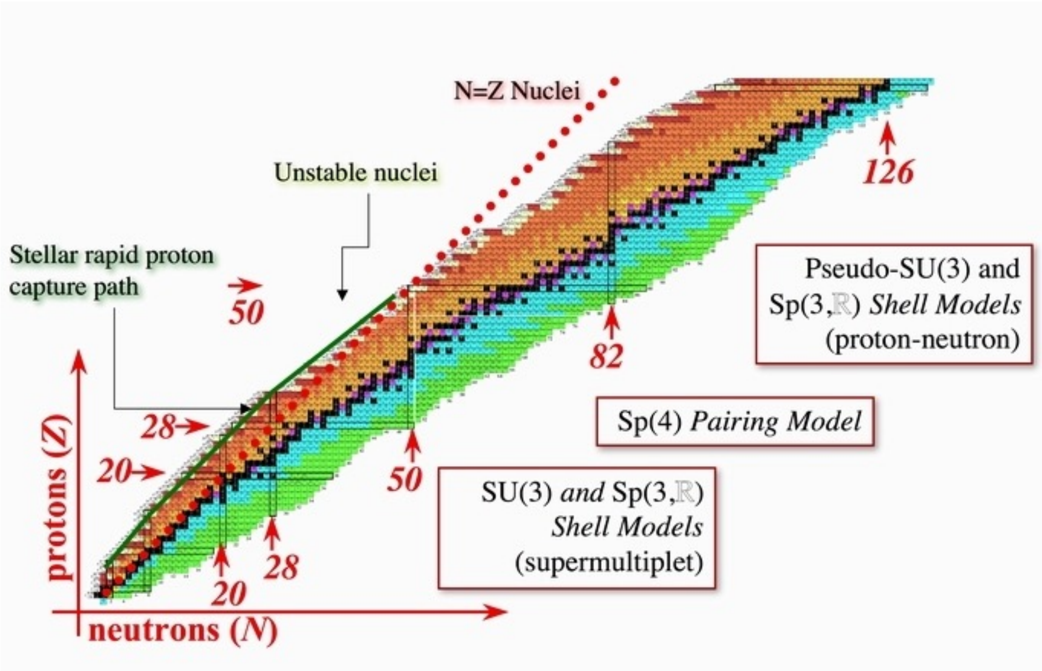
The Commissioning of TRACE

Outcome of the test:

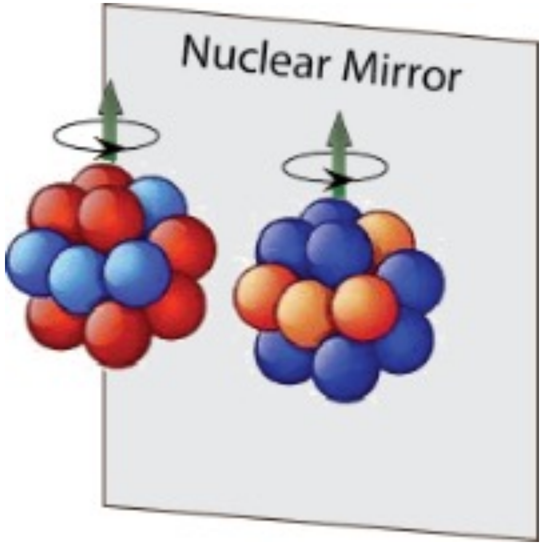
1. **In-beam** test of the new components (Preamp., kapton cables, …)
2. **Particle ID** capabilities with E-DE and PSA
3. **Grouping scheme** for the readout technique
   A. DE layer
   B. E layer



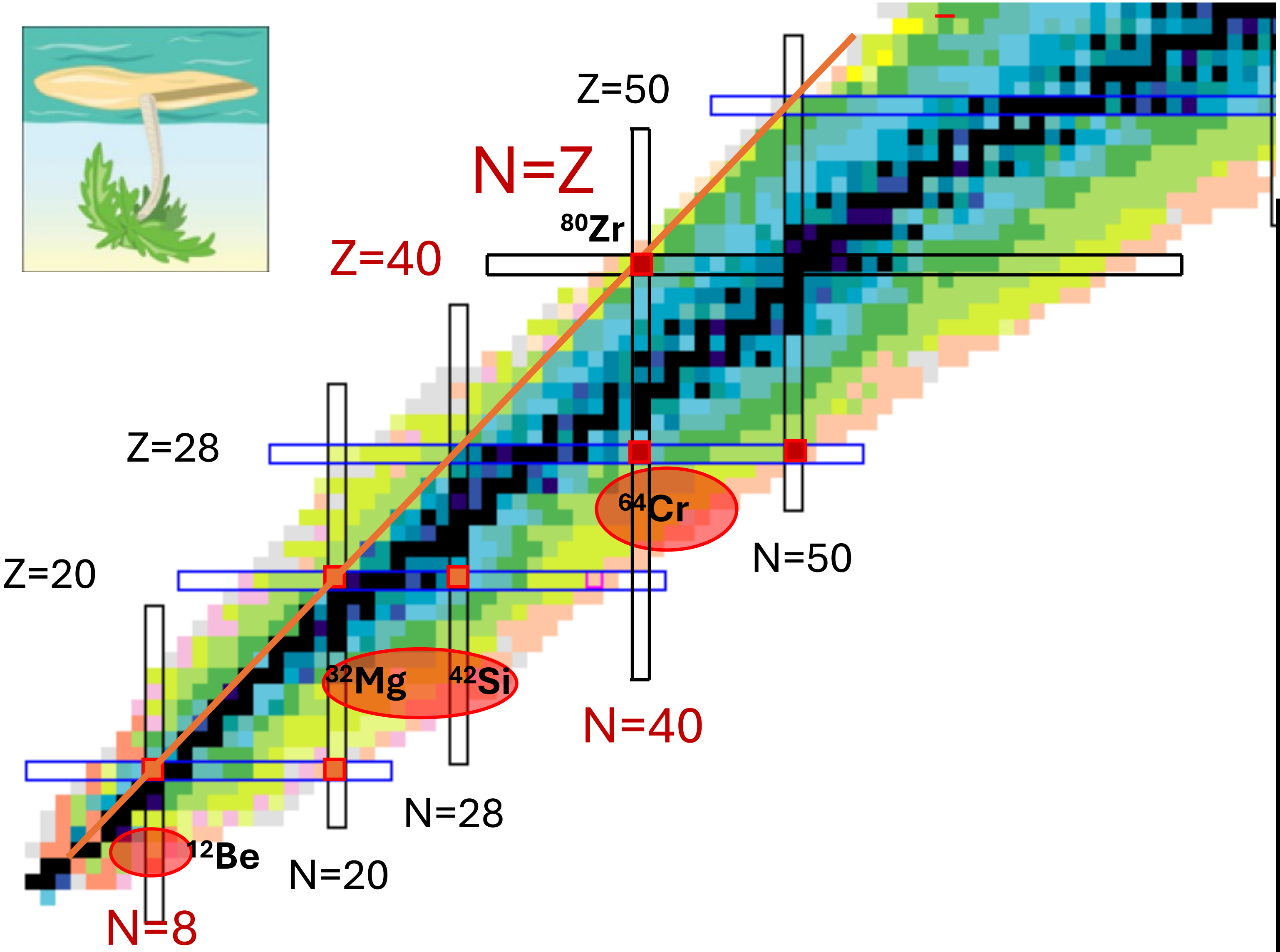
G. Corbari

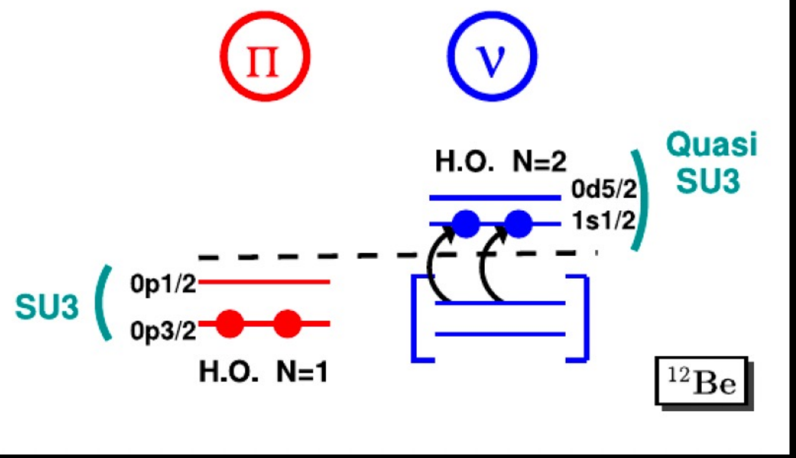


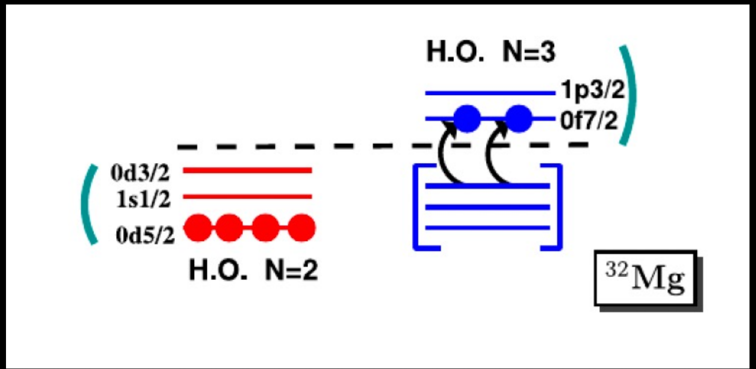
GASPEC: N=Z nuclei

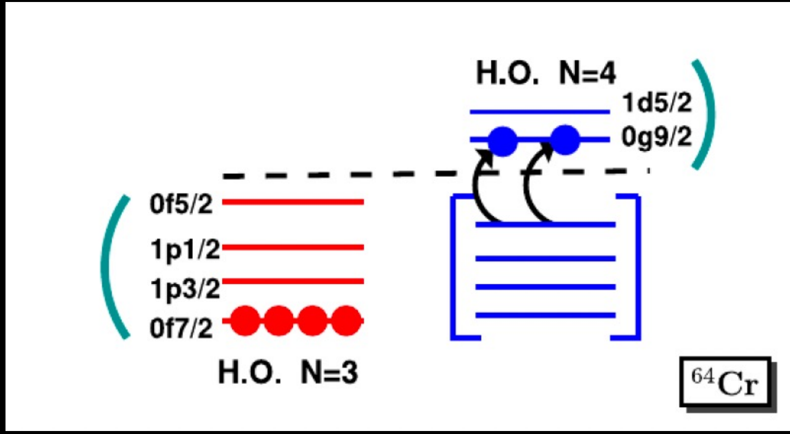


A recent example: islands of inversion at N=Z at NSCL





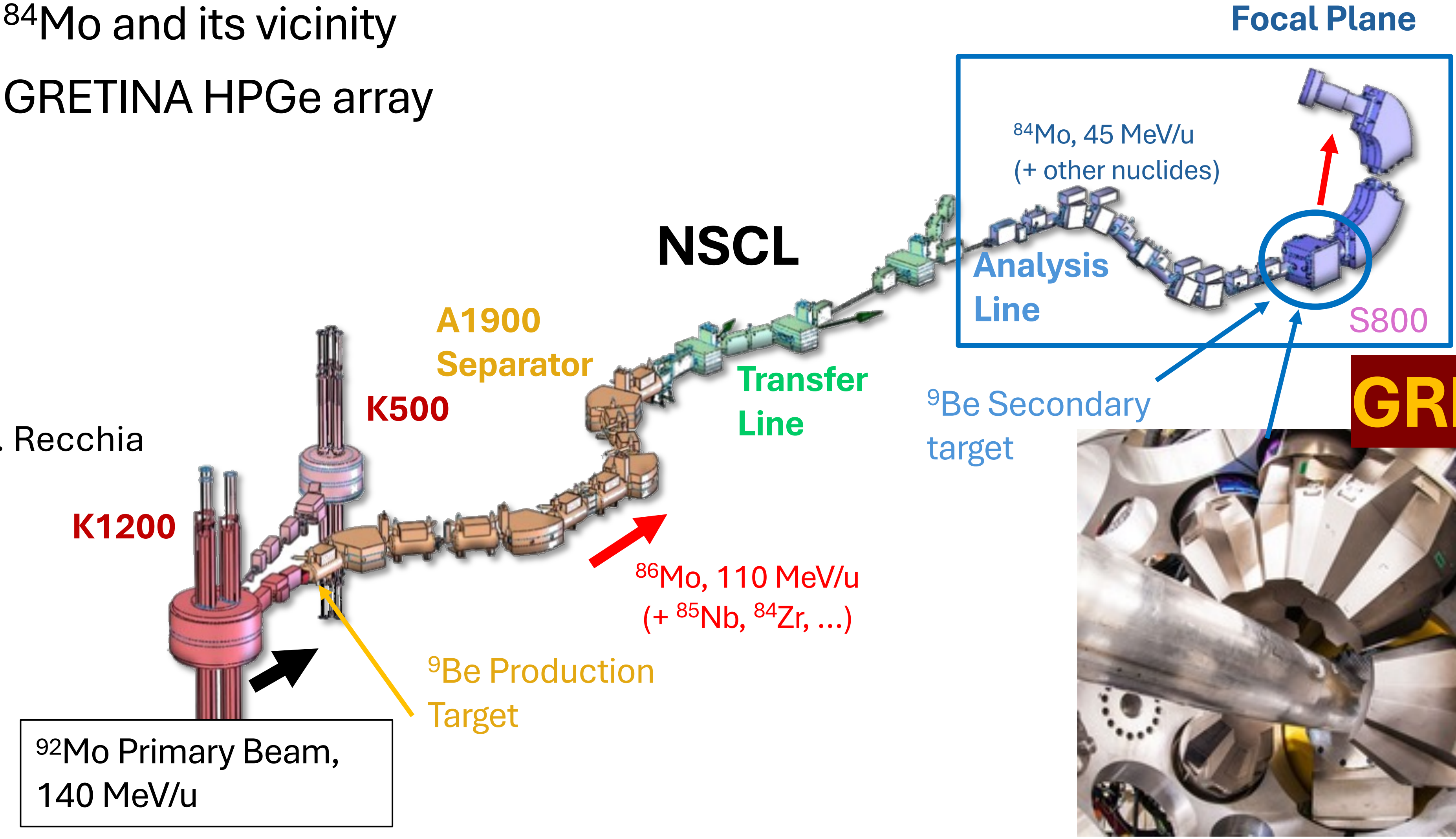




A recent example of collaboration: ^{84}Mo (Z=42) experiment at NSCL

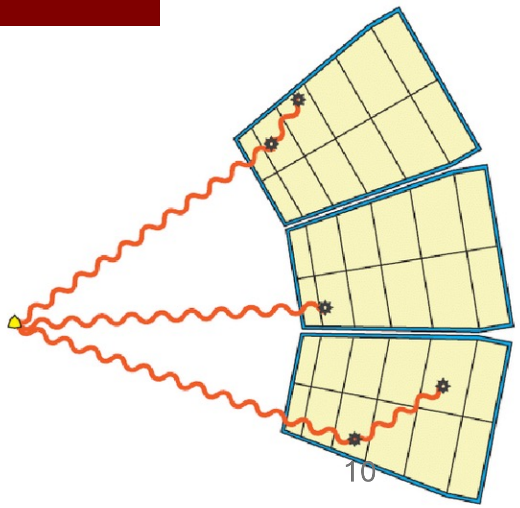
Lifetime measurement for the low-lying states in ^{84}Mo and its vicinity

GRETINA HPGe array



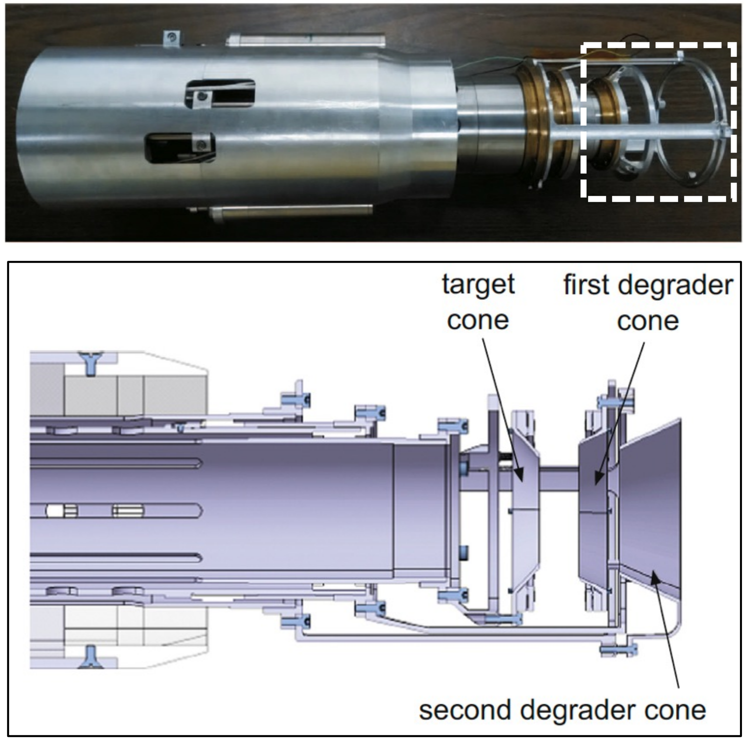
F. Recchia

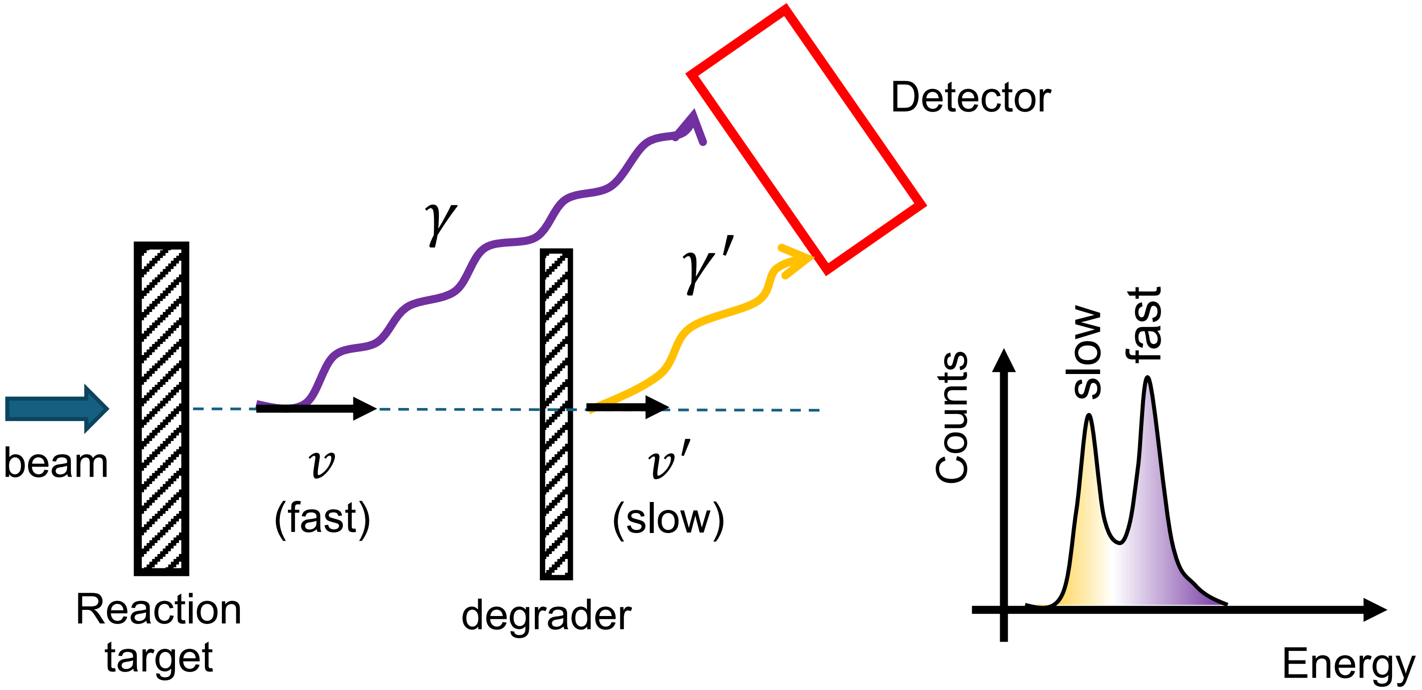
GRETINA



The experiment at NSCL

- ❑ GRETINA was coupled to the plunger TRIple PLunger for EXotic beams (TRIPLEX)
- ❑ With a secondary target, the TRIPLEX plunger

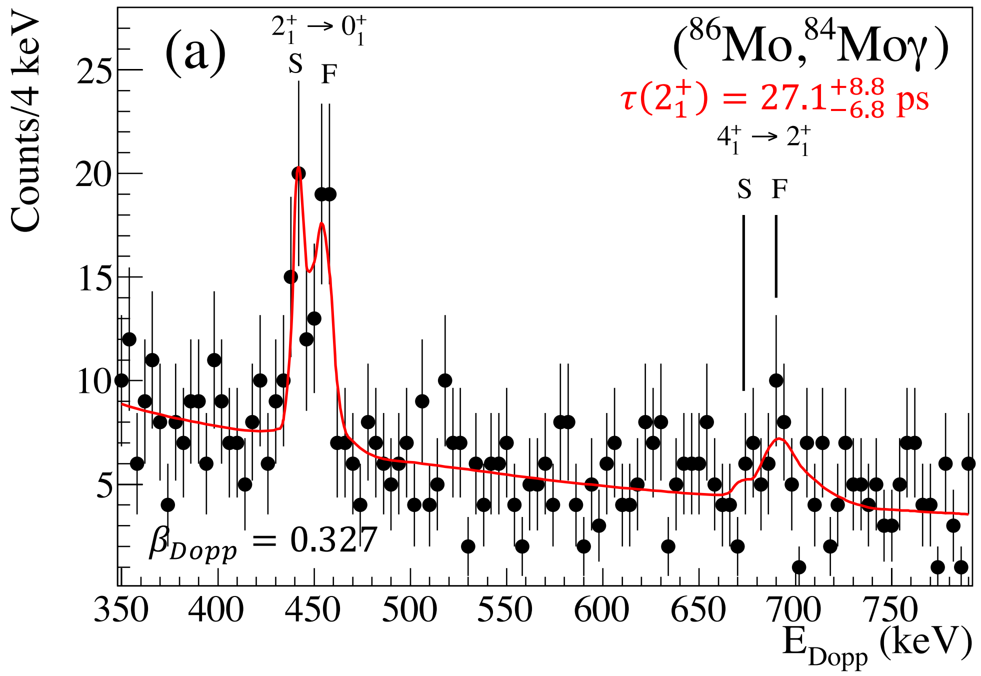


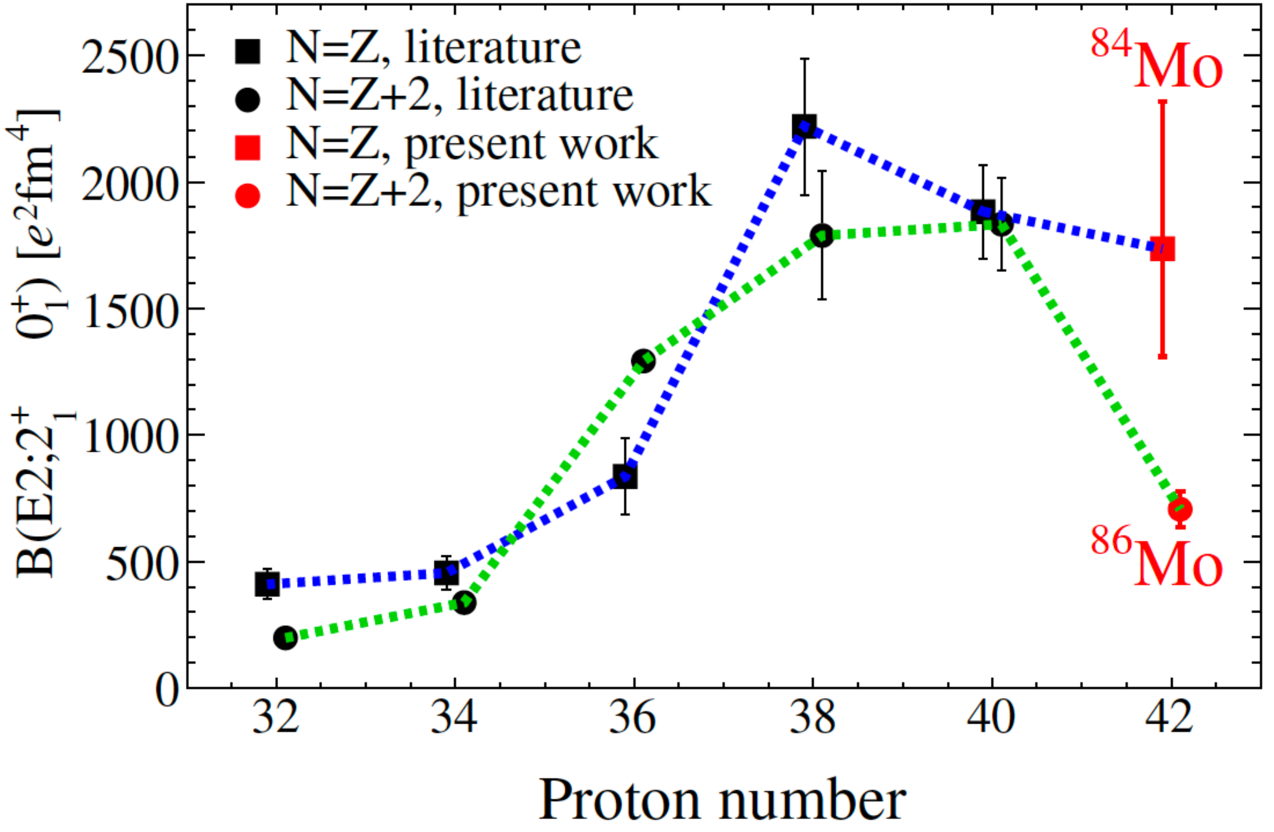


*H. Iwasaki et al., Nuclear Inst. and Methods in Physics Research A **806**, 123 (2016)*

F. Recchia

$B(E2;\ 2_1^+ \to 0_1^+)$ along N=Z





J. Ha post-doc work

- First 2$^+$ state in ^{84}Mo understandable in terms of **prolate deformation**
- **Inclusion of *$d_{5/2}$* (above N=Z=50) is needed** – lifetime shorter than expected - quadrupole correlations

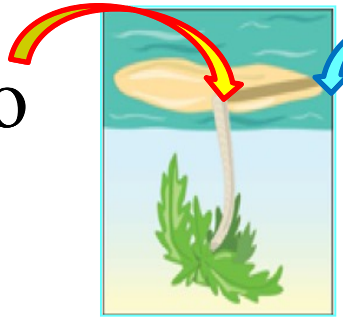
F. Recchia

The isospin-symmetric island of Inversion

Along the N=Z line, proton and neutron particle-hole excitations **contribute coherently**, thus **enhancing the quadrupole correlations** and giving rise to the Isospin-symmetric Island of Inversion at N=Z=40

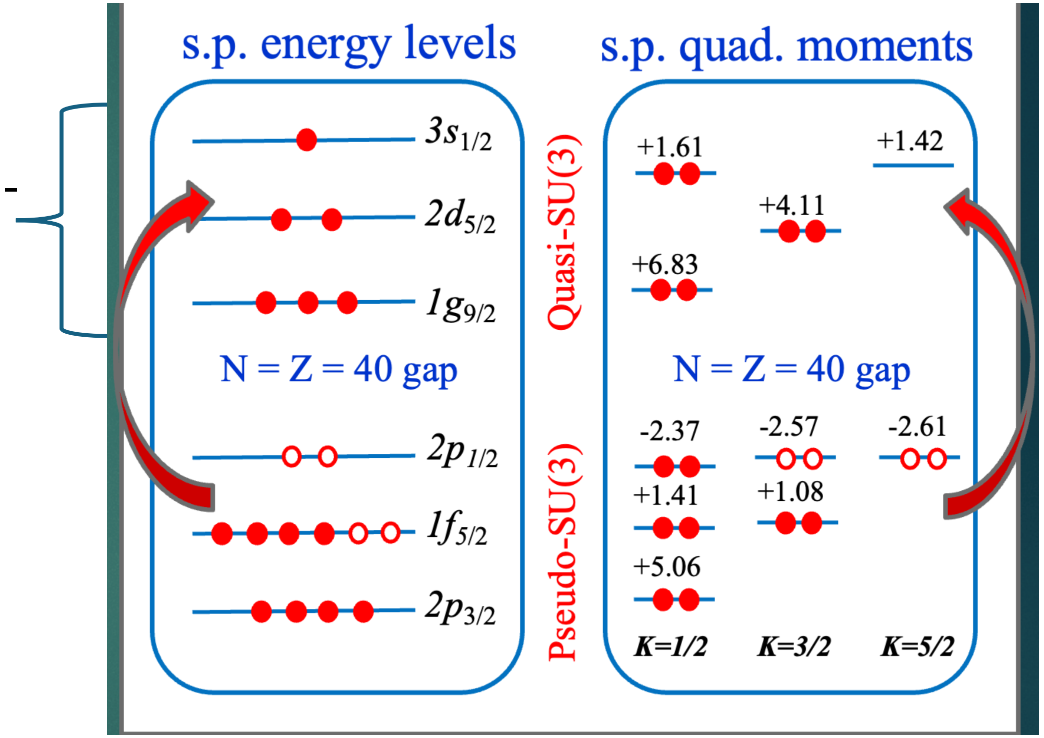
^{84}Mo

8p-8h



^{86}Mo

mixing of np-nh



^{84}Mo: same configuration for protons and neutrons.

Quadrupole correlations favor np-nh excitations.

Accepted in Nat. Comm.

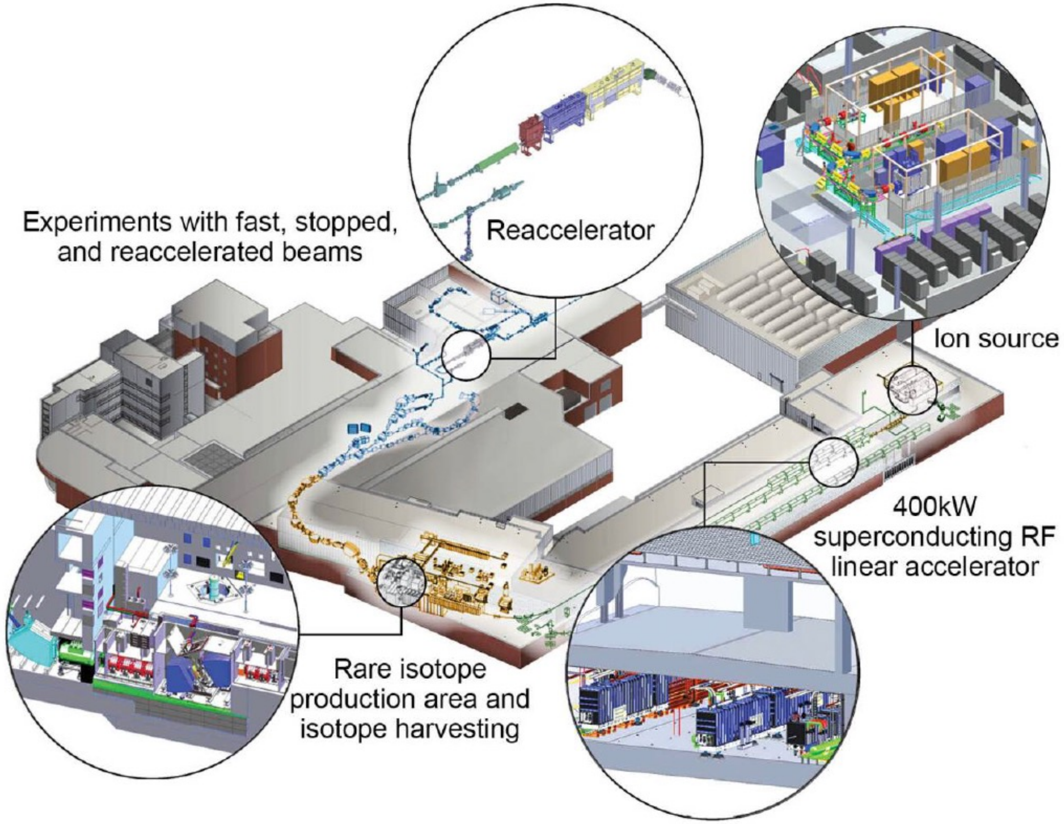
Opportunities for N=Z beams at FRIB

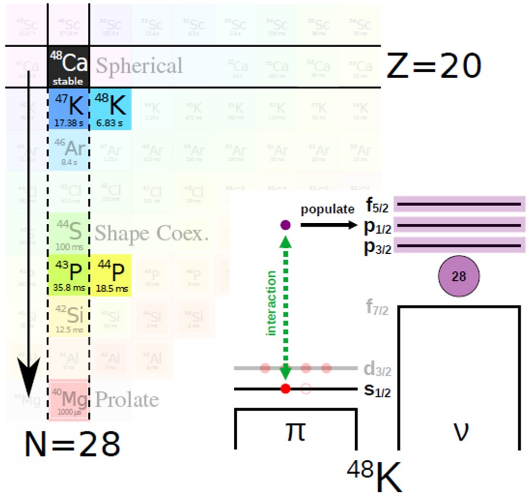
- N=Z region in the $g_{9/2}$ shell (^{80}Zr-^{100}Sn):

- fast beams 10^3-10^{-1} pps: (p,2p), n-knockout, rel. Coulex, decay spectroscopy

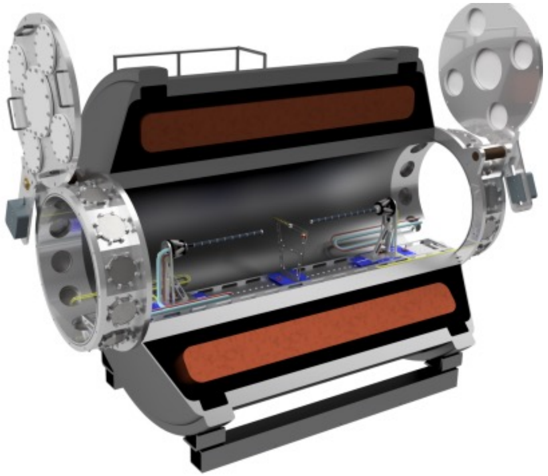
- reaccelerated beams 10^2-10^{-3} pps: safe Coulex, (p,p')

- High-spin ISB behavior in mirror nuclei A=44, 46 (N=20)

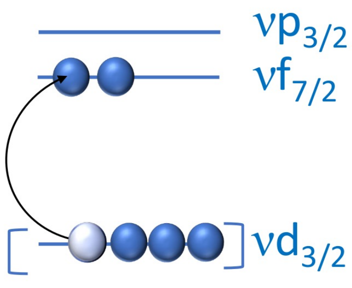




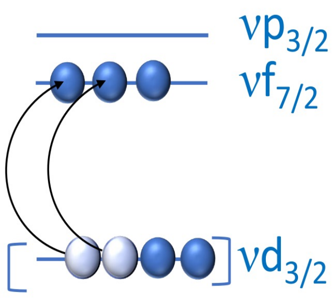
GASPEC : Direct reactions combined with γ-ray spectroscopy



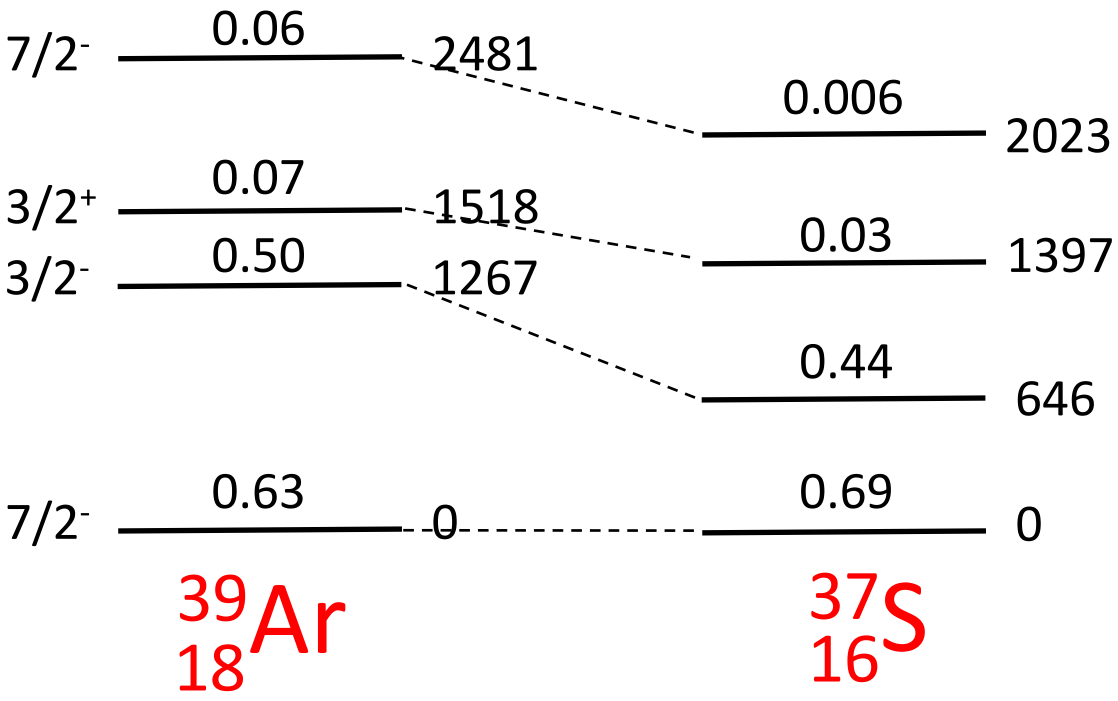
Intruder states and collectivity in N = 21 ^{39}Ar and ^{37}S



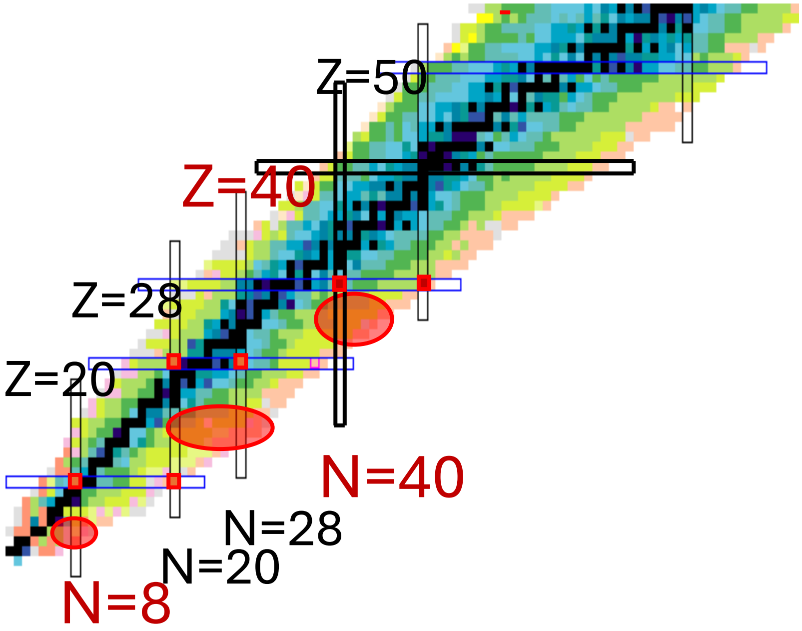
3/2⁺ (1h-2p)



7/2⁻ (2h-3p)



- Onset of collectivity and intruder states is more and more important moving towards the island of inversion
- Although in ^{38}Ar transition probability are well known, the data for ^{37}S, closer to the IOI is absent



L. Zago PhD thesis

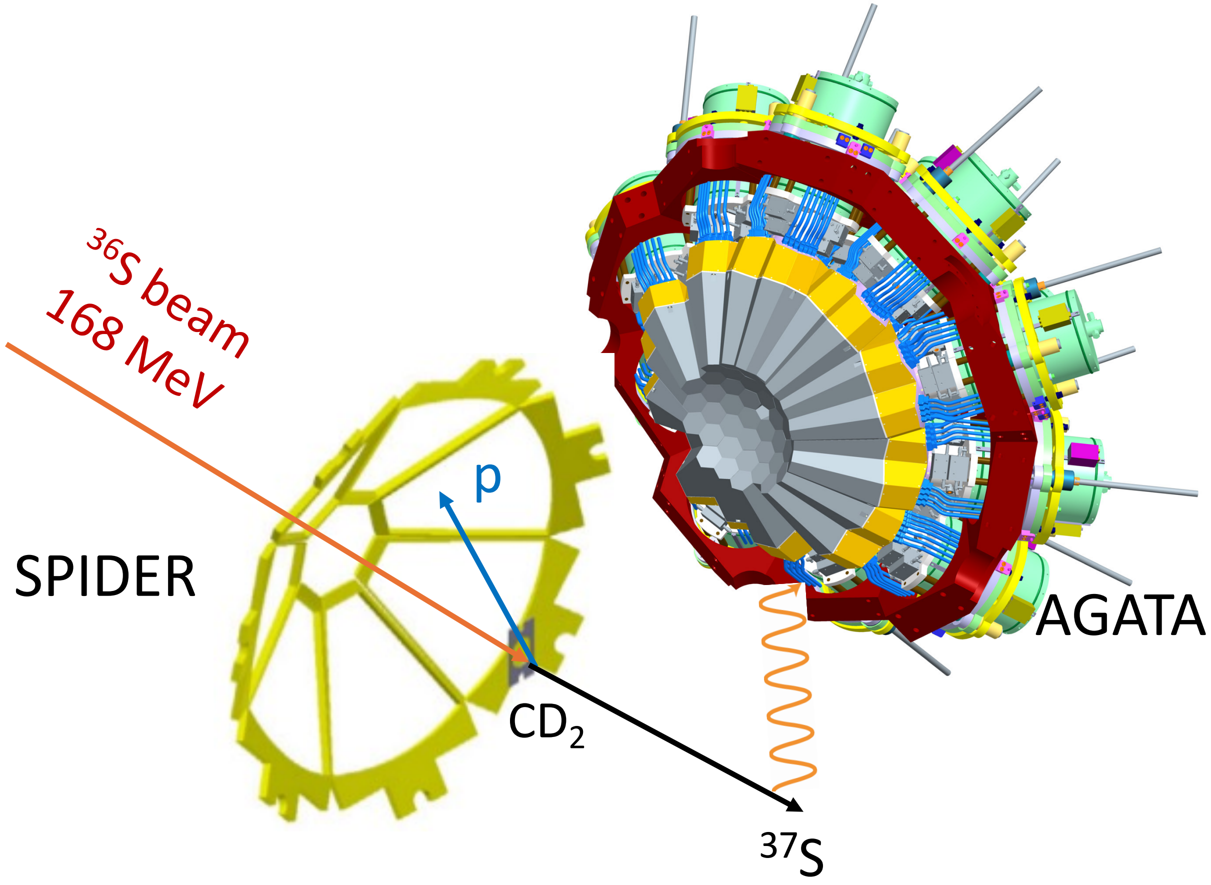
E. Caurier, F. Nowacki, and A. Poves, Phys. Rev. C **90** (2014) 014302

E. K. Warburton, Phys. Rev. C **35** (1987) 2278; Phys. Rev. C **37** (1988) 754

R. Chapman et al., Phys. Rev. C **93** (2016) 044318

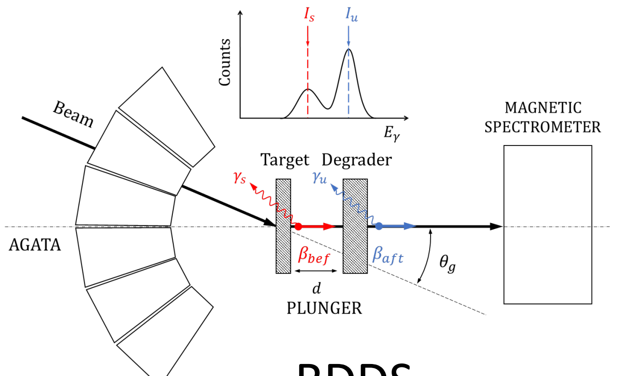
The experiment at LNL

$^{36}S(d,p)^{37}S$ at 4.6 MeV/u

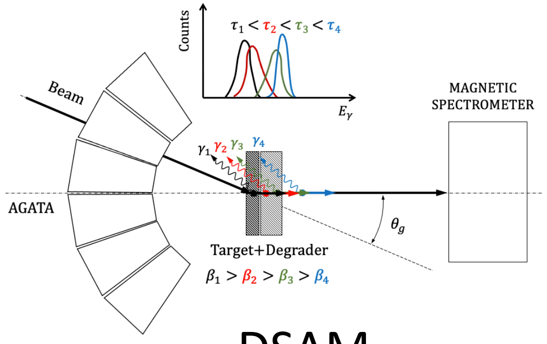


- High selectivity to a given set of excited states
- High control on Ex -> control on feeding transitions

- $3/2^+$ level expected to be in the range **10-100 ps** -> RDDS
- $7/2_2^-$ level expected to be in the range **50-500 fs** -> DSAM

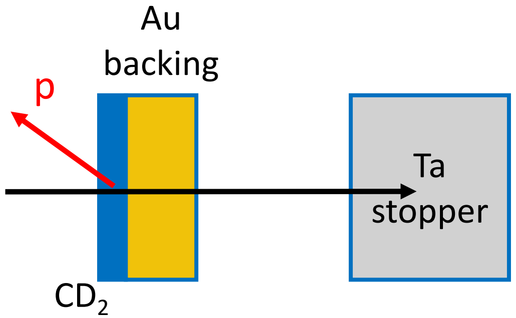


RDDS

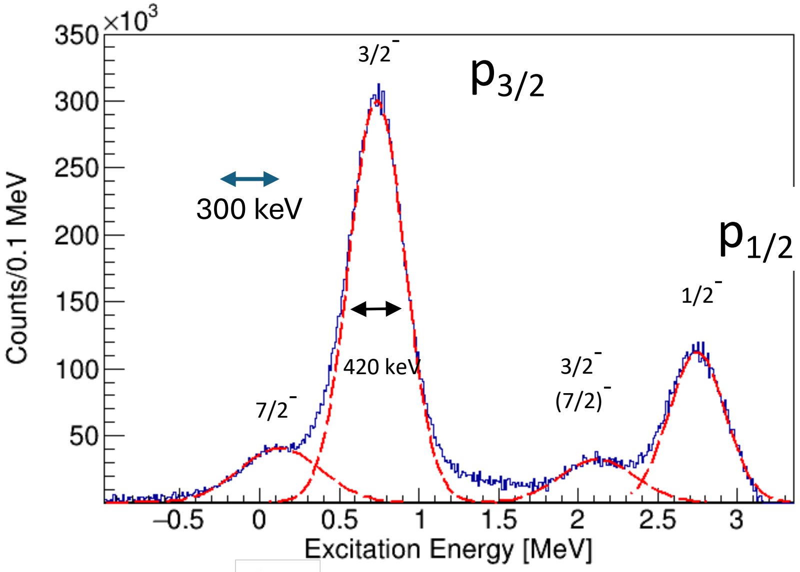


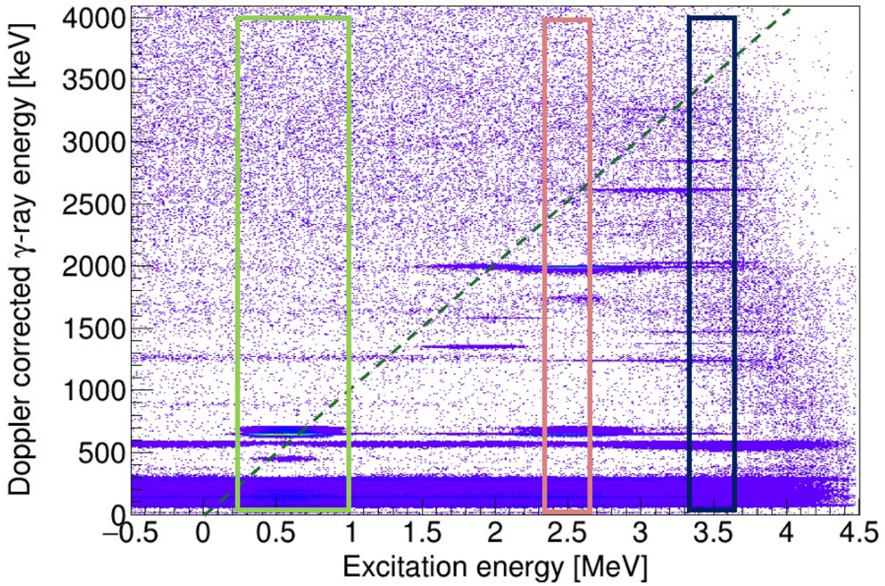
DSAM

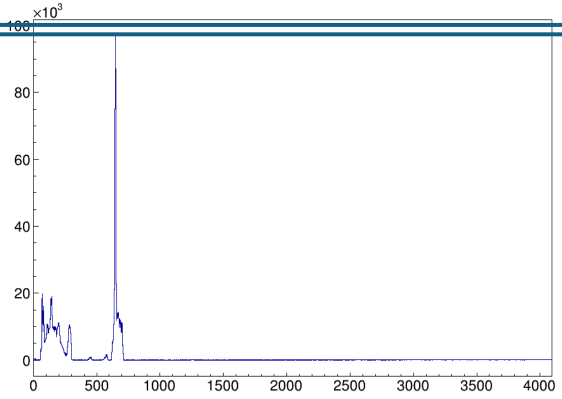
Combination of the two techniques in a single experiment

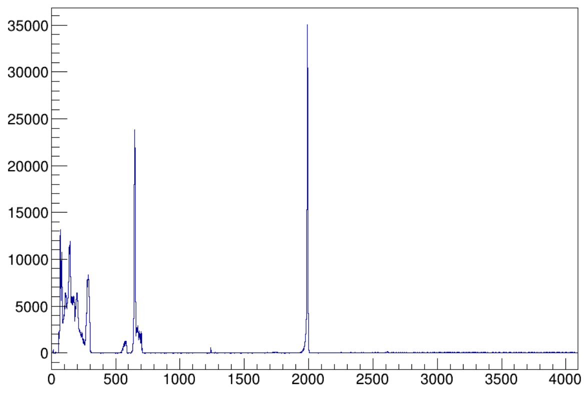


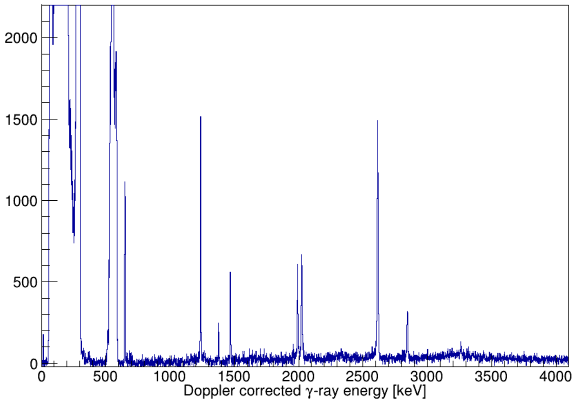
Particle - γ ray coincidences in ^{37}S

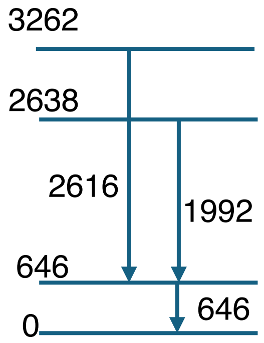


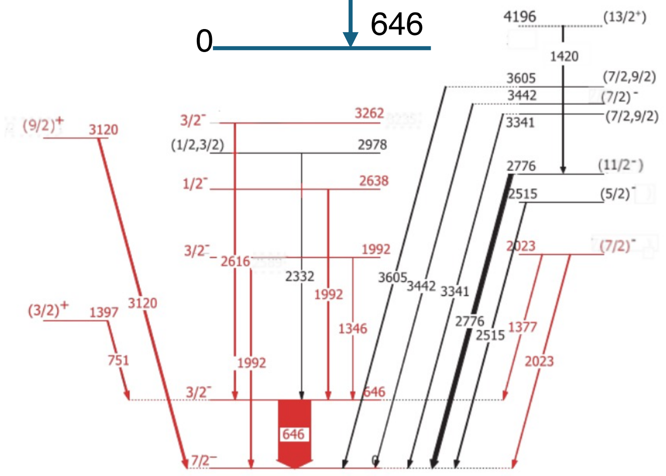












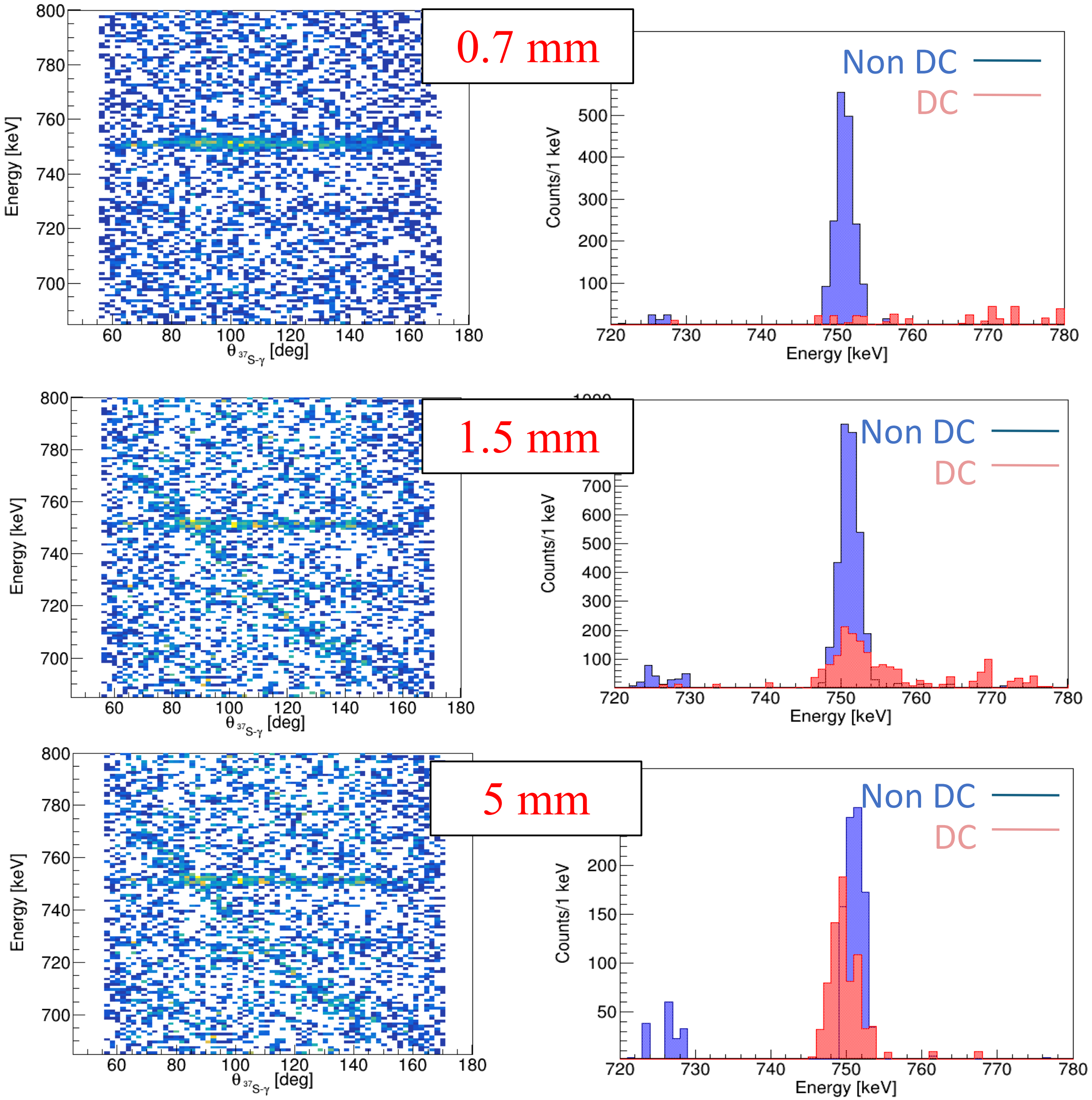
States of interest clearly observed

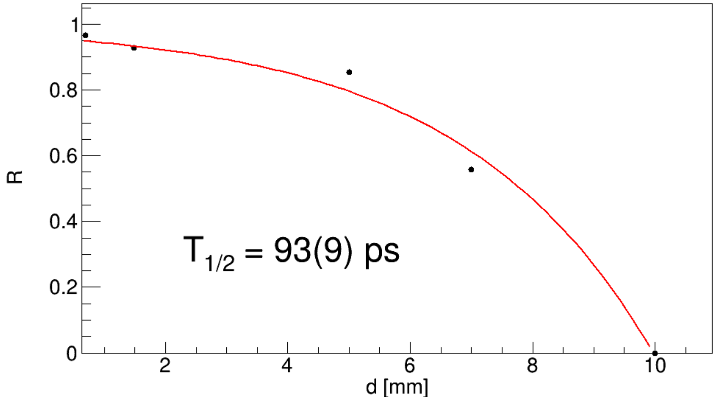
Feeder control

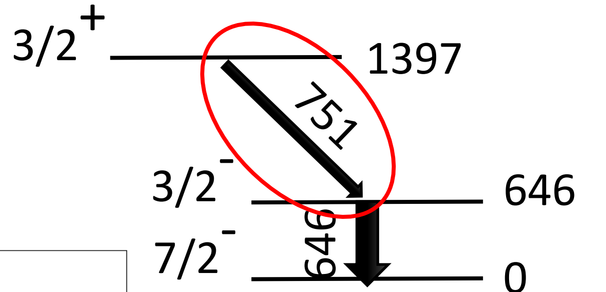
Adapted from Grocutt *et al.*, PRC **106**, 024314 (2022)

All spectroscopic results agree with previously published measurements

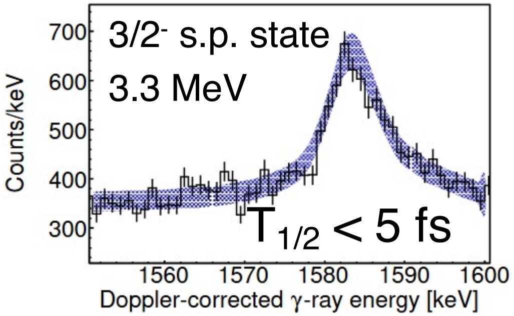
Lifetime results in ^{37}S

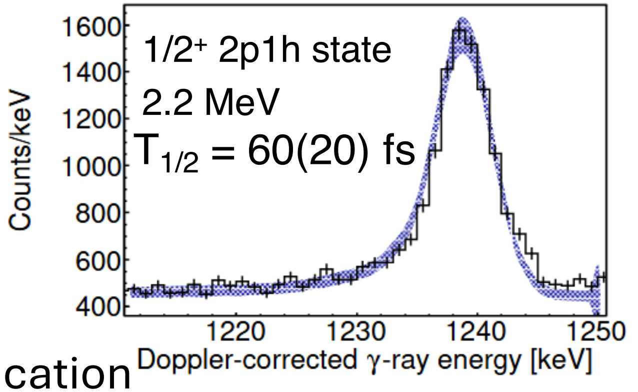






$B(E1) = 1.12*10^{-5}\ e^2fm^2$
$= 1.56*10^{-5}$ W. u.



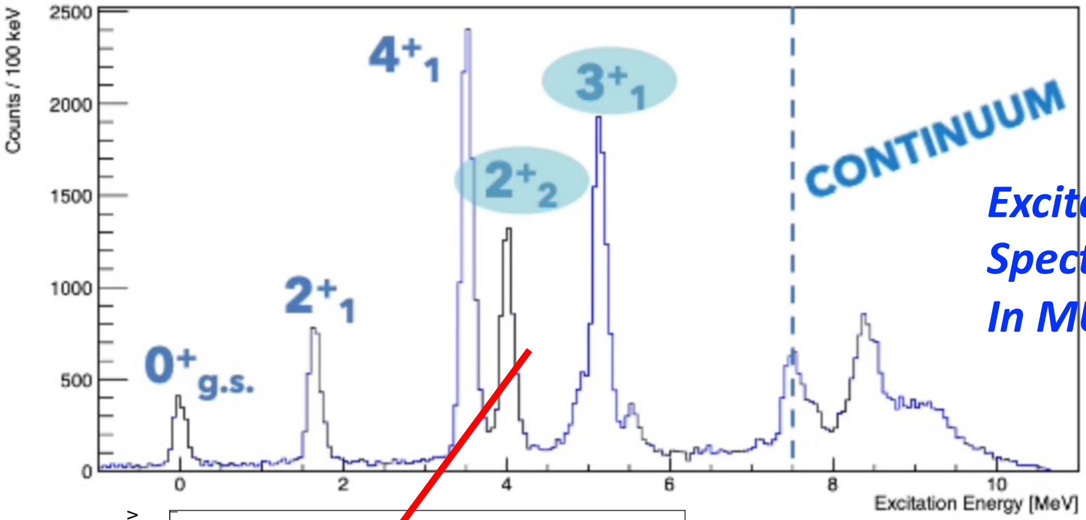


To be submitted for publication

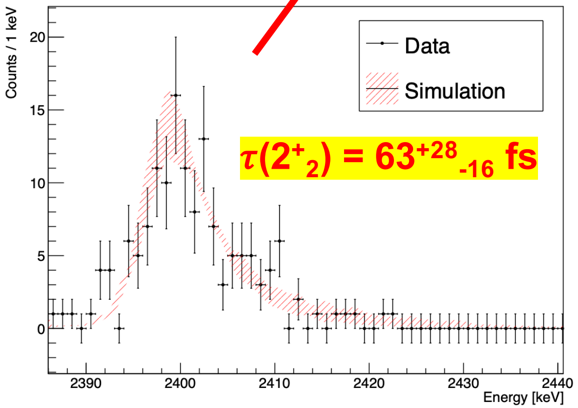
Lifetime measurement in ^{20}O using ^{19}O(d,pγ) and DSAM

Three-body forces

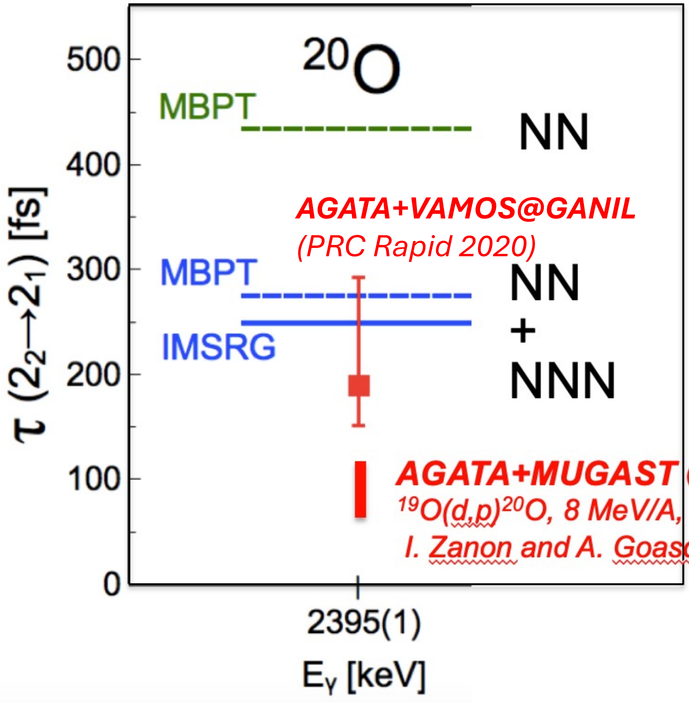
E. Clement (GANIL) and A. Goasduff (INFN-LNL)
PhD Thesis I. Zanon (INFN-Ferrara, LNL)

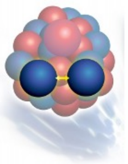


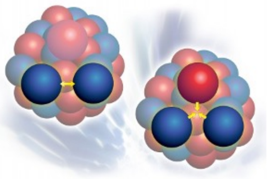
Excitation Energy Spectrum In MUGAST



γ-ray Spectrum in AGATA





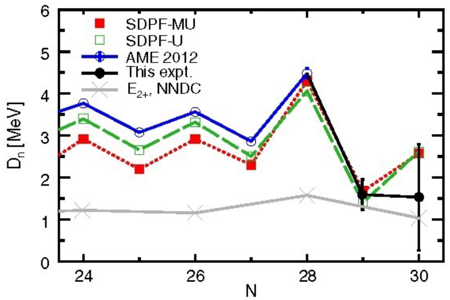


Published in Phys. Rev. Lett.

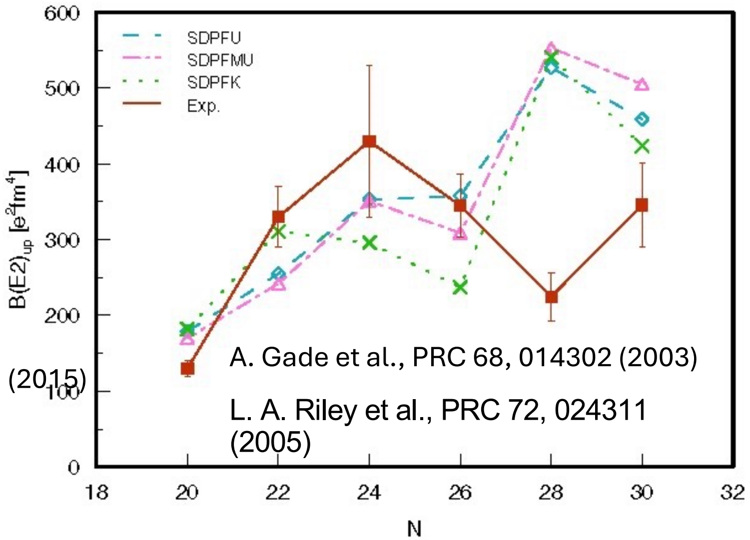
The strange case of N=28

Excellent SM theory for neutron-space related quantities:

- confirming N=28 shell closure in ^{46}Ar
- SDPF interaction describes valance-core neutrons interaction very well

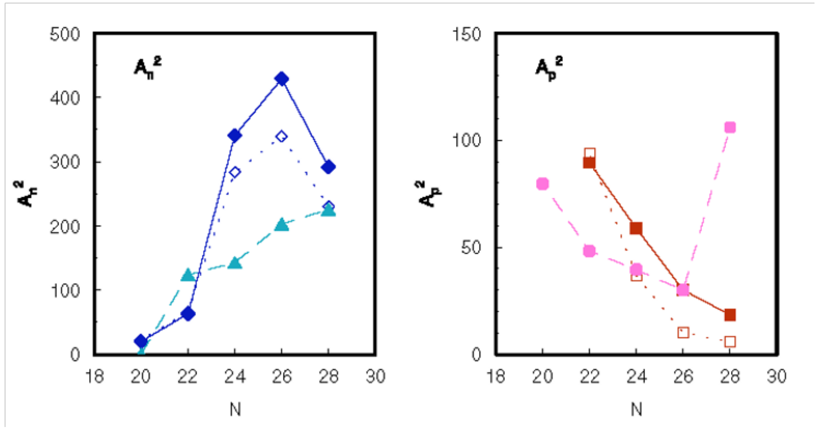


Z. Meisel et al. PRL 114, 022501 (2015)



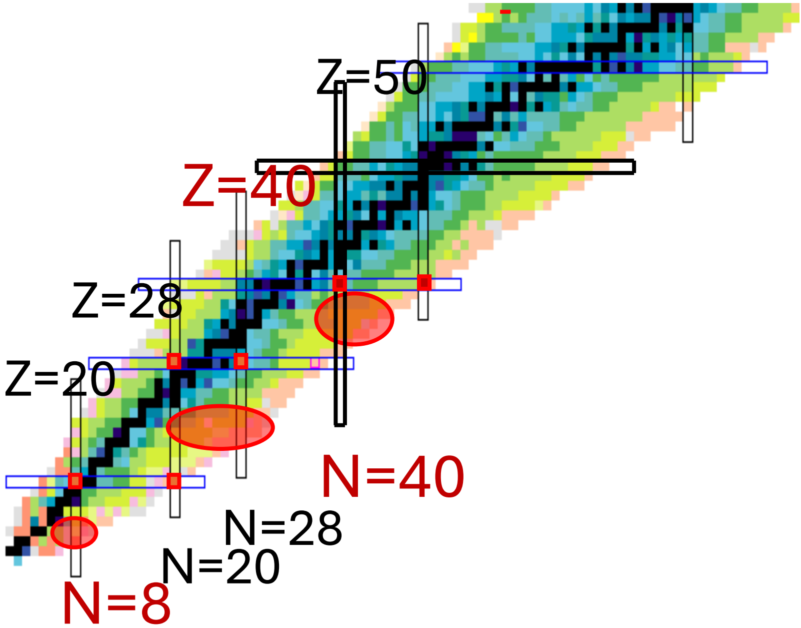
A. Gade et al., PRC 68, 014302 (2003)

L. A. Riley et al., PRC 72, 024311 (2005)

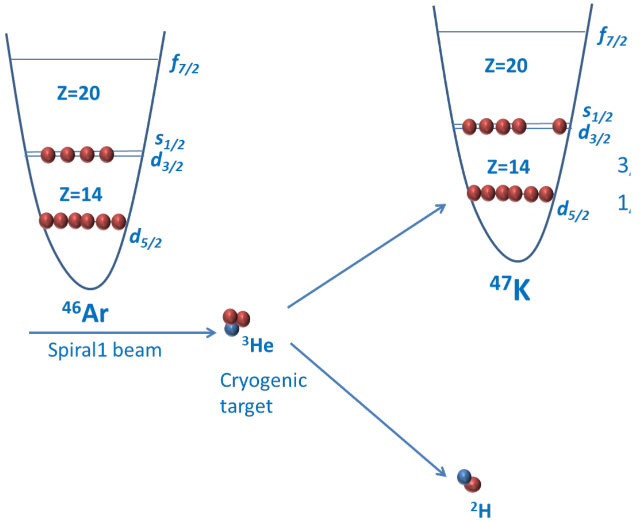


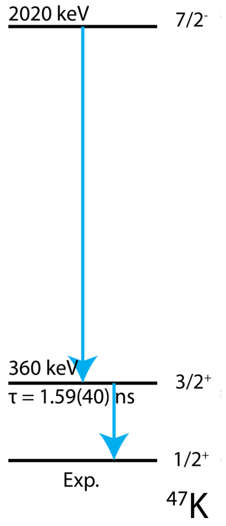
S. Calinescu et al., PRC 93, 044333 (2016)

Large discrepancy with the measured B(E2) value at N=28: problem with the proton E2 contribution ?



Direct proton-adding reaction to probe the ^{46}Ar ground state wave function



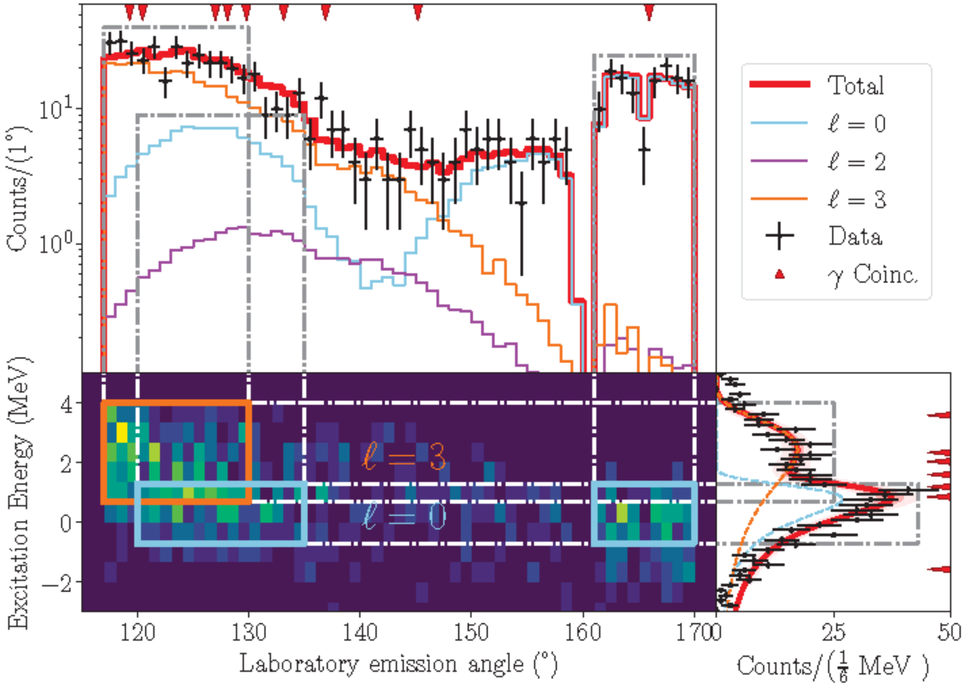


Proton bubble at N=28 ?

$^{46}Ar(^{3}He,d\gamma)\,^{47}K$

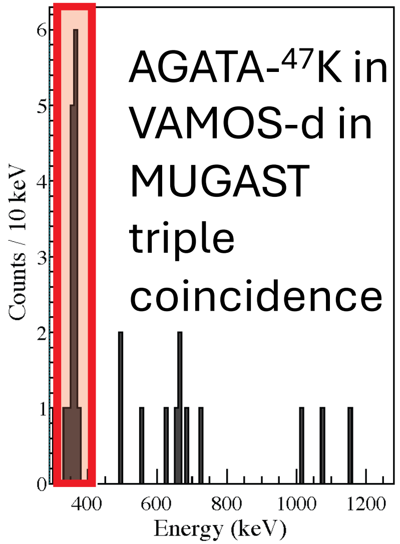
proton transfer
to probe π matrix element

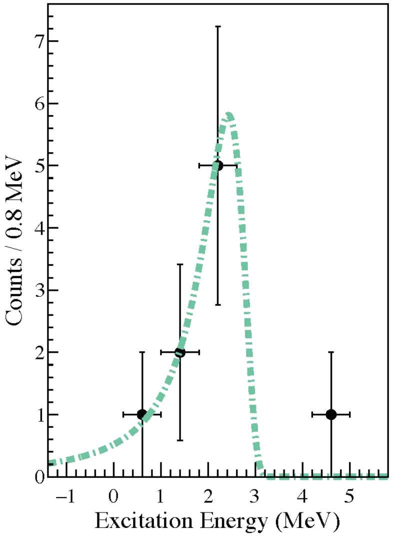
deuteron angular distribution in MUGAST



PhD Thesis D. Brugnara (Padova) 2022
Premio VILLI 2022

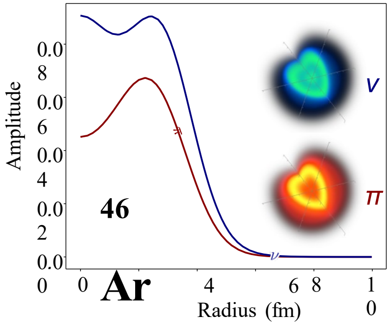
Measurement of $\pi s_{1/2}$ depletion in ^{46}Ar
→ indication of possible change
in the πs1/2-πd3/2 proton orbitals
Theory ab initio C. Barbieri (Milano)





$C^2S[L]/C^2S[L=0]$	$3/2^+$ state	$7/2^-$ state
SDPF-U	0.63	2.6
Experiment	$0.10^{+0.11}_{-0.10}$	$1.10^{+0.18}_{-0.15}$

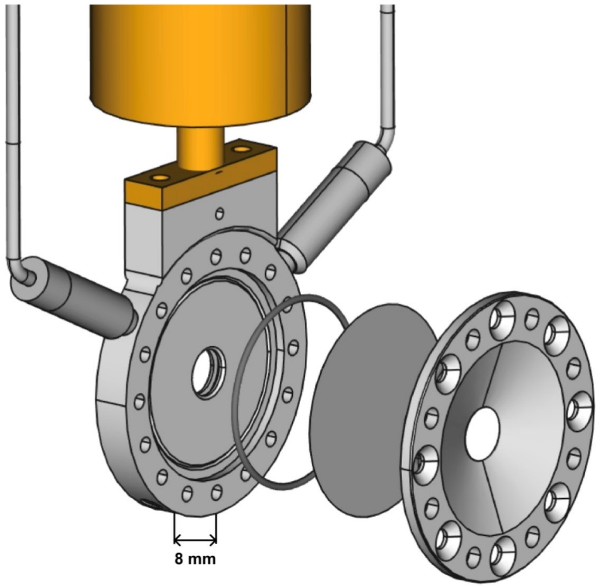
- **$\pi s_{1/2}$ empty, $\pi d_{3/2}$ full !**
- The proton WF of the g.s. of ^{46}Ar is not correctly described

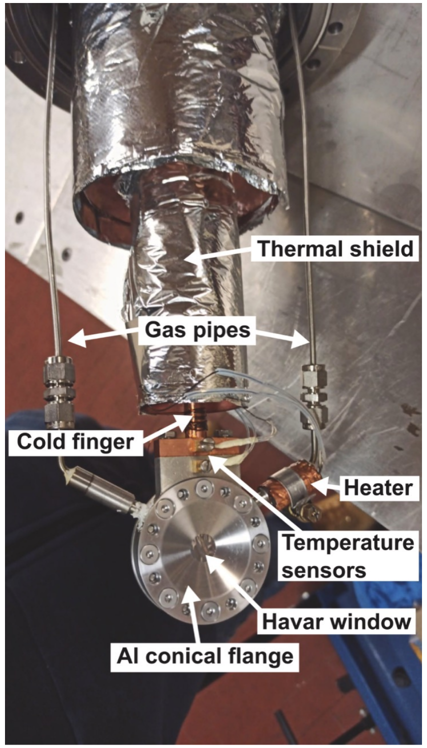


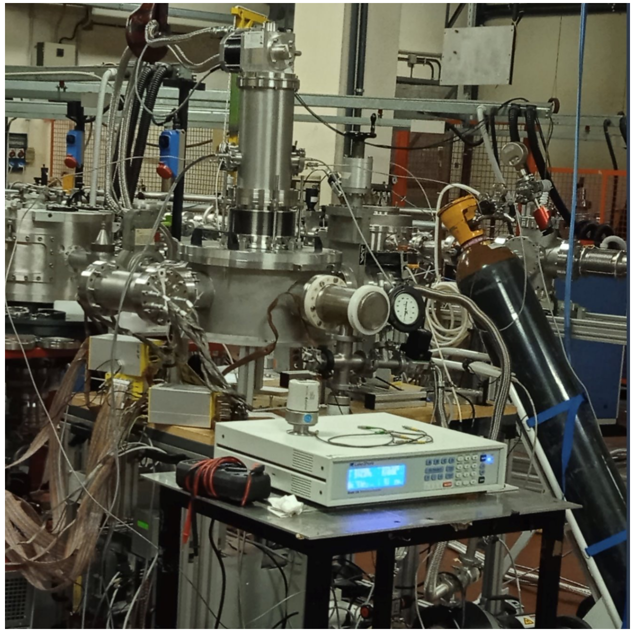
Submitted for publication

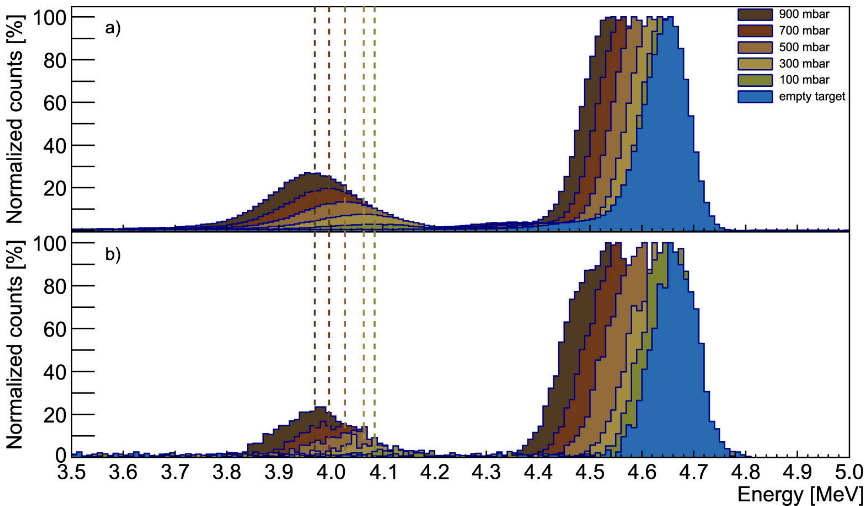
CTADIR – cryogenic targets for direct reactions

- Cryogenic ^{3,4}He target at 9-10 K
- Target density $10^{20\text{-}21}$ at/cm^2
- Cooled with cryocooler
- Fully compatible with AGATA-GRIT
- Al body to be transparent to γ rays
- Commissioning with proton beam









M. Sedlák, at al. Nucl. Instr. and Meth. A, 1080, 2025,170626,

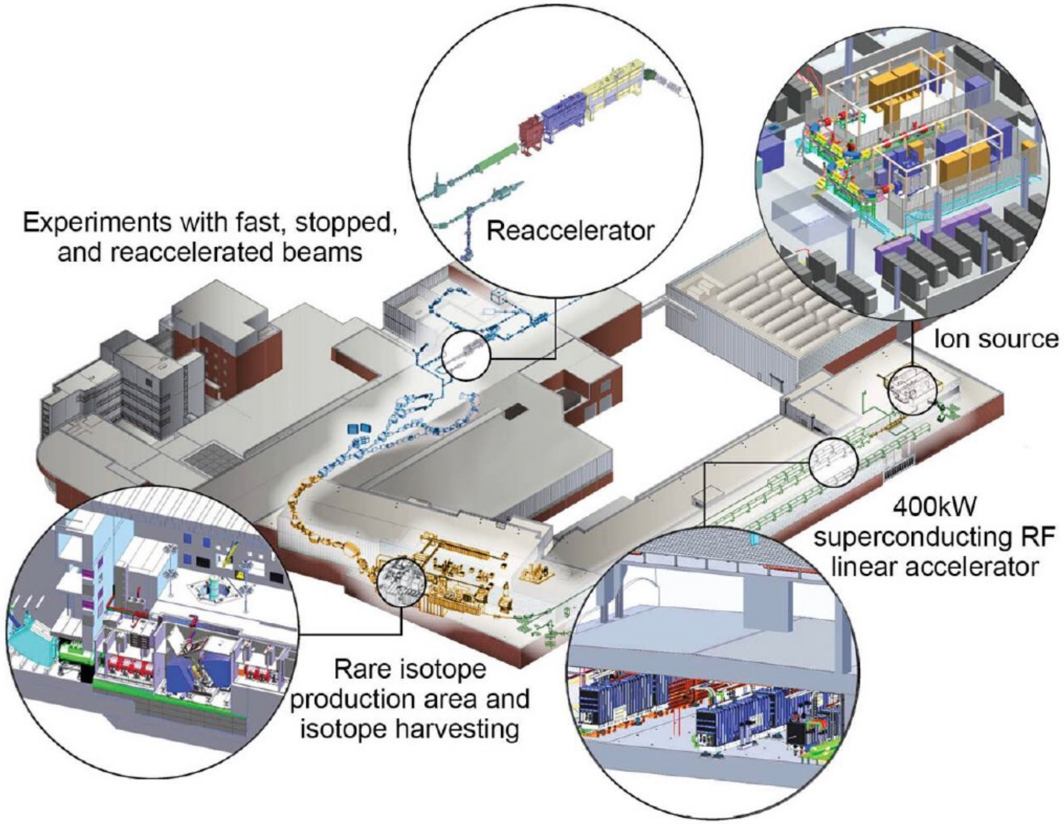
Perspectives with FRIB beams

- A rich and diversified intrumentation is already present at FRIB
- We can contribute with «specific» detectors/devices in selected cases
- We can propose physics cases in specific regions of the nuclide charts

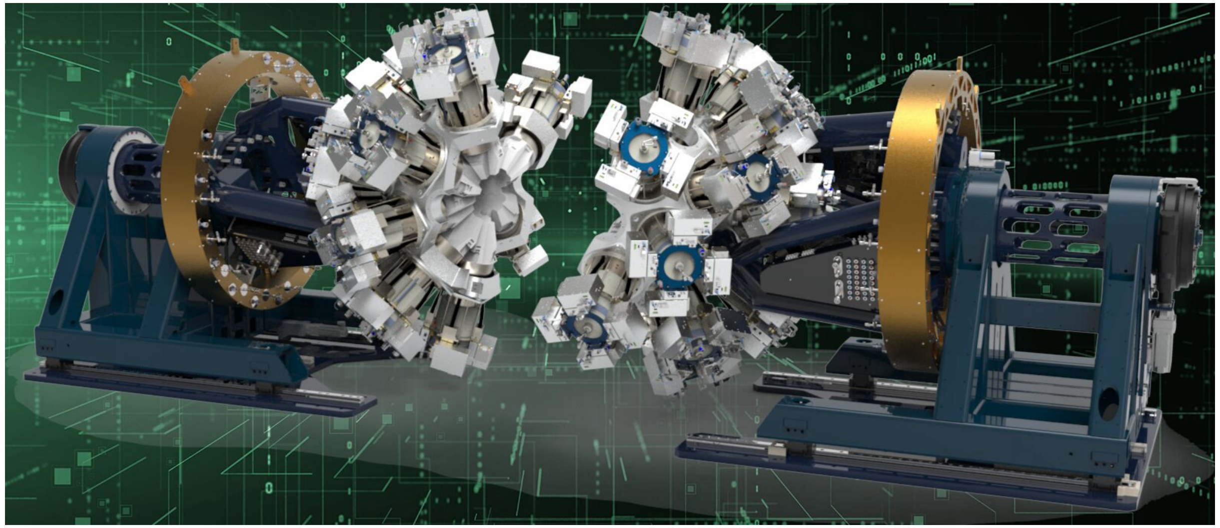
  - lifetimes of excited states after fast/reacc. proton/neutron knockouts/trasnfers

  - use of cryogenics targets for particle and γ-ray spectroscopy (DSAM possibilities to be investigated)

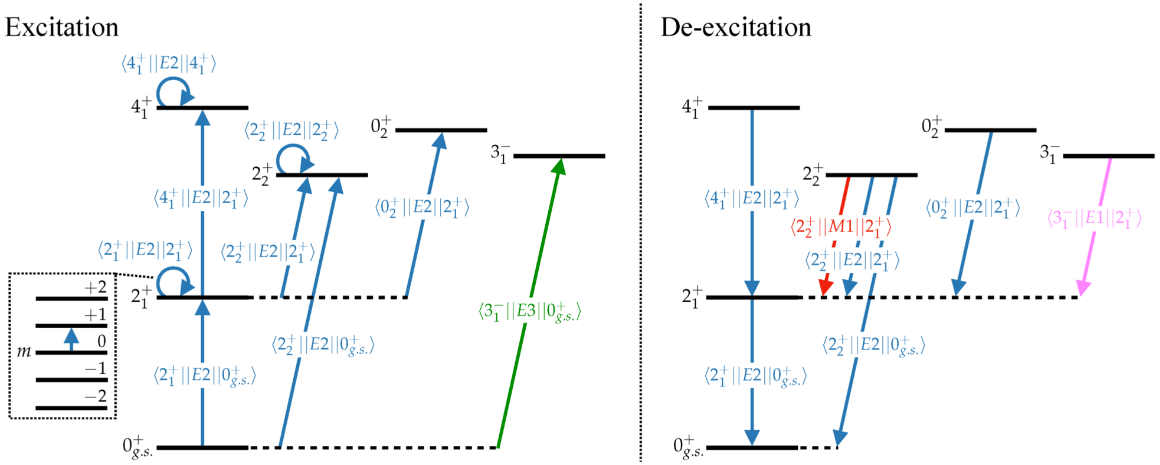
  - nuclear structure in odd-odd or odd-even nuclei using γ-ray spectroscopy for cross section to individual levels



See F. Galtarossa’s talk for possible cases at FRIB



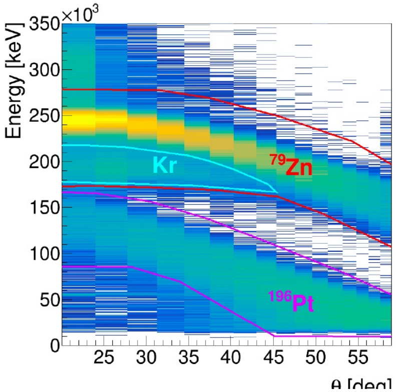
GASPEC : Coulomb excitations

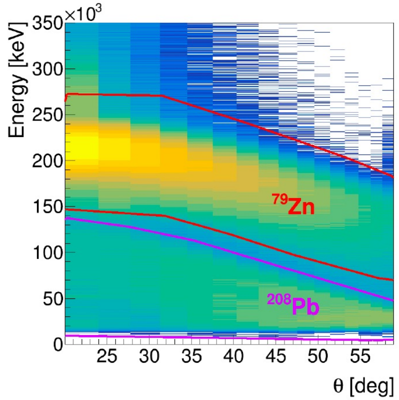


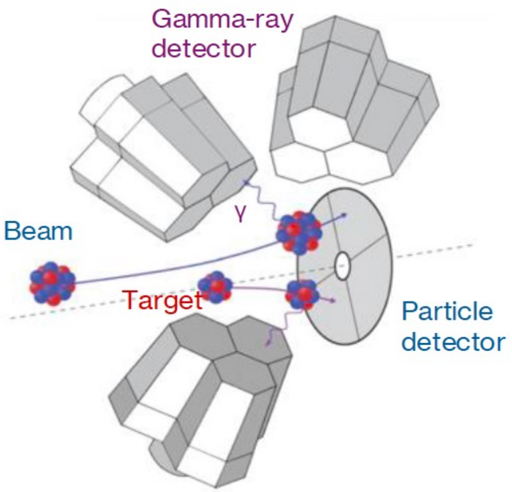
Coulomb excitation with segmented γ-ray arrays
Example: ^{79}Zn at ISOLDE

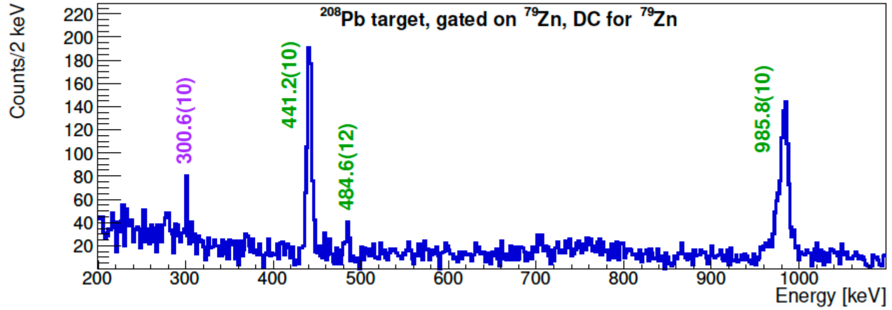
- ^{79}Zn gs, intruder $1/2^+$ isomer, states both in the exotic beam
- Coulex at 4 MeV/u on ^{208}Pb, ^{196}Pt targets

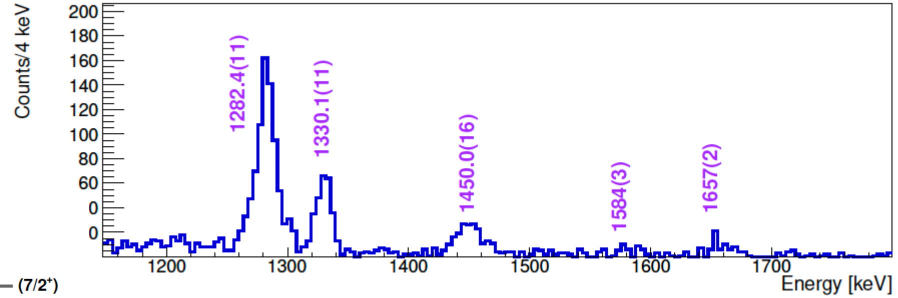
Particle spectra (forward)

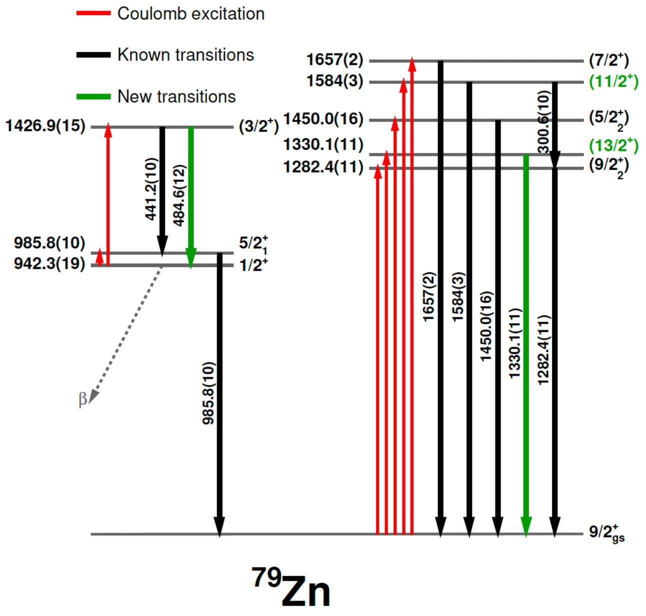












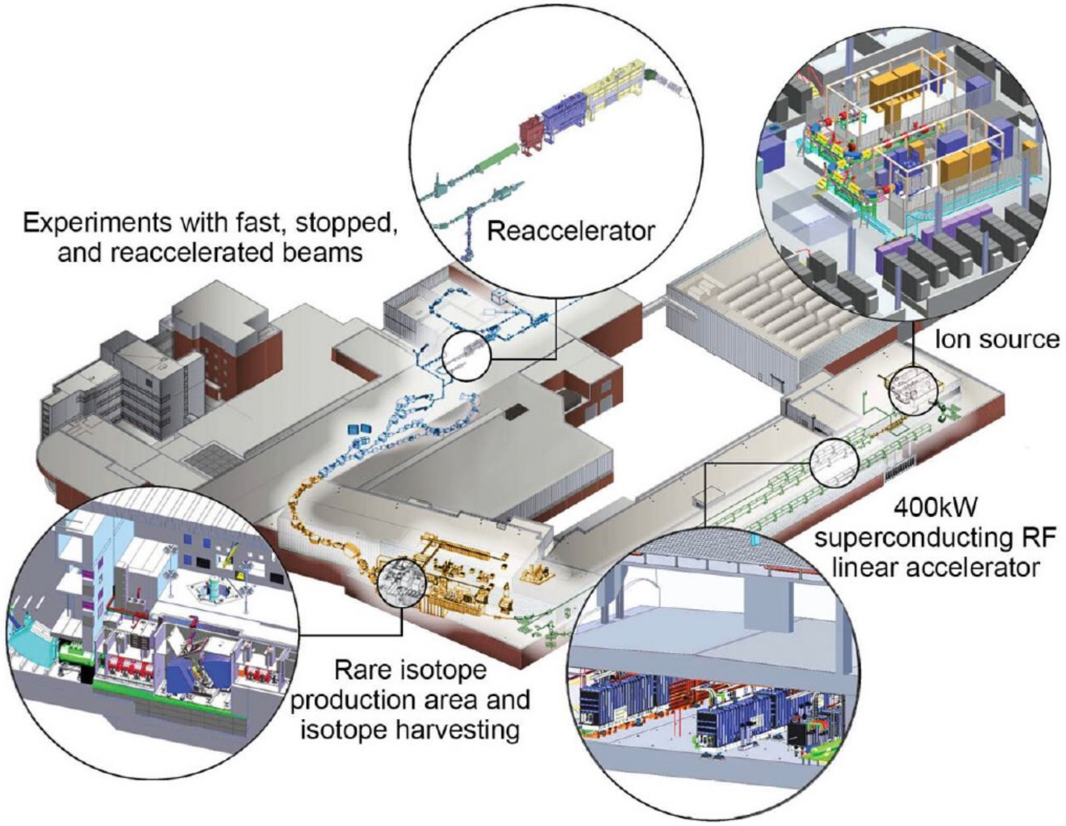
- Measurement of the B(E2) on the gs and intruder $1/2^+$ isomer (GOSIA code analysis)
- Comparison with LSSM describing intruder structures in ^{78}Ni

F. Angelini PhD thesis

Coulomb excitation at FRIB

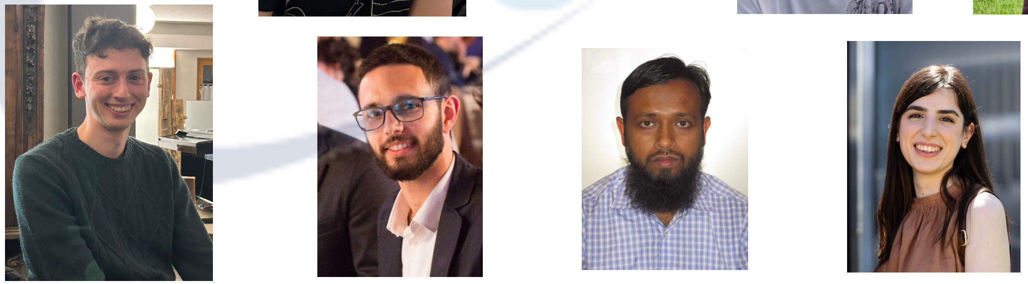
See M. Rocchini's talk for possible cases at FRIB

- Different RIBs production method $\Longrightarrow$ Differents species available
- Availability of reaccelerated beams: proper beam energy for Coulex
- What setup for Coulex ?
- Level of purity of the beams?
- Complementary data from β-delayed γ-ray and conversion electron spectroscopy



The young strength of GAMMA: PhD, Postdocs

9 nationalities !



And... new ones !

THANK YOU FOR YOUR ATTENTION !