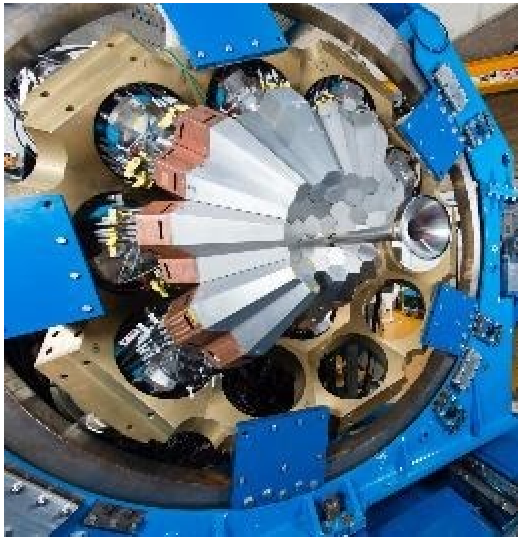
The Advanced GAmma Tracking Array (AGATA): Recent Experimental results

Andres Gadea (IFIC-CSIC, Spain)

on behalf the AGATA Collaboration



Nuclear Structure and Dynamics NSD2019

May 13th-17th 2019, Venice, Italy

IFIC INSTITUT DE FÍSICA CORPUSCULAR

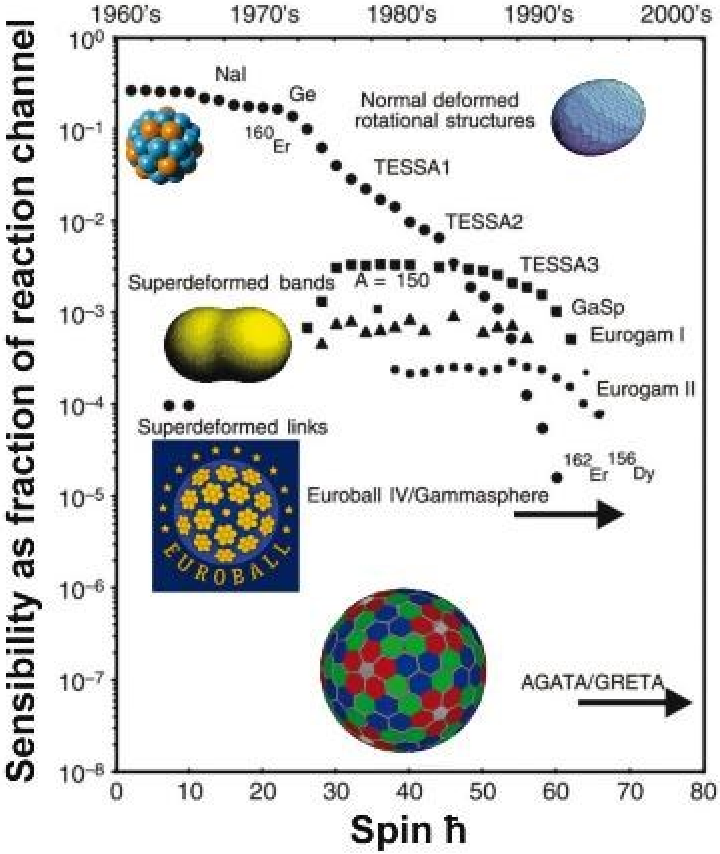
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

AGATA ADVANCED GAMMA TRACKING ARRAY

AGATA

(Advanced GAmma Tracking Array)

Encapsulation



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

6660 high-resolution digital electronics channels

High throughput DAQ / Capability to record sampled pulses

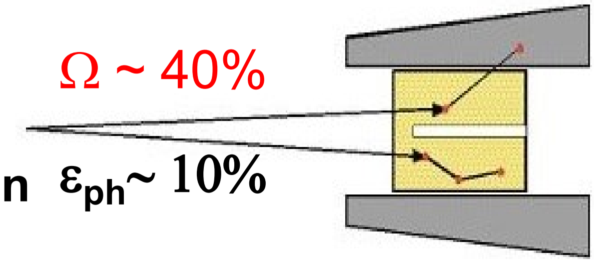
Pulse Shape Analysis → position sensitive operation mode

γ-ray tracking algorithms → maximum efficiency and P/T

Tracking Arrays

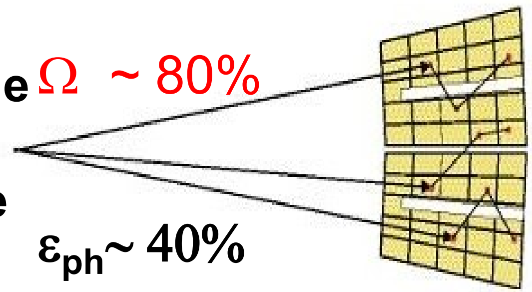
Primarily design to maximize Efficiency and P/T of the high resolution γ-ray detector arrays

1. **Maximizing the active solid angle without loosing signal/noise ratio**
2. **Improving the Energy resolution on all experimental conditions, even at high emission velocities**
3. **Maximizing the performance of the detectors, even in conditions of heavy duty with radiation damage**



Compton Suppressed

- solid angle taken by the AC shields
- large opening angle ➔ poor energy resolution

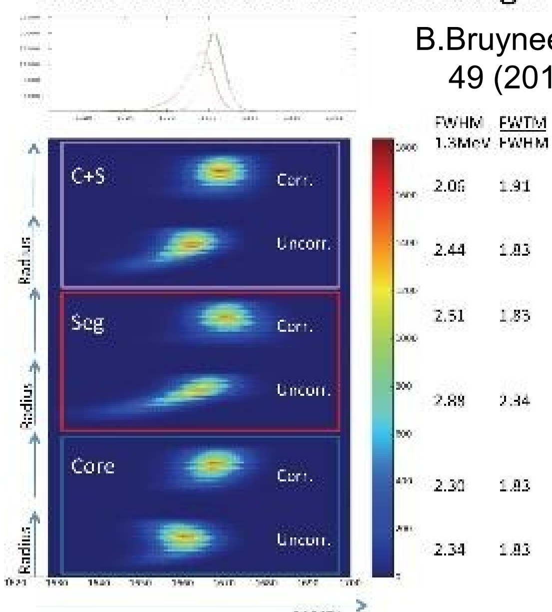


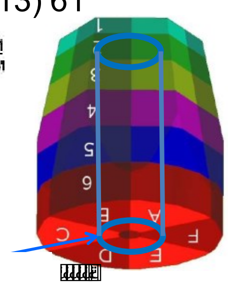
Tracking array

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

Correction of neutron damage

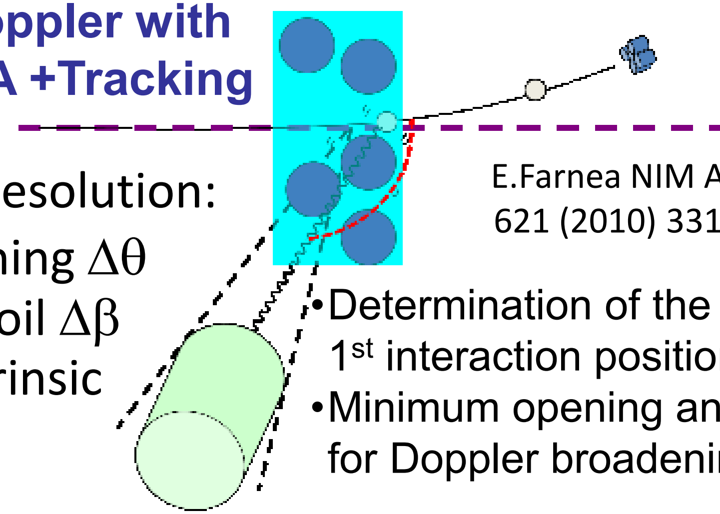
B.Bruyneel EPJ A 49 (2013) 61





- Radial dependency of charge trapping

Doppler with PSA +Tracking



Total Resolution:

Opening $\Delta\theta$

Recoil $\Delta\beta$

Intrinsic

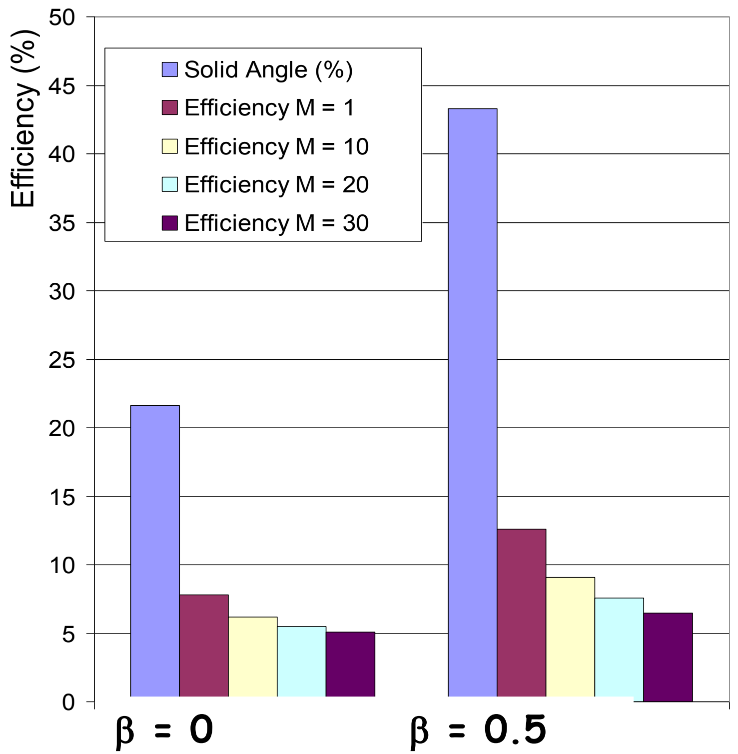
E.Farnea NIM A 621 (2010) 331

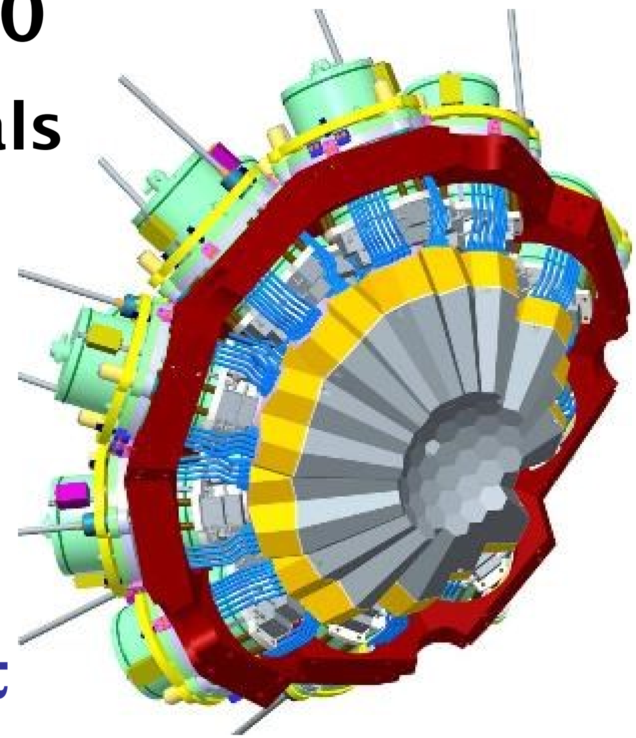
- Determination of the 1st interaction position
- Minimum opening angle for Doppler broadening

The AGATA Phase 1

2009-(2015) 2020

- Phase 1 of AGATA (4/3π)→ 60 crystals
- MoU ongoing, ~85 % achieved, Extended until 2020
- Available Triple and Double clusters
- The first "real" tracking sub-array

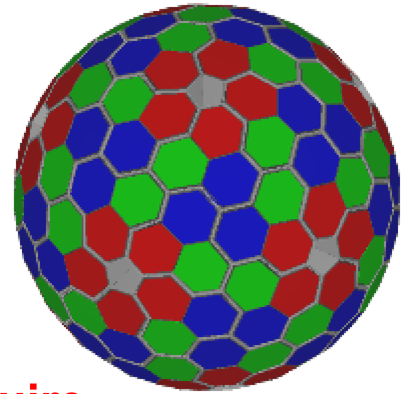




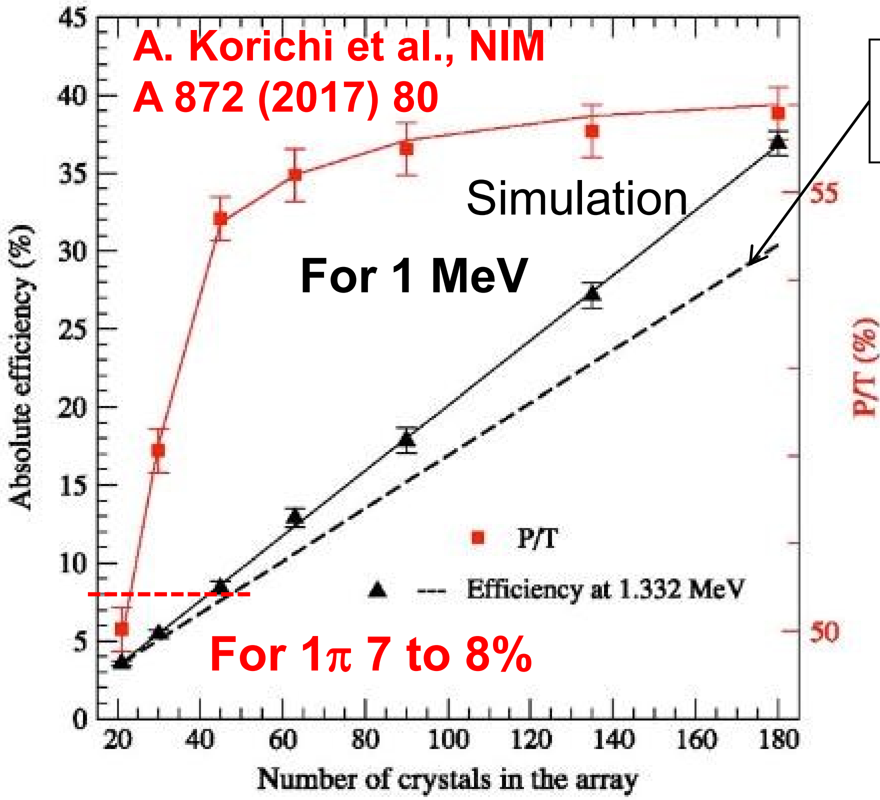
AGATA 1π

- To be used at RIB and High Intensity Stable beam facilities
- Coupled to spectrometers, trackers, neutron and LCP arrays, etc…
- 45 detectors will be achived by 2019

AGATA 4π Performance simulations



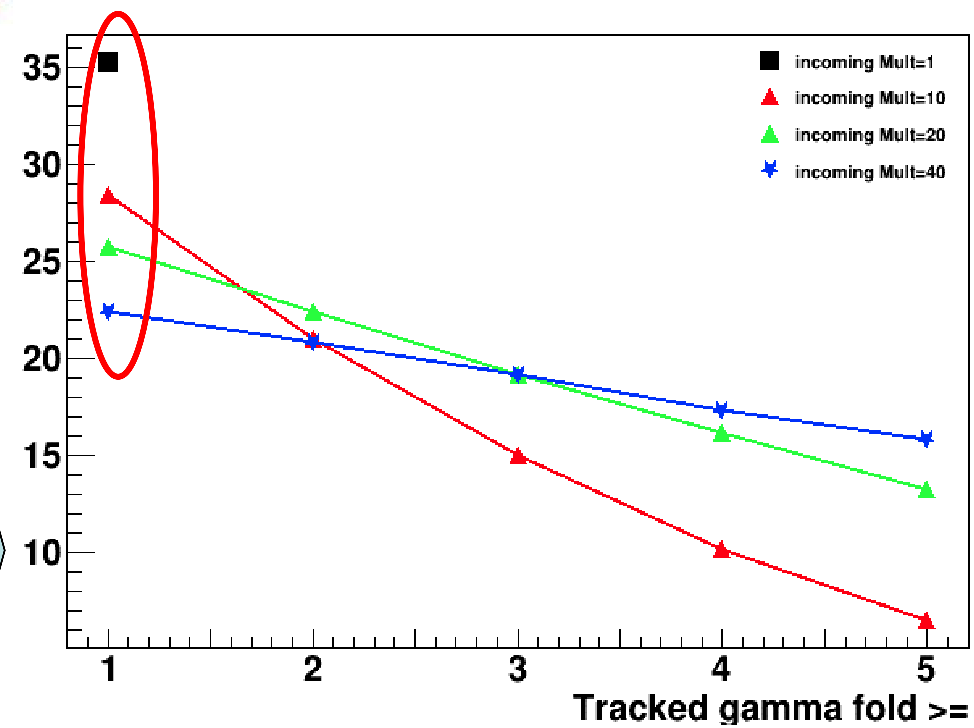
Efficiency and P/T Monte Carlo simulations for the 180 Capsules set-up with Tracking



Linear Scaling from known efficiencies

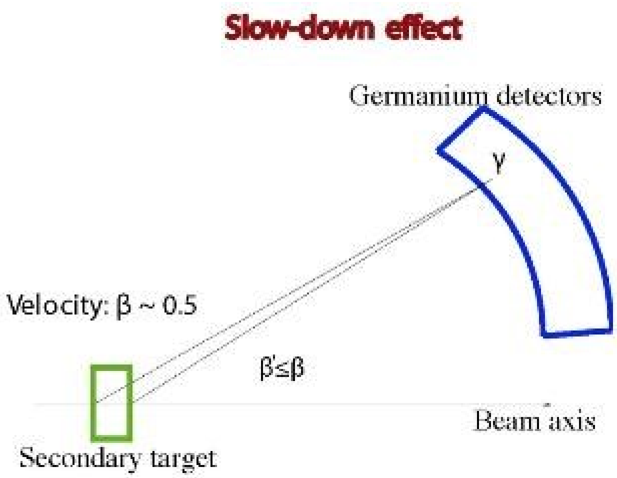
These expectations require the PSA improvements regarding multiple interactions in one segment.

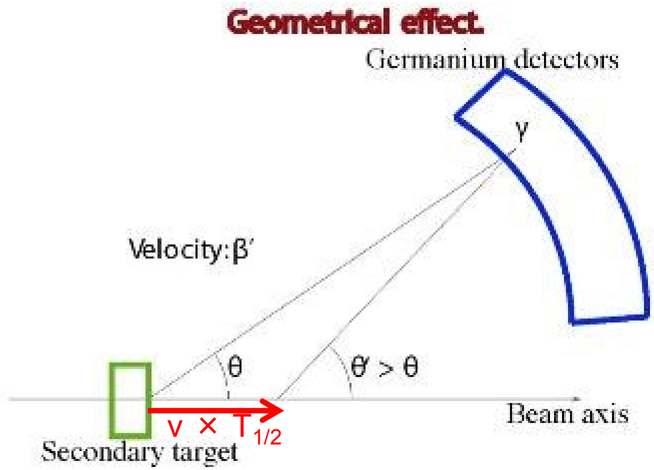
Efficiency depends as well on the γ-ray multiplicity
Recent Upgraded Simulations by M.Labiche (STFC)

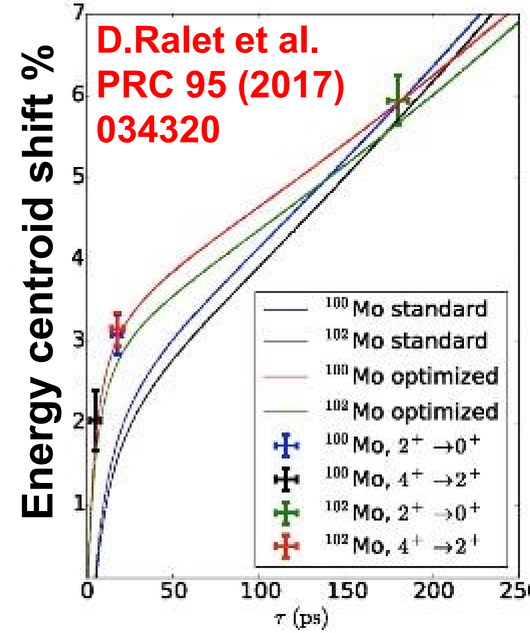


CSNSM-Orsay, STFC-Daresbury

In-Flight Geometrical Line-Shape Lifetime Measurement Techniques



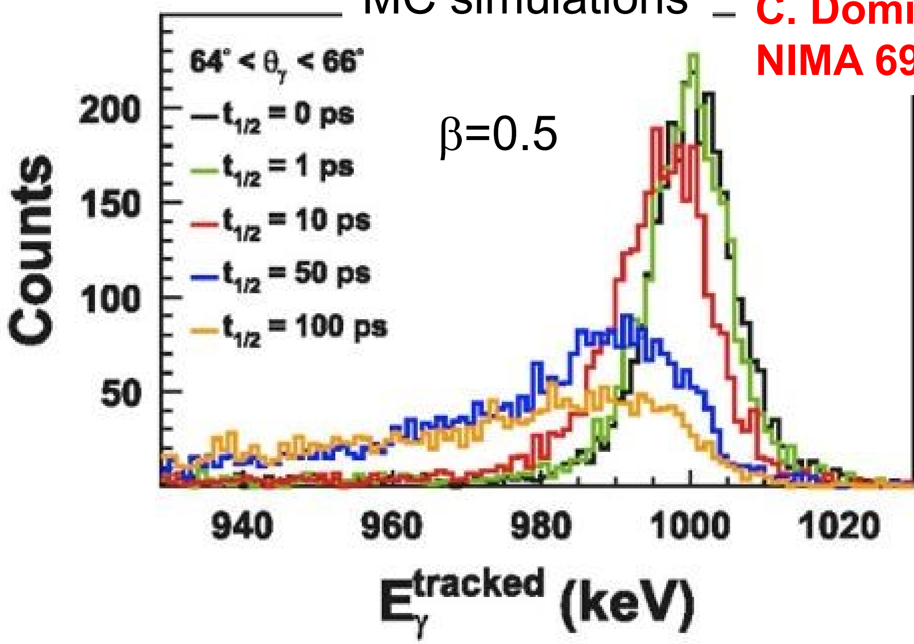




D.Ralet et al. PRC 95 (2017) 034320

MC simulations

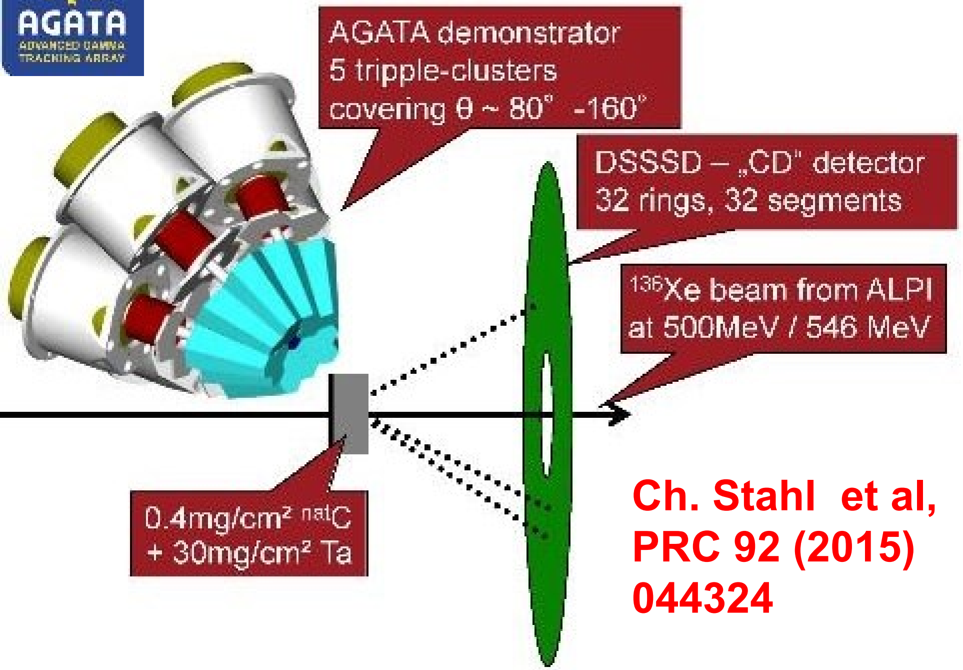
C. Domingo-Pardo et al, NIMA 694 (2012) 297



- New "DSAM-like" technique based on the position sensitivity and the Doppler correction.
- Possible to measure down to 1 to 10 ps lifetimes with relativistic RIBs.

D.Ralet PhD Thesis

Continuous-Angle DSAM



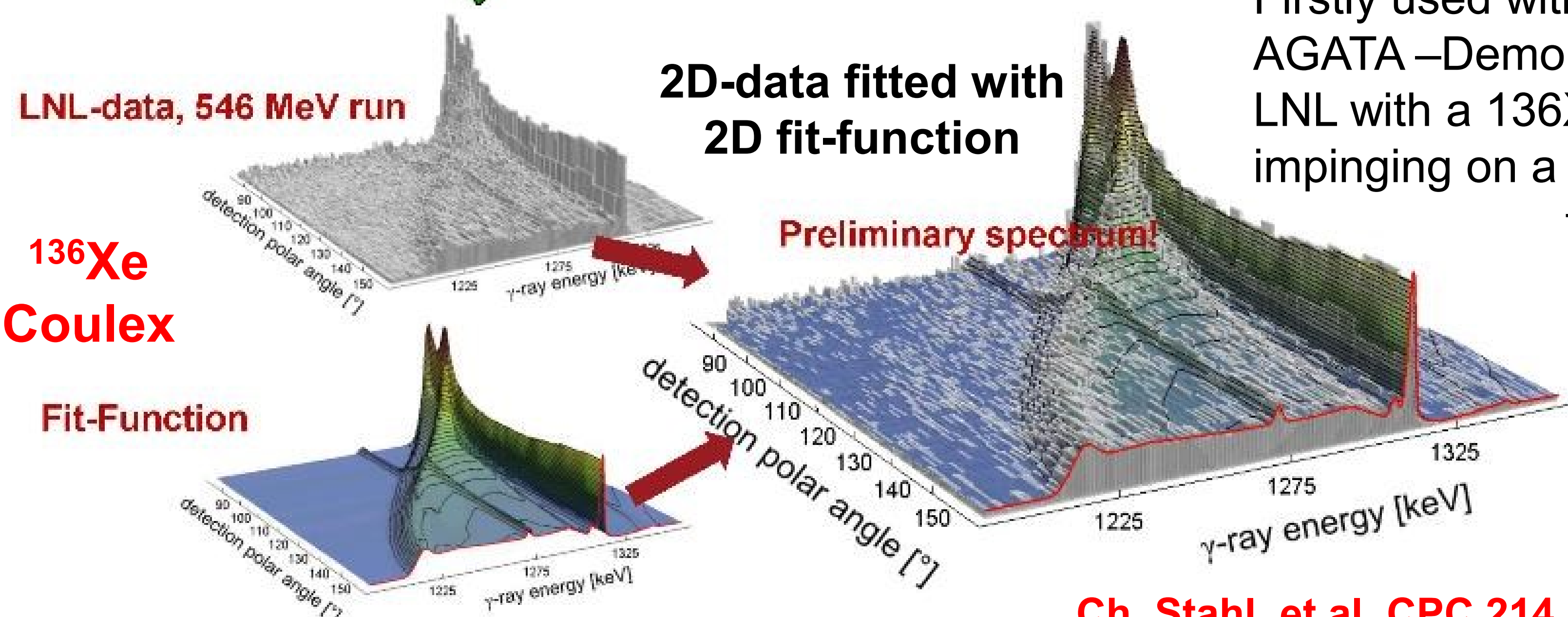
The continuous-angle DSAM represents an advancement of the "conventional" DSAM. It extends the γ-ray lineshapes analysis as a function of γ -ray energy to a lineshape analysis as a function of both γ-ray energy and polar angle of the γ-ray detection.

Also the Geometrical Line-Shape lifetime measurement available for long lifetimes

Ch. Stahl et al, PRC 92 (2015) 044324

Firstly used with the AGATA –Demonstrator at LNL with a 136Xe beam impinging on a ^{nat}C + Ta target.

^{136}Xe Coulex

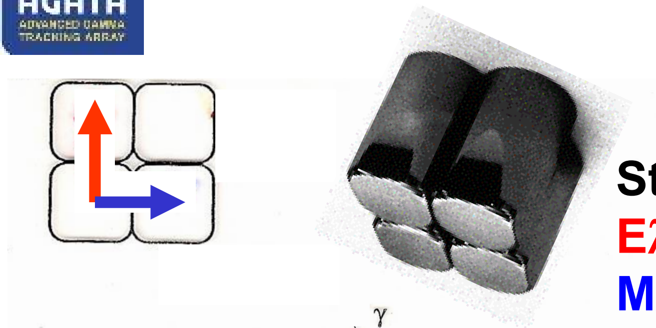


Ch. Stahl et al, CPC 214 (2017) 174

Linear Polarization measurements with AGATA

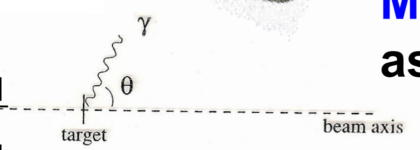
$$\frac{d\sigma}{d\Omega} = \frac{r_0^{\,2}}{2}\left(\frac{E'}{E}\right)^2 \left[\frac{E'}{E} + \frac{E}{E'} + sin^2(\theta)(1 + P\,cos(2\varphi)\right]$$

O. Klein and Y. Nishina – Z. Phys. 52 (1929) 853



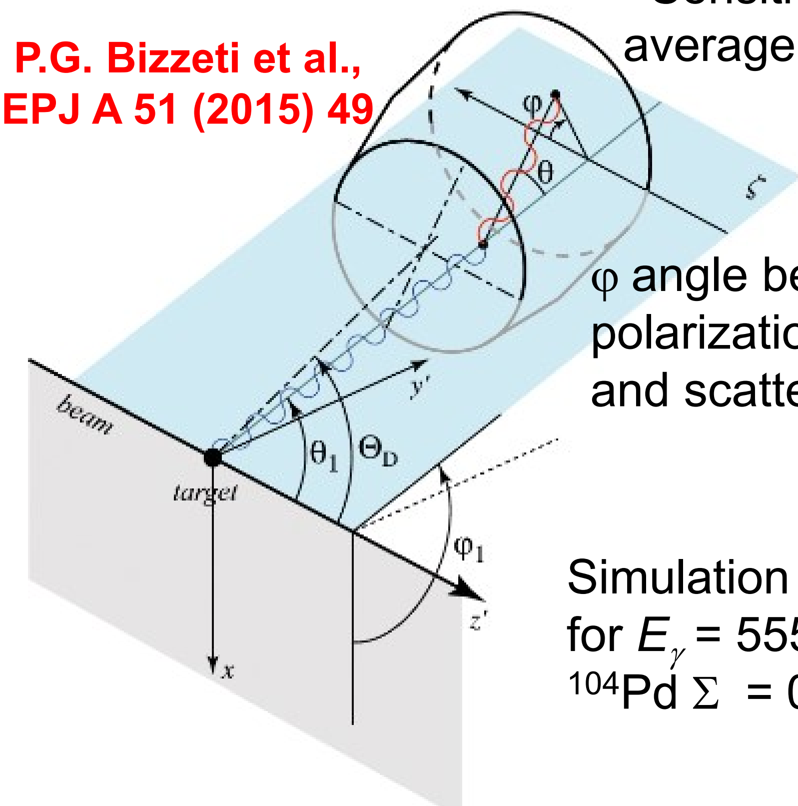
Stretched
Eλ positive &
Mλ negative
asymmetry

$$A = \frac{N_\perp - N_{||}}{N_\perp + N_{||}}$$



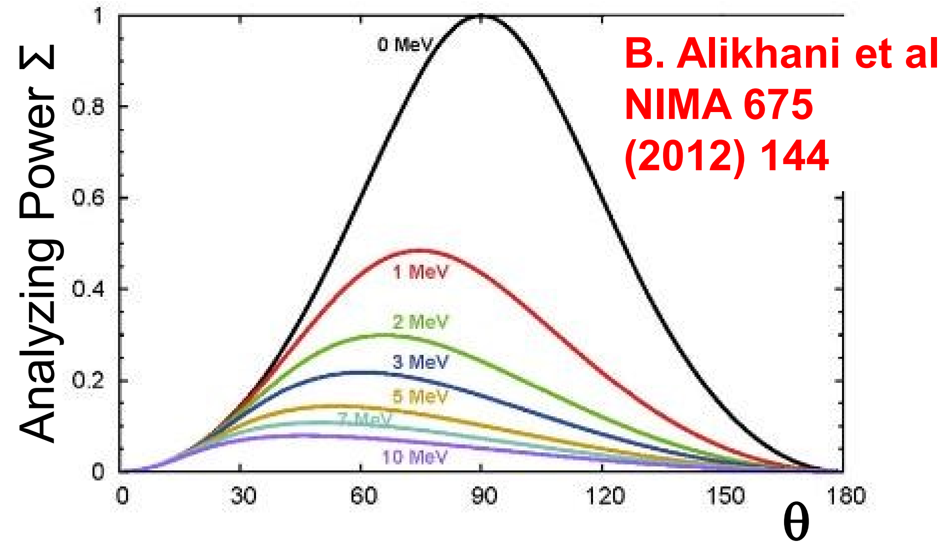
Sensitivity Q
average Σ on θ

P.G. Bizzeti et al.,
EPJ A 51 (2015) 49



φ angle between polarization plane and scattering plane

Simulation value for E_γ = 555.8 keV
^{104}Pd Σ = 0.439



B. Alikhani et al.
NIMA 675
(2012) 144

N_c	Experimental asymmetry A_s	Calculated polarization P	Analyzing power A_{exp}
3	-0.136 ± 0.014	-0.262	0.520 ± 0.053
4	-0.132 ± 0.014	-0.273	0.483 ± 0.052
5	-0.157 ± 0.014	-0.286	0.547 ± 0.049
6	-0.070 ± 0.014	-0.208	0.338 ± 0.067
7	-0.079 ± 0.014	-0.157	0.506 ± 0.089
8	-0.102 ± 0.014	-0.227	0.450 ± 0.062
Average			0.484 ± 0.024

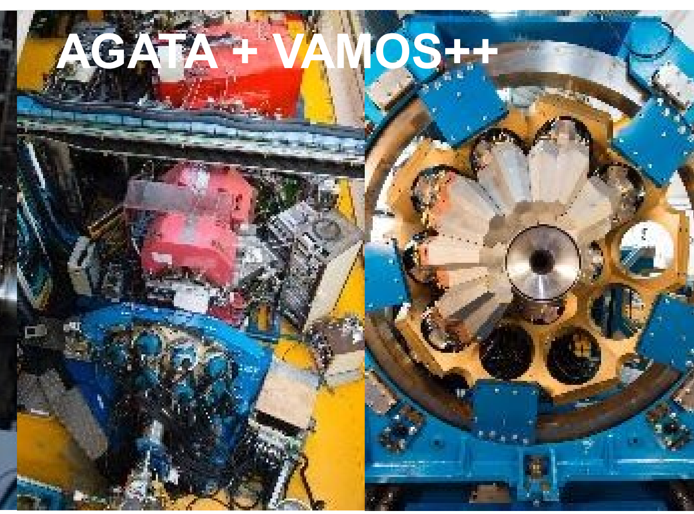
AGATA Early Implementations

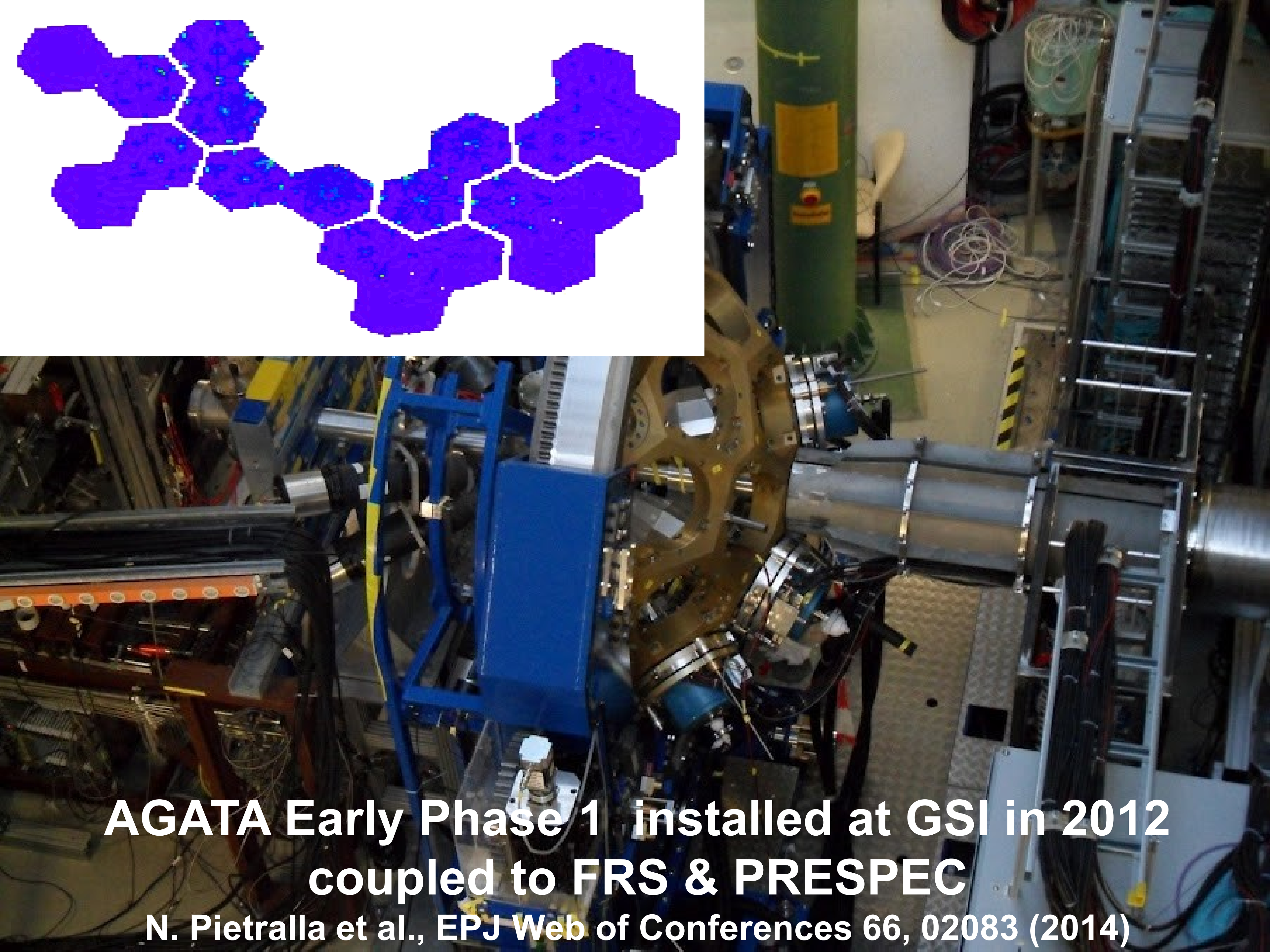
With the AGATA early sub-arrays the scientific activity has been done at the three hosting Laboratories

- **INFN – LNL, Italy:** hosted the first implementation of AGATA, the AGATA Demonstrator, in 2010 and 2011. The experimental activity was done with AGATA coupled to PRISMA, HELENA, DANTE and TRACE

- **GSI, Germany :** hosted AGATA from 2012 to 2014 coupled with FRS and the PRESPEC detectors (tracker, LYCCA etc…)

- **GANIL / SPIRAL1, France :** are hosting AGATA presently. Experimental activity coupled to VAMOS++, PARIS, NEDA+DIAMANT, MUGAST, VAMOS-GFM, etc…



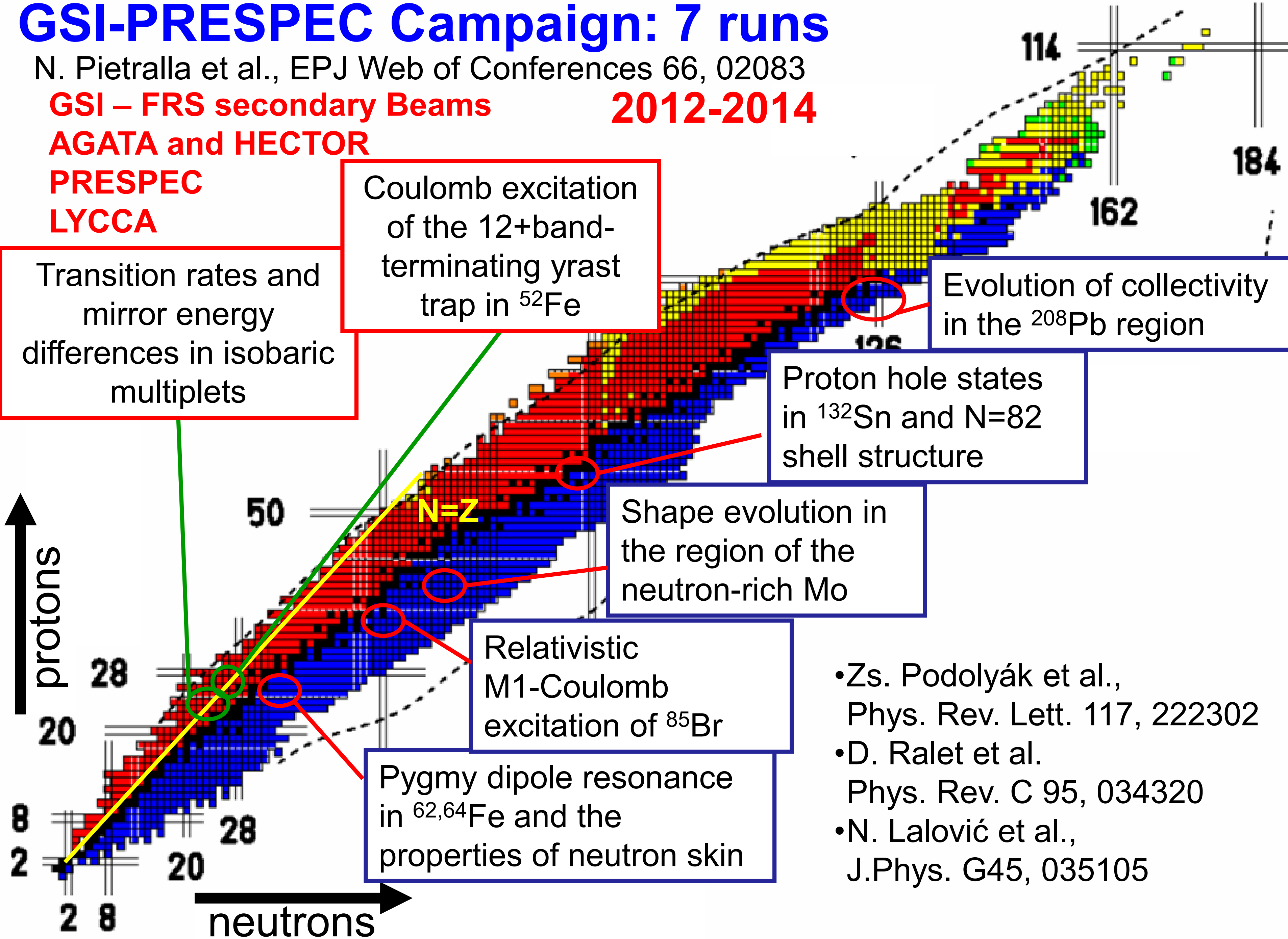

AGATA Early Phase 1 installed at GSI in 2012
coupled to FRS & PRESPEC
N. Pietralla et al., EPJ Web of Conferences 66, 02083 (2014)

GSI-PRESPEC Campaign: 7 runs

N. Pietralla et al., EPJ Web of Conferences 66, 02083

GSI – FRS secondary Beams
AGATA and HECTOR
PRESPEC
LYCCA

2012-2014



- Zs. Podolyák et al., Phys. Rev. Lett. 117, 222302
- D. Ralet et al. Phys. Rev. C 95, 034320
- N. Lalović et al., J.Phys. G45, 035105

GSI-PRESPEC AGATA Campaign

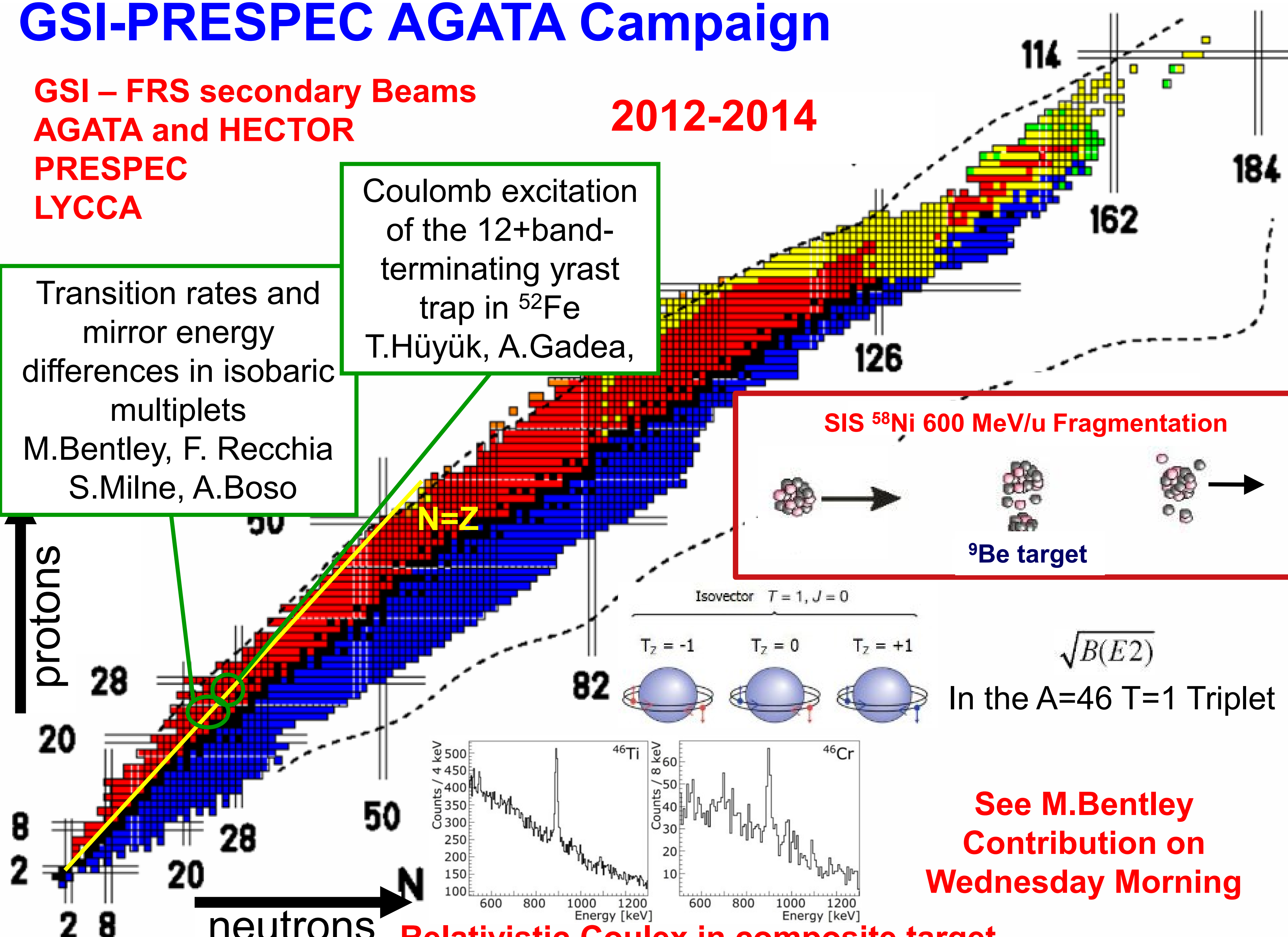
GSI – FRS secondary Beams
AGATA and HECTOR
PRESPEC
LYCCA

2012-2014

Coulomb excitation of the 12+band-terminating yrast trap in ^{52}Fe
T.Hüyük, A.Gadea,

Transition rates and mirror energy differences in isobaric multiplets
M.Bentley, F. Recchia
S.Milne, A.Boso

SIS ^{58}Ni 600 MeV/u Fragmentation



$\sqrt{B(E2)}$

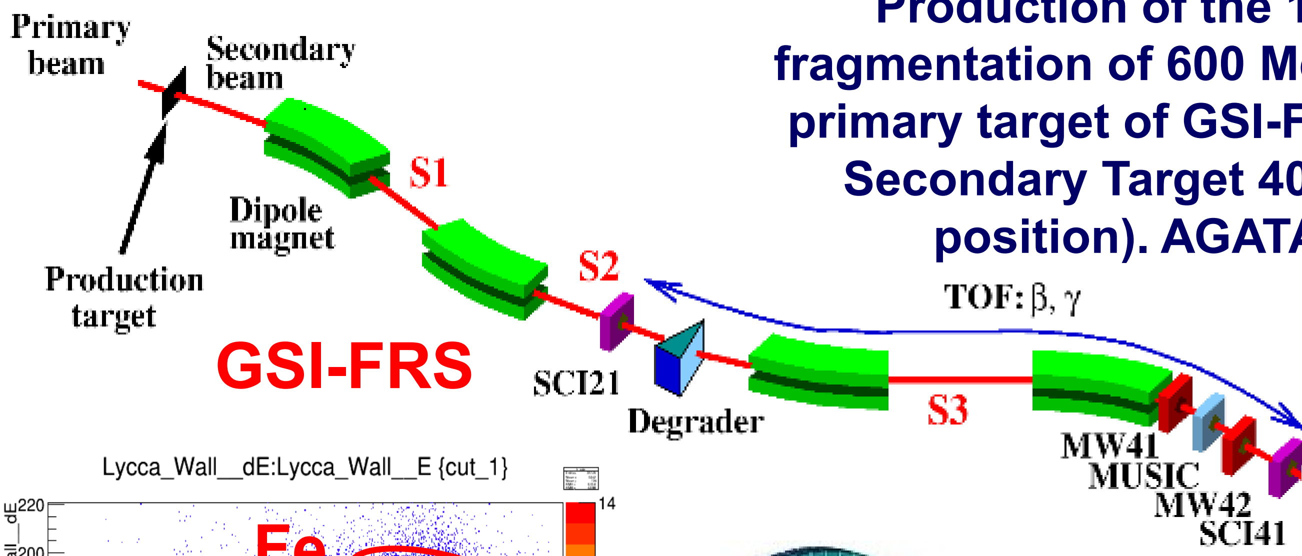
In the A=46 T=1 Triplet

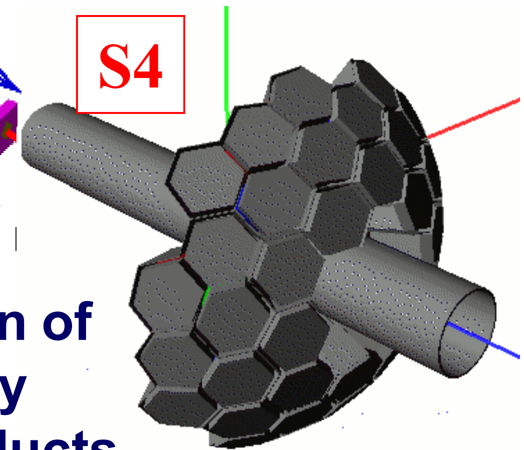
Relativistic Coulex in composite target

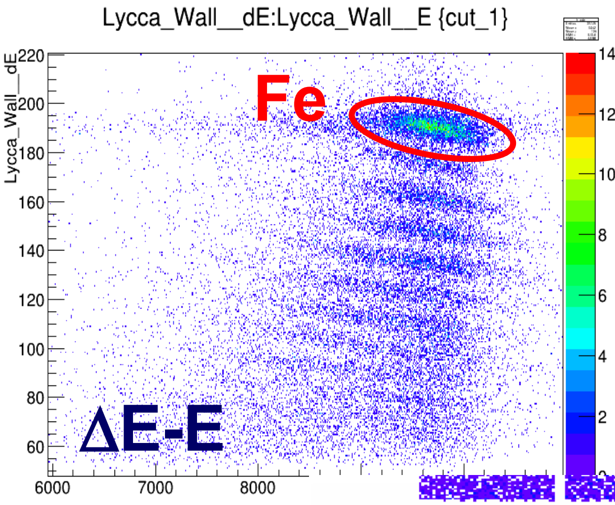
See M.Bentley Contribution on Wednesday Morning

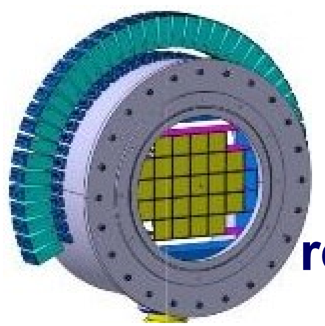
Experiment

Production of the 12+ isomeric beam y fragmentation of 600 MeV.A ^{58}Ni on a ^{9}Be 4g/cm^2 primary target of GSI-FRS. Three seconds Spill Secondary Target 400mg/cm2 Au (forward position). AGATA-PRESPEC setup









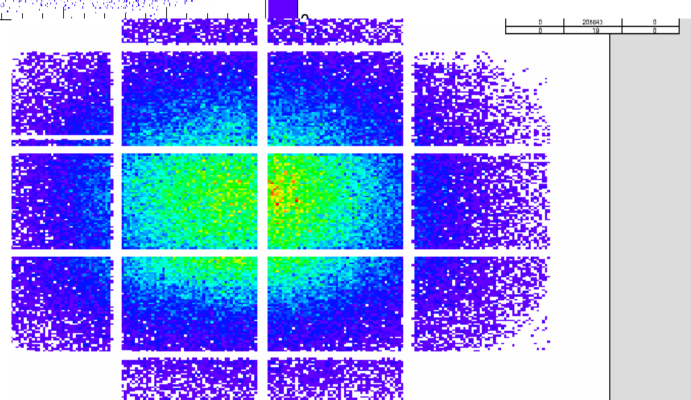
LYCCA
Identification of secondary reaction products

Determination of isomeric ratio: β-decay with thick stopper: ~10%

Z identification

.

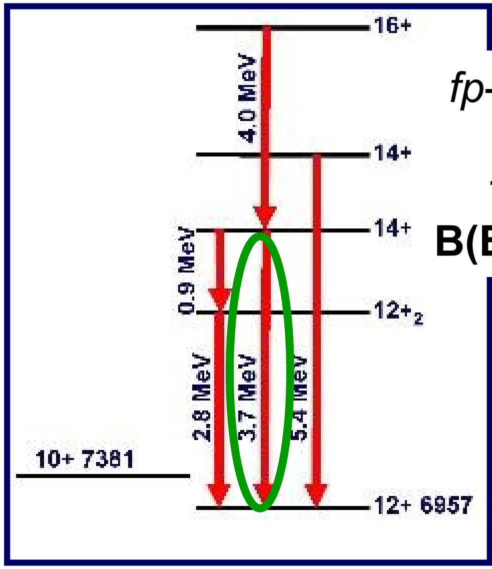
Scattering angle



β=0.51
Secondary Target-AGATA distance 8cm

$^{52}Fe^{g.s.,12+}$ Relativistic Coulex

Tayfun Hüyük PhD thesis



fp-Shell LSSM
GXPF1
14+ → 12+
B(E2)=27 e^2fm^4

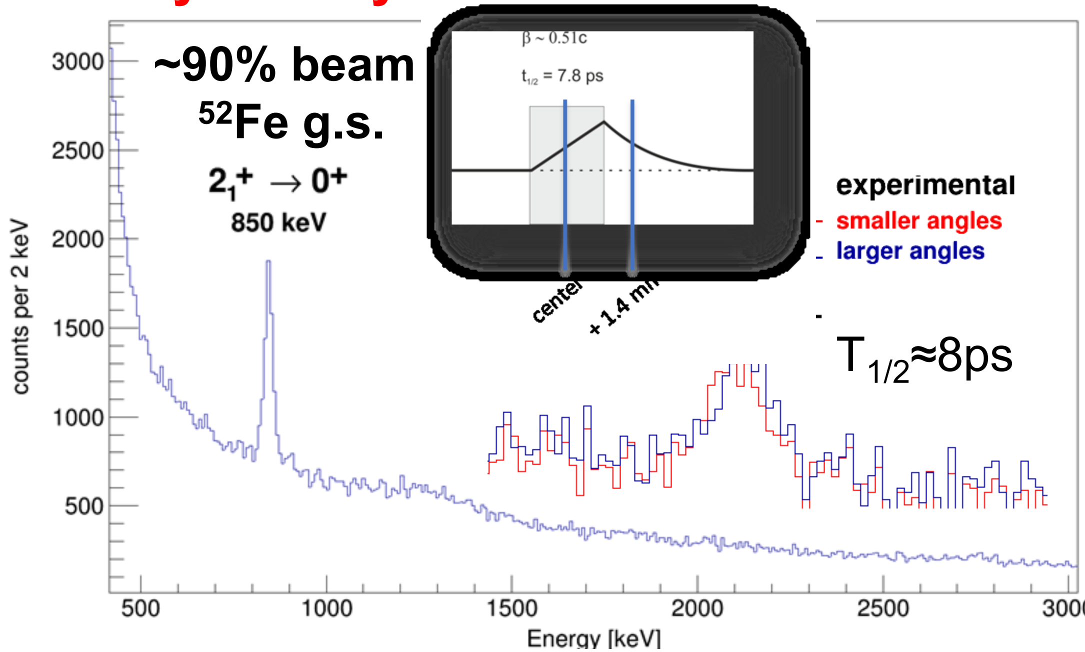
g.s.→2^+_1B(E2)= 820 e^2fm^4
K.L.Yurkewicz PRC **70**, 034301

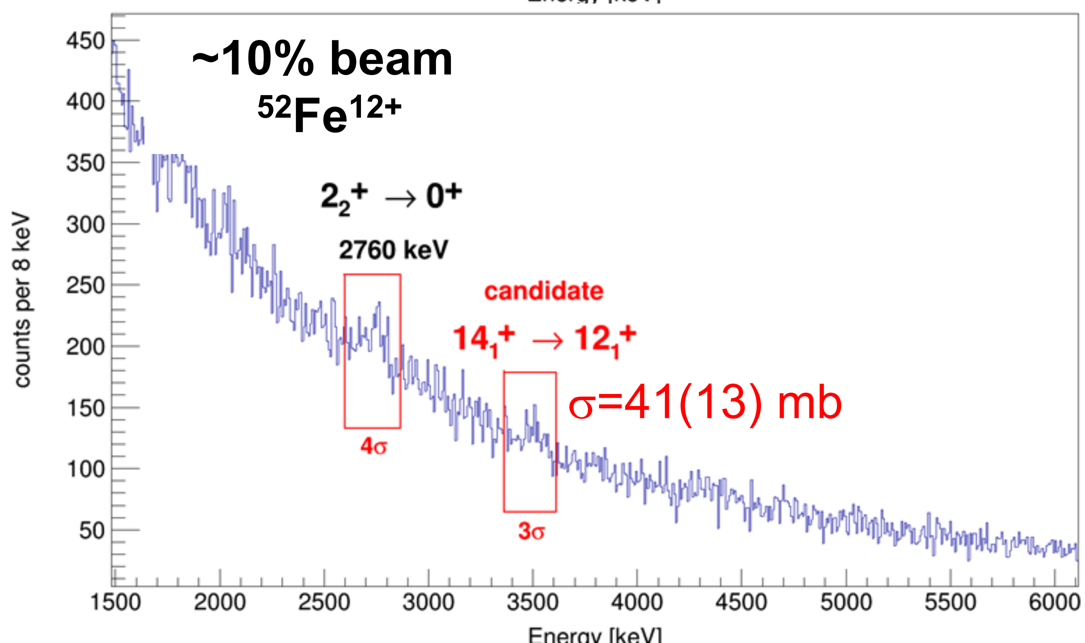
g.s.→

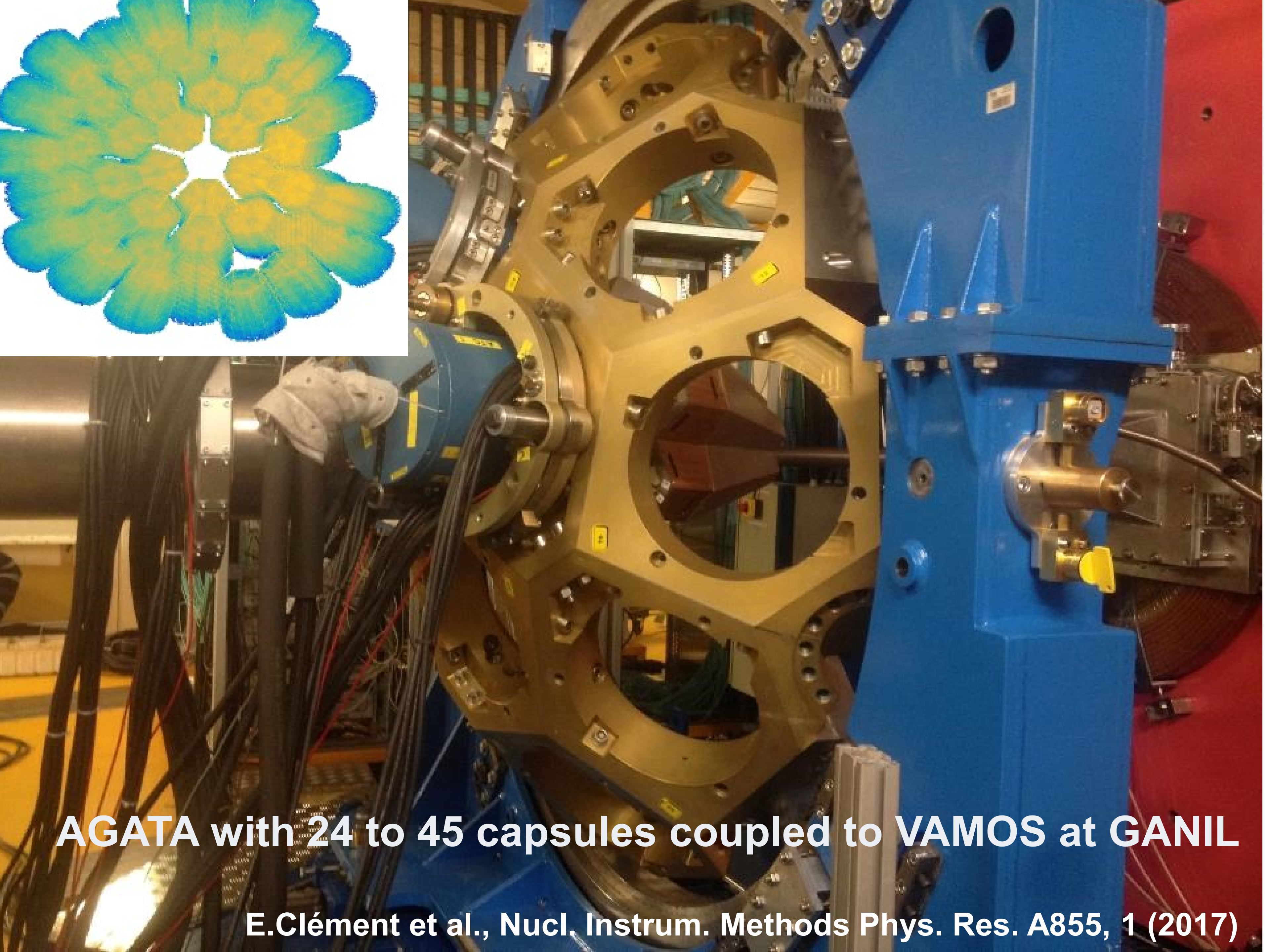
- **2_1^+** σ=106(5) mb;
  B(E2)=900(40) e^2fm^4; $T_{1/2}$=7.1(4) ps

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

Comparison to FRESCO calculations with T. Furumoto O.P.





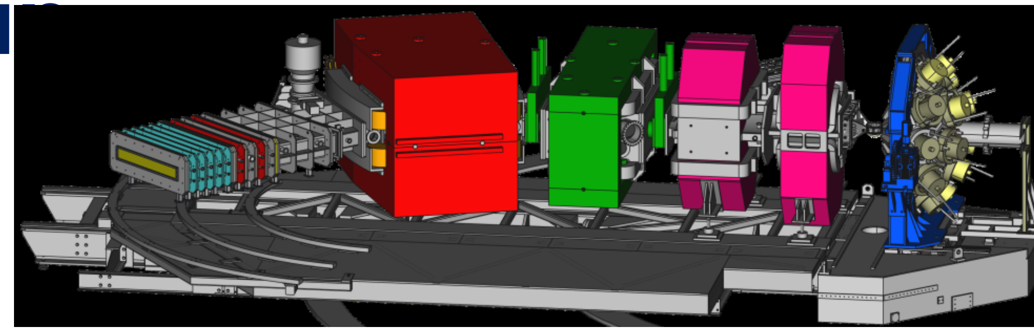


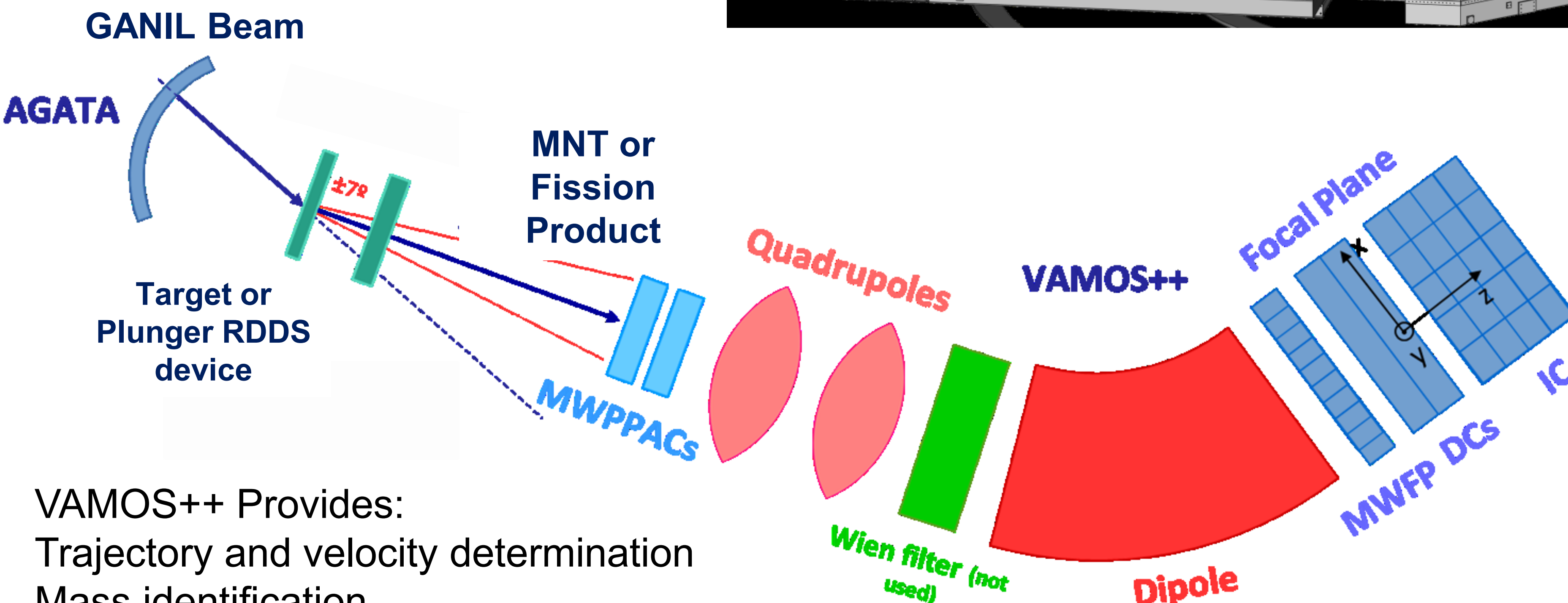
AGATA with 24 to 45 capsules coupled to VAMOS at GANIL

E.Clément et al., Nucl. Instrum. Methods Phys. Res. A855, 1 (2017)

Experimental Setup
for AGATA + VAMOS++

Multi Nucleon Transfer, Deep Inelastic and Reaction Induced Fission





VAMOS++ Provides:
Trajectory and velocity determination
Mass identification
- Nucleus trajectory reconstruction
- Velocity measurement
- Total energy measurement

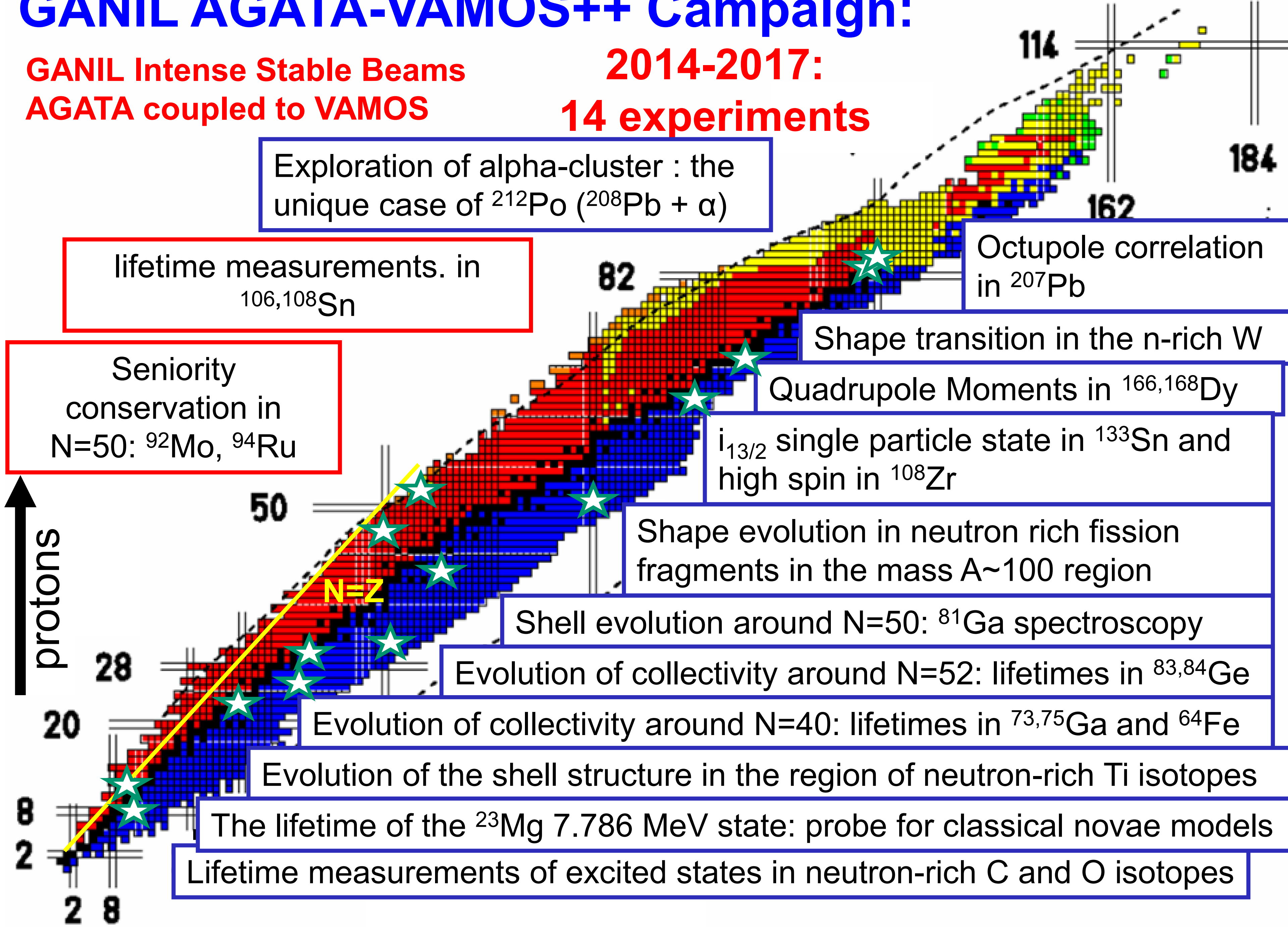
Z identification
- Energy measurement (E-E method)

Trigger MWPPAC & MWFP & GAMMA

GANIL AGATA-VAMOS++ Campaign:

GANIL Intense Stable Beams
AGATA coupled to VAMOS

2014-2017:
14 experiments



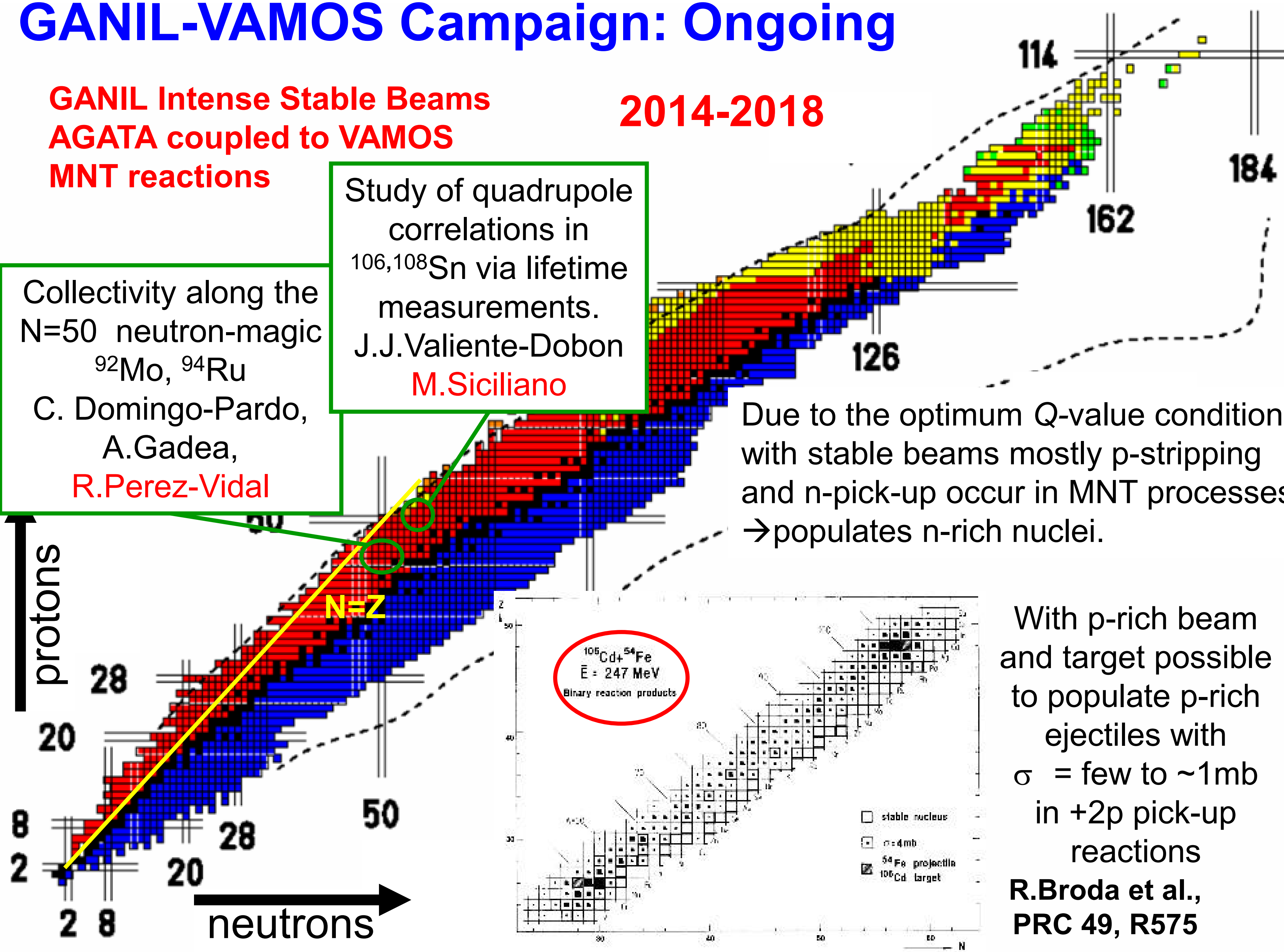
GANIL-VAMOS Campaign: Ongoing

GANIL Intense Stable Beams
AGATA coupled to VAMOS
MNT reactions

2014-2018

Study of quadrupole correlations in ^{106,108}Sn via lifetime measurements.
J.J.Valiente-Dobon
M.Siciliano

Collectivity along the N=50 neutron-magic ^{92}Mo, ^{94}Ru
C. Domingo-Pardo,
A.Gadea,
R.Perez-Vidal

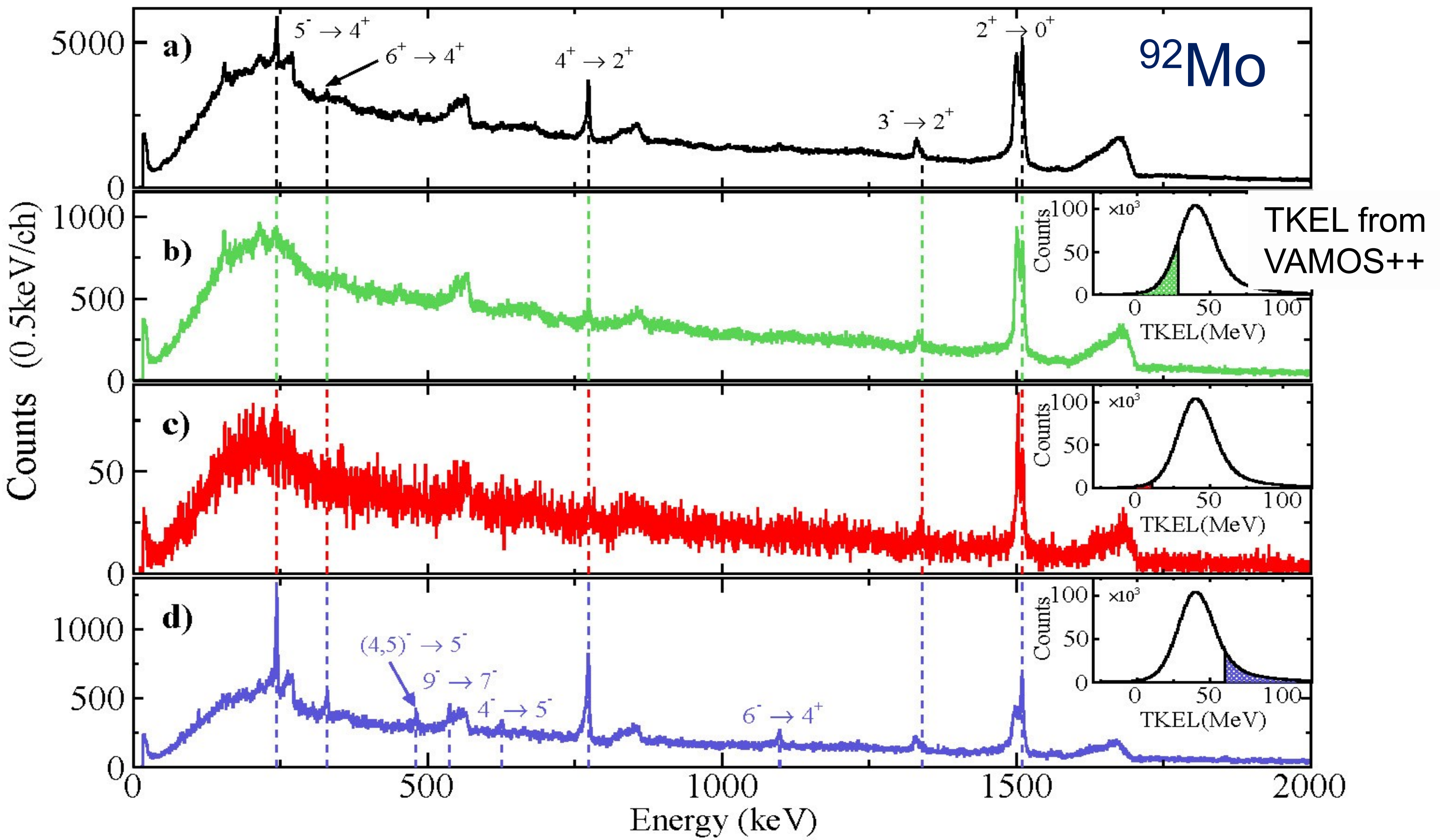


Due to the optimum *Q*-value condition with stable beams mostly p-stripping and n-pick-up occur in MNT processes →populates n-rich nuclei.

With p-rich beam and target possible to populate p-rich ejectiles with σ = few to ~1mb in +2p pick-up reactions

R.Broda et al., PRC 49, R575

Experimental Setup: Limiting feeding with the TKEL Condition

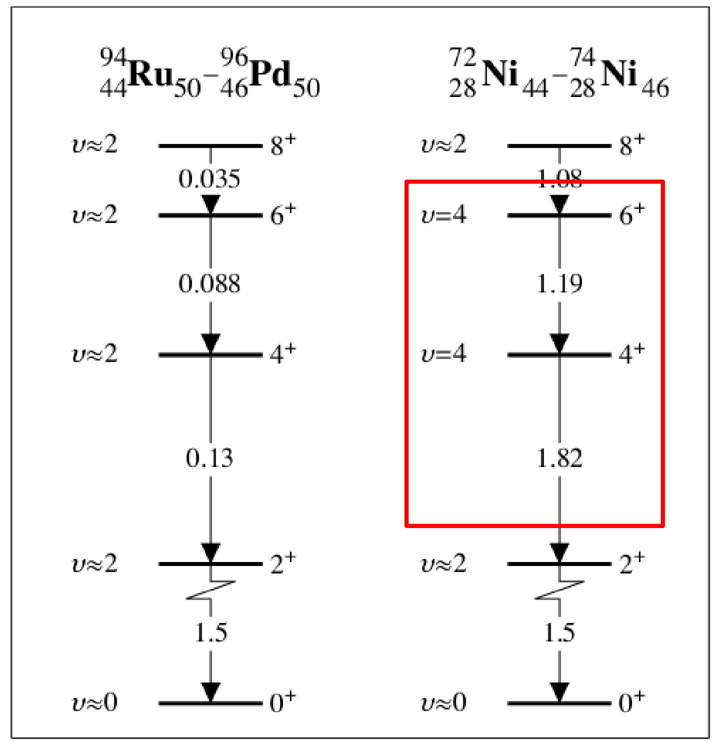


Investigation of the Seniority Conservation in the $\pi g_{9/2}$ shell

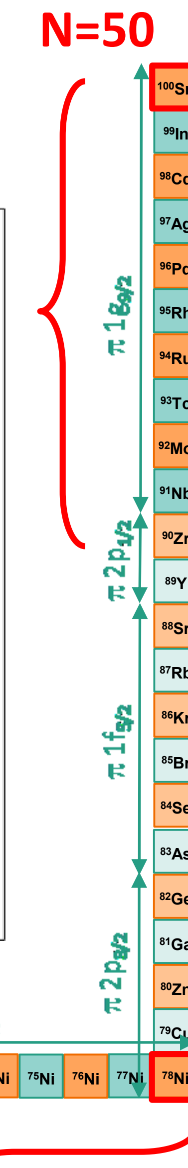
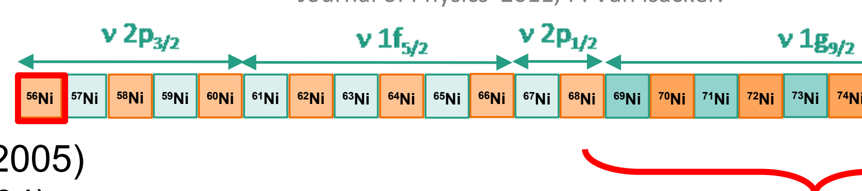
$g_{9/2}$ Shell: seniority might be not conserved

- Shell Model orbitals for valence along N=50 are the same as for valence along Z=28
- Same nuclear structures for Valence Mirror Symmetry Partners (?)
- Indeed similar 2+ and 4+ excitation energy towards ^{100}Sn and ^{78}Ni
- Effective two-body interaction is very different along $g_{9/2}$ near ^{100}Sn and around ^{78}Ni
- Suggested in ^{94}Ru and ^{96}Pd 4+ have υ=2 character and ^{72,74}Ni have υ=4 character
- Seniority conservation breaking occurs via the mixing of υ=2 and υ=4) and might be possible for j=9/2

Valence Mirror Symmetry Partners



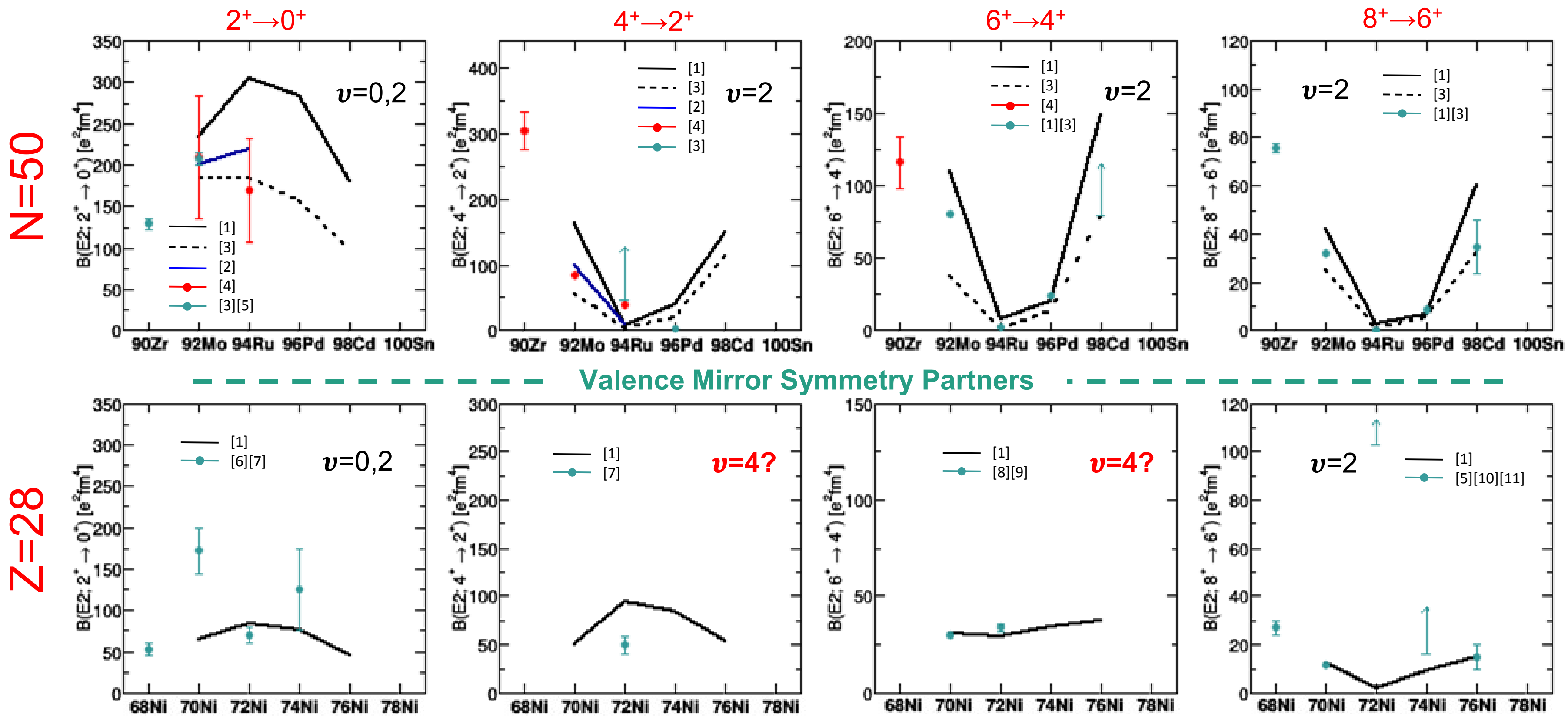
Journal of Physics 2011, P. Van Isacker.

A.F. Lisetskiy et al., Eur. Phys. J. A 25, s01, 95 (2005)
A.F. Lisetskiy et al,. Phys. Rev.C 70, 044314 (2004).
P. Van Isacker Int. Jour. of Mod. Phys. E, Vol . 20, 191 (2011)
P. Van Isacker et al., Phys. Rev. Lett. 100, 052501 (2008)

Seniority Conservation in the $\pi g_{9/2}$ shell

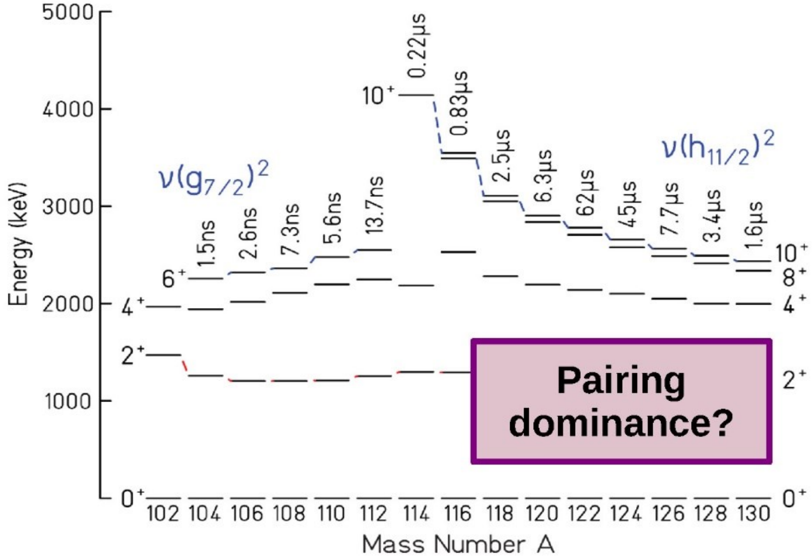
R.Perez-Vidal, A.Gadea, C.Domingo-Pardo et al, in preparation

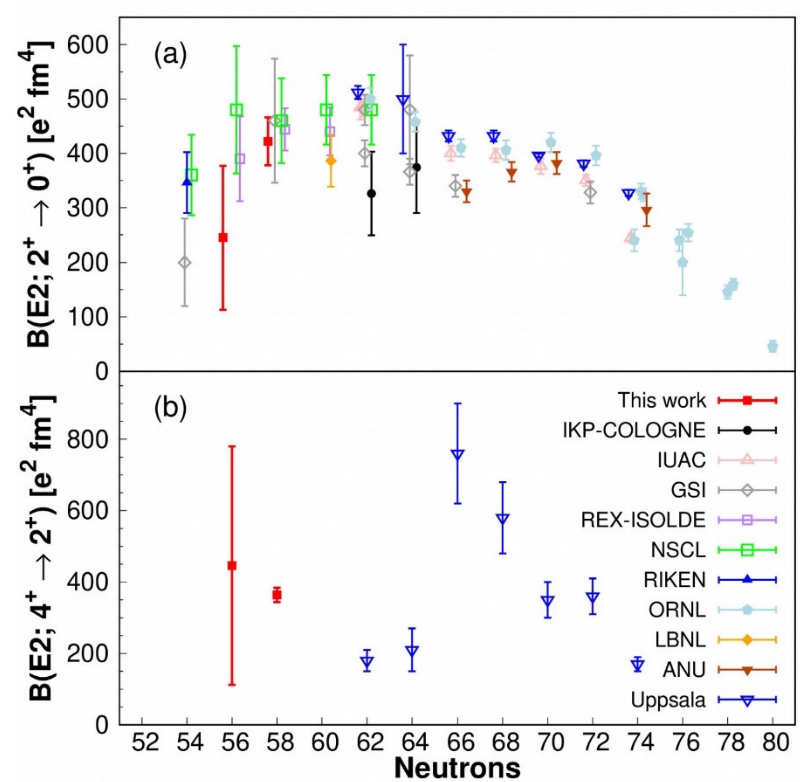


[1] A.F. Lisetskiy et al. PRC 2004
[2] A. Gargano Private communication
[3]H. Mach et al. PRC 2017
[4]R.M. Pérez-Vidal et al. This work
[5]NNDC
[6] T. Marchi et al PRL 2014
[7] K. Kolos et al PRL 2016
[8] C.J. Chiara et al PRC 2015
[9] A.I. Morales et al. PRL 2018
[10] M. Sawicka et al PRC 2003
[11] A.I. Morales et al. PRC 2016

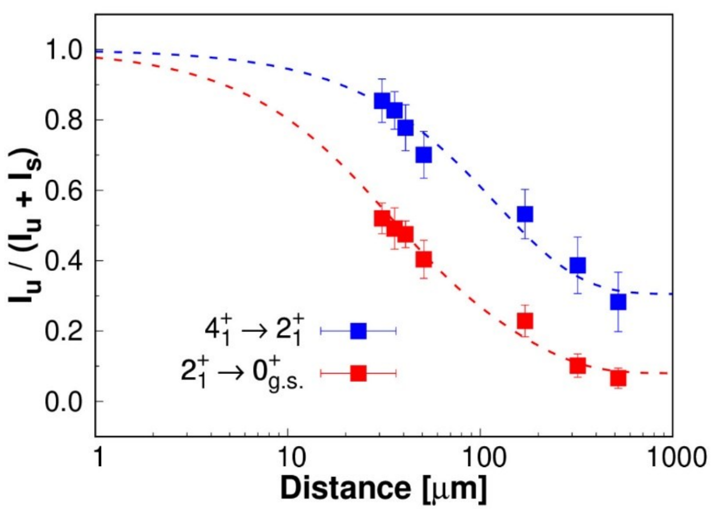
Seniority well preserved in the N=50 isotones along the $(\pi g_{9/2})^n$ excitations

Lifetime Measurements in ^{106,108}Sn.





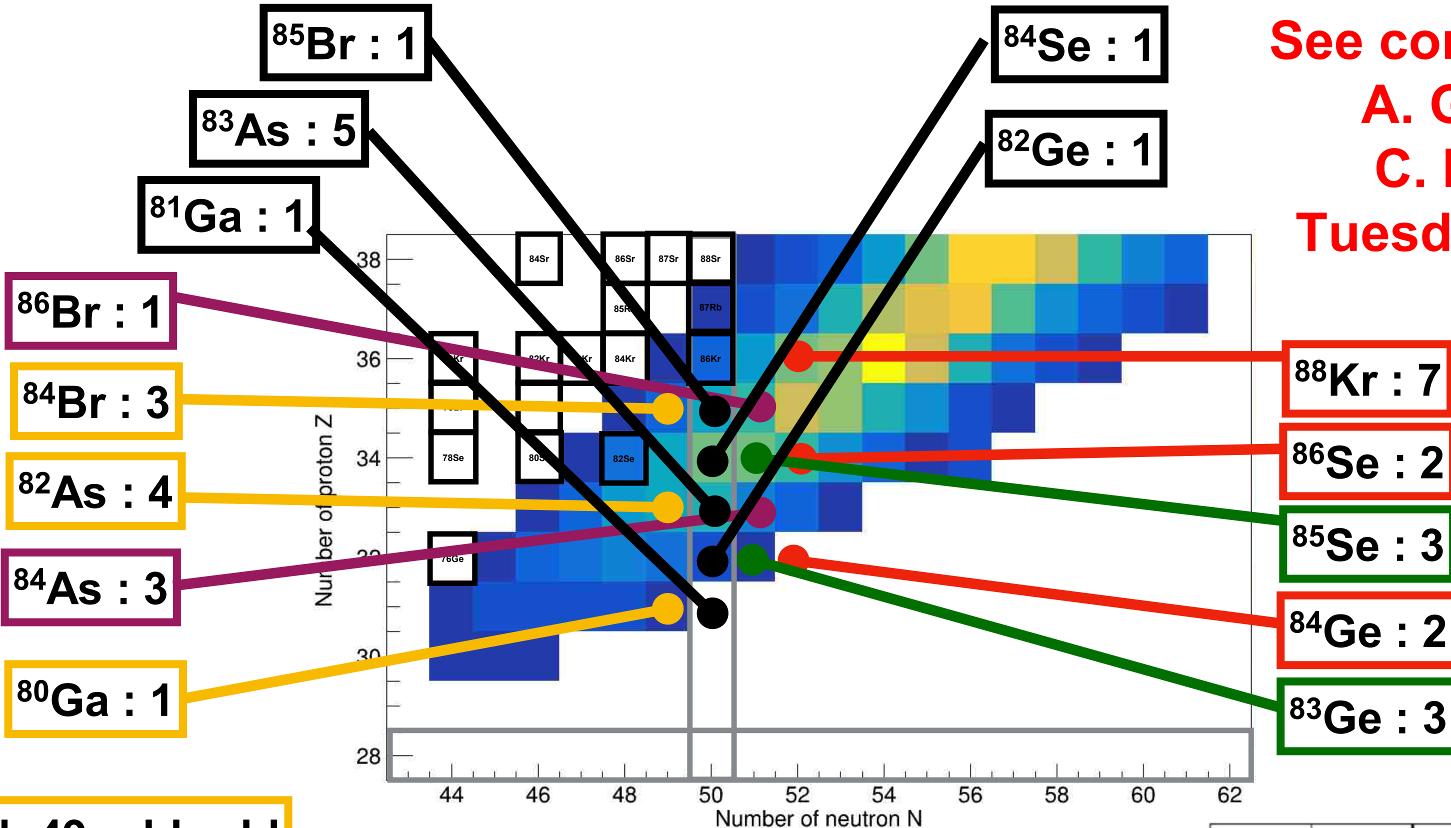
- **Direct population of the states**, avoiding the experimental limitations due to the “seniority” isomers
- **Complementary information** to Coulomb-excitation measurements
- Extend the investigation **above the 2_1^+** excited state



See M. Siciliano contribution on Thursday afternoon – Sala Vivaldi

“Interplay between quadrupole and pairing correlations close to 100Sn from lifetime measurements”

Evolution of collectivity around N=52: lifetimes in the vicinity of ^{78}Ni



See contributions of A. Gottardo & C. Delafosse Tuesday afternoon

N=49 odd-odd

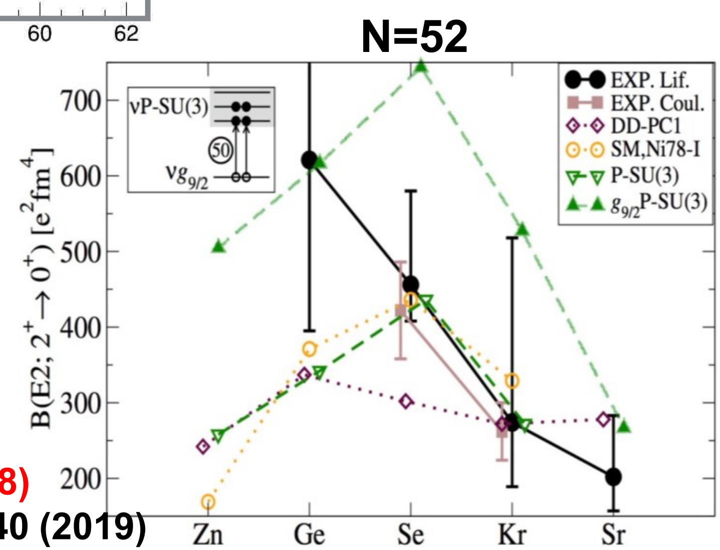
N=50

N=51 even-odd

N=51 odd-odd

N=52 even-even

Sudden increase of collectivity in ^{84}Ge : hint of pseudospin symmetry



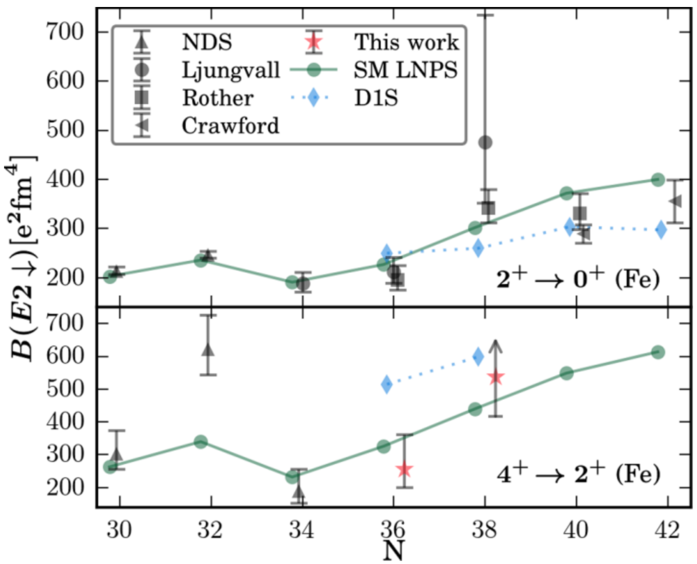
C. Delafosse et al PRL 121, 192502 (2018)
C. Delafosse et al. Acta. Phys. Pol. B 50 633-640 (2019)

Shell evolution in the vicinity of Z=28 and N=40

Interplay of the monopole terms of the interaction with multipole terms, like pairing and quadrupole. Collecting spectroscopic data like transition probability constraining the theoretical description of the Island of inversion from N=28 to N=40, i.e. influence of the νg9/2 and νd5/2 orbits, of the proton excitations across Z=28 and evolution of collectivity with the proton $f_{7/2}$ orbital ocupation

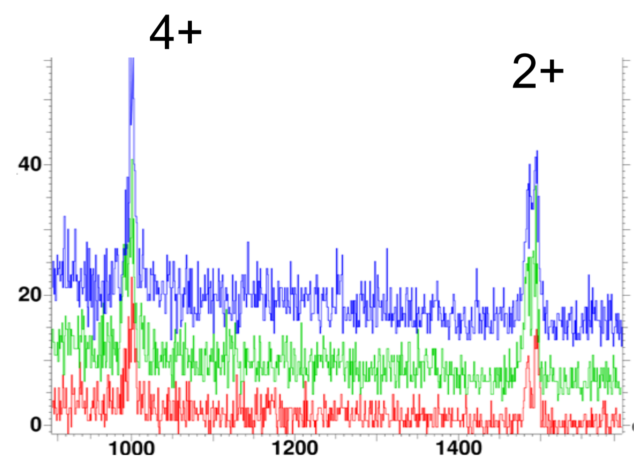
See contribution of A. Goldkuhle Tuesday afternoon

Lifetimes of the 4^+ states in $^{62;64}$Fe and the $11/2^-$ in $^{61;63}$Co and ^{59}Mn



M. Klintefjord et al., PRC 95, 024312 (2017)

Lifetimes in ^{54}Ti and in neighboring isotopes

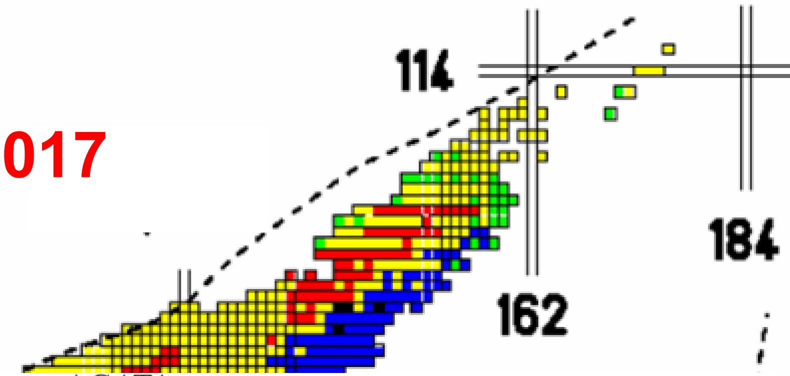


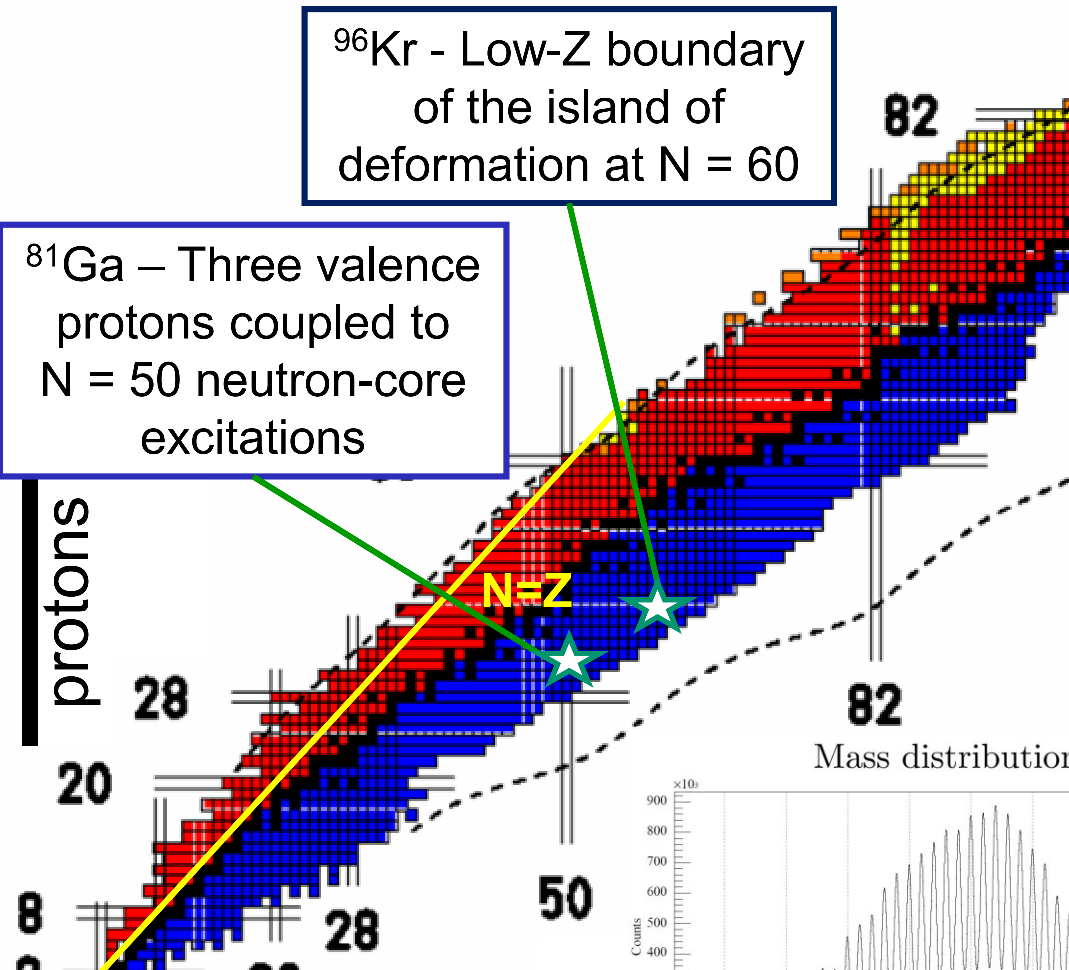
A. Goldkuhle et al. Letter in preparation

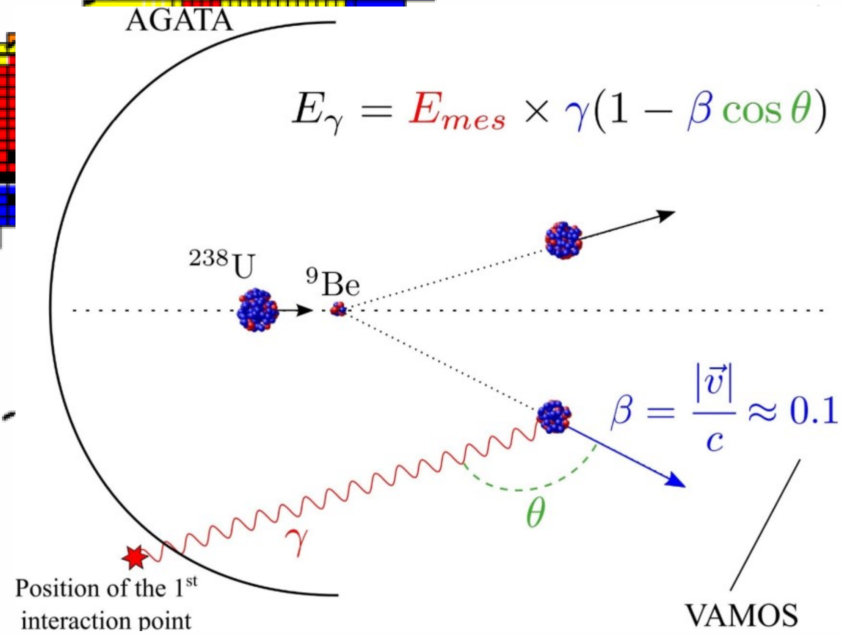
GANIL-VAMOS++ Campaign:

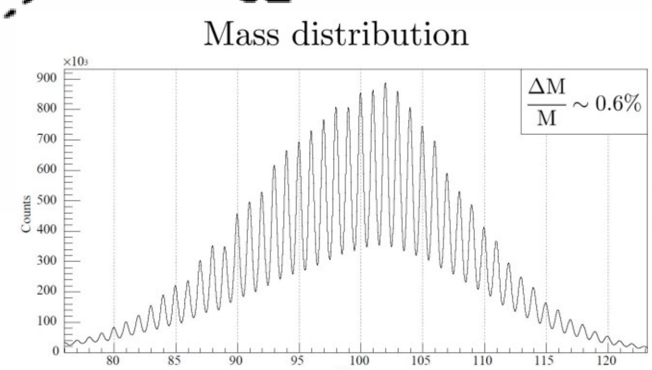
Transfer and fusion induced fission reactions in inverse kinematics with ^{238}U beams

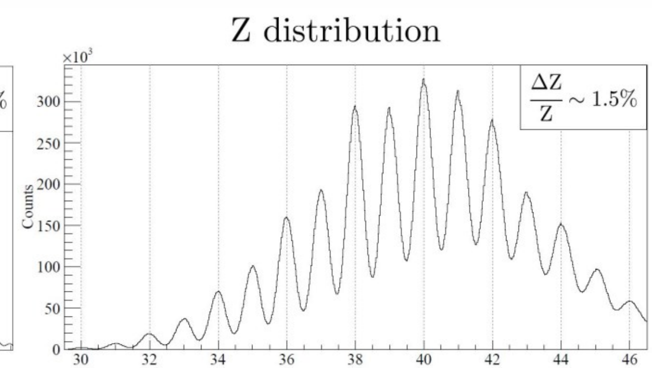
2014-2017







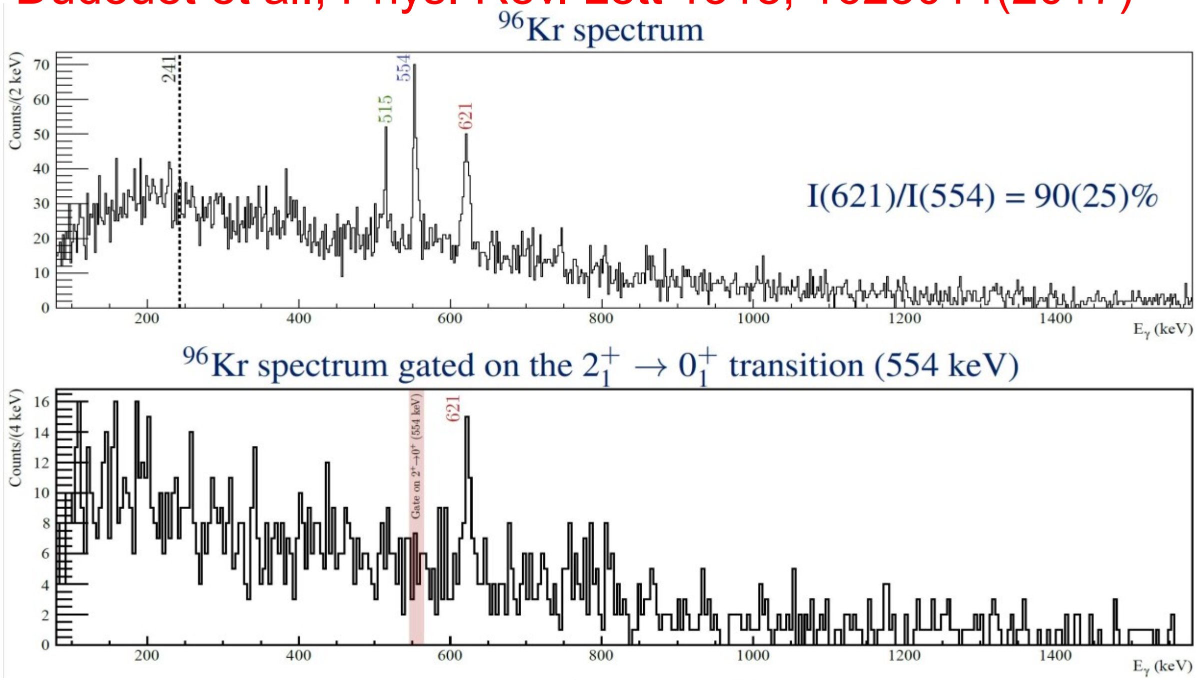


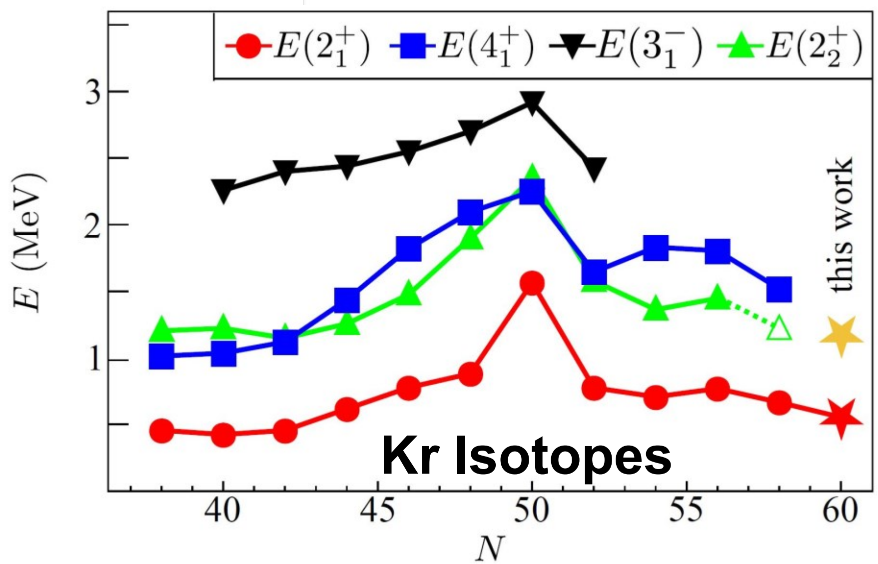


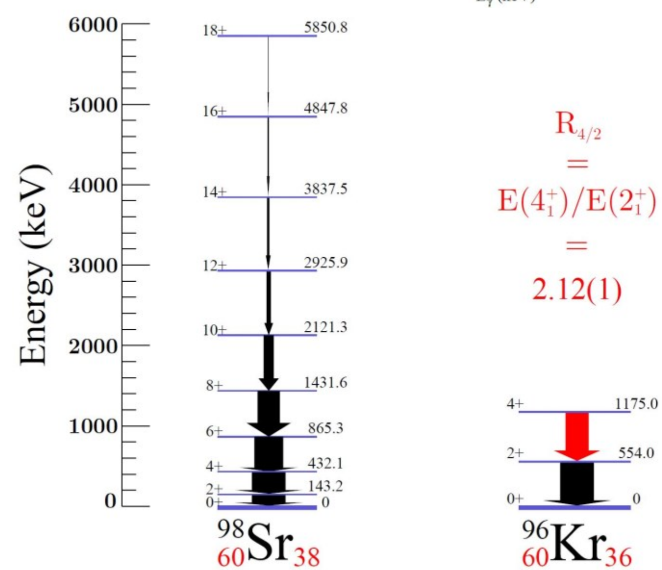
96Kr - boundary of the island of deformation at N = 60

J. Dudouet, A Lemasson, G. Maquart, G. Duchêne et al,

J. Dudouet et al., Phys. Rev. Lett 1318, 1625014(2017)







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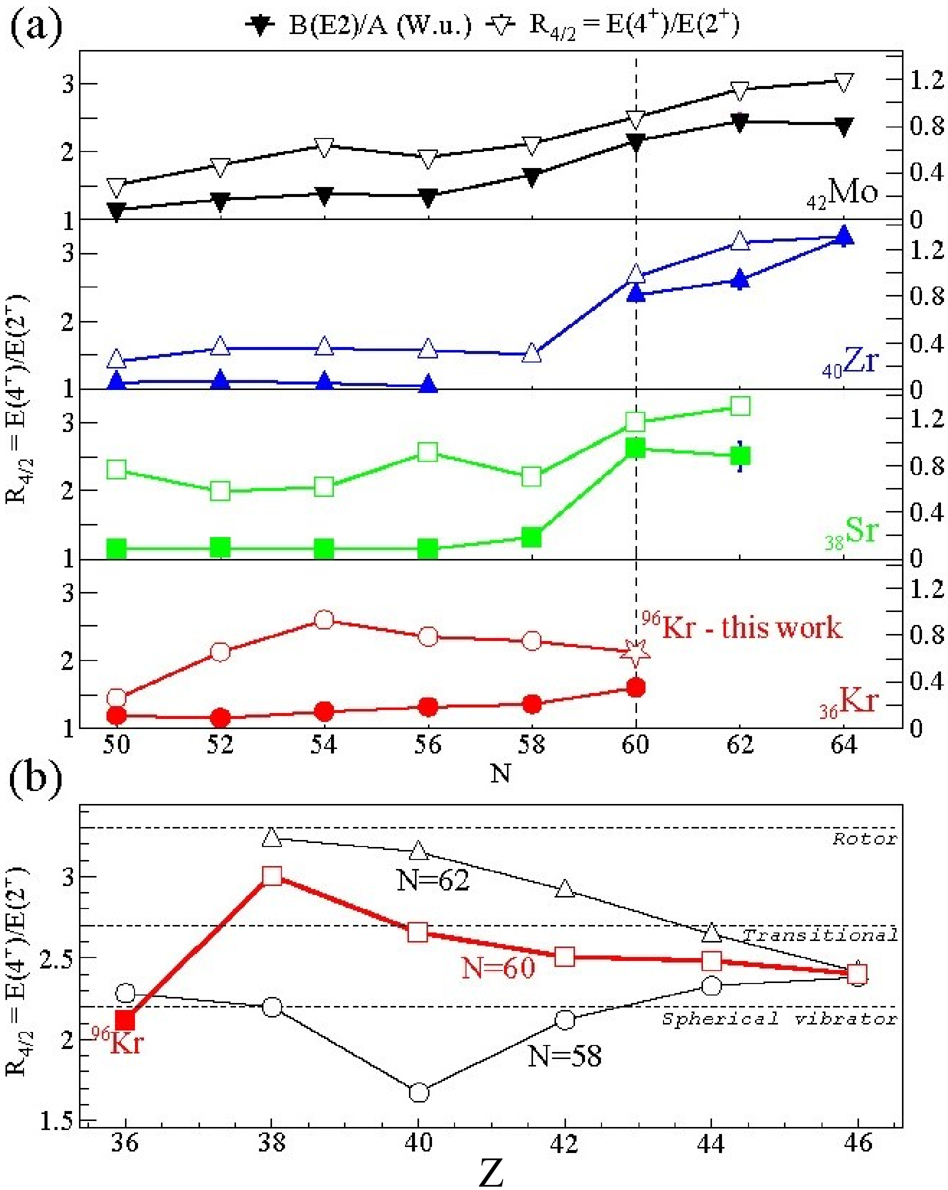
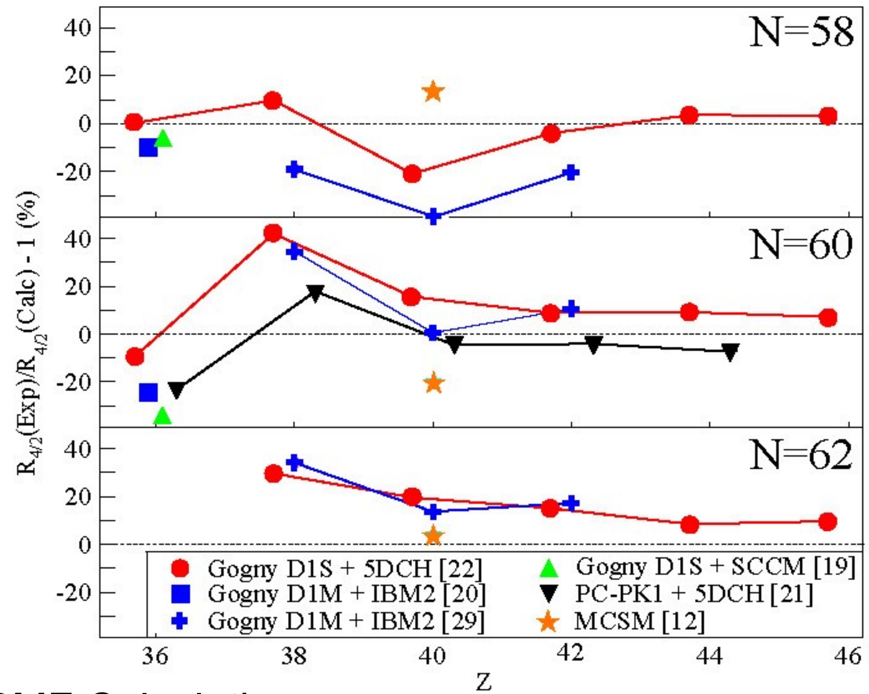




BMF Calculations:

- Gogny D1S+5DCH: J.-P. Delaroche PRC 81
- Gogny D1M+IBM2: M. Albers NPA 899, 1, K. Nomura PRC 94
- Gogny D1S+SCCM: T. R. Rodriguez, PRC 90
- PC-PK1+5DCH: J. Xiang, PRC 93

MCSM: T. Togashi PRL 117

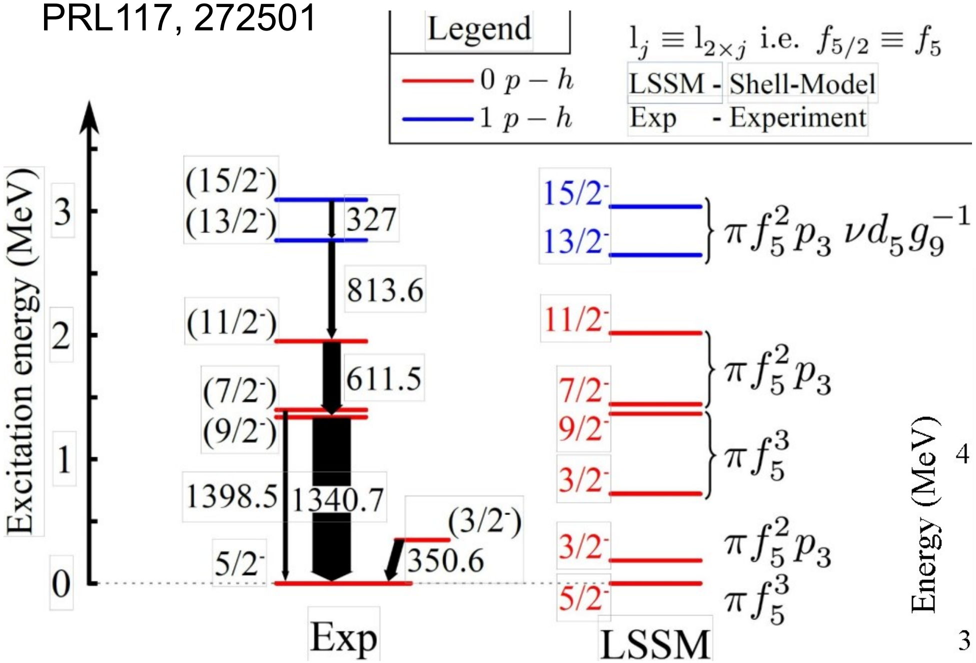
(Reproduce the Zr transition along N=60: due to $\pi g_{9/2}$-$\nu g_{9/2}$ coupling)

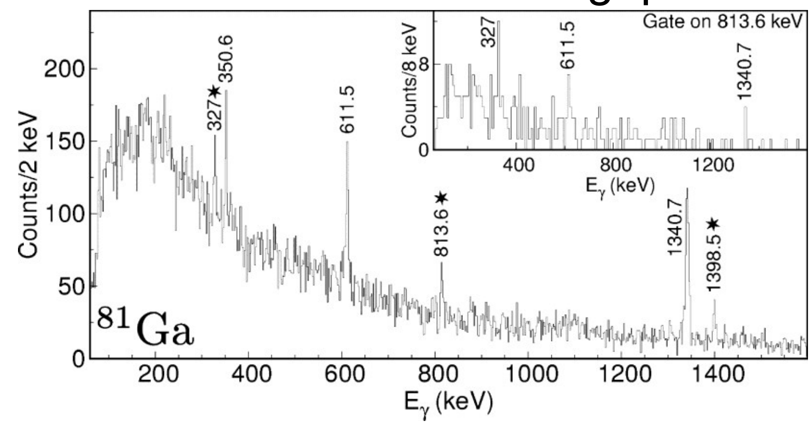
^{81}Ga – Three valence protons coupled to N = 50 neutron-core excitations

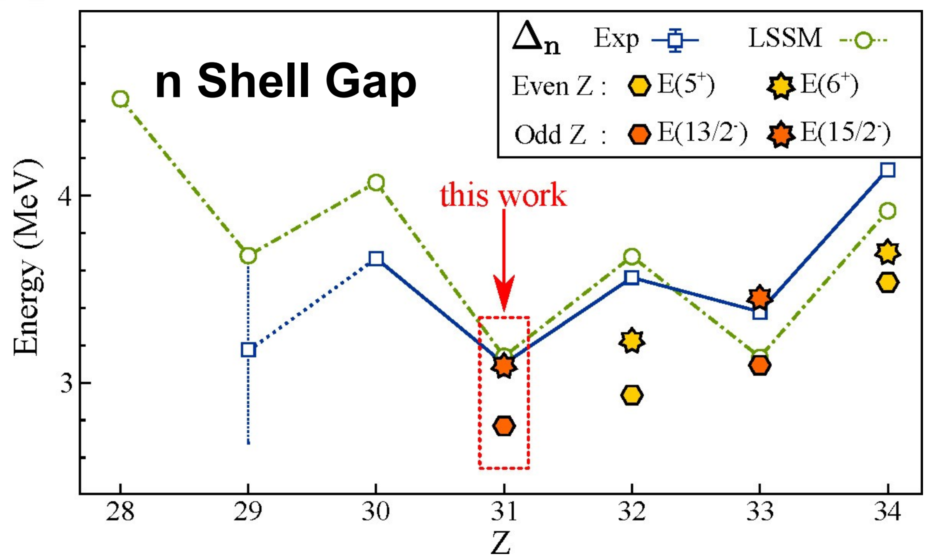
J. Dudouet et al.,
Submitted to
Phys. Rev. Lett

The quenching of the N=50 gap towards 78Ni can be investigated looking at the Spectroscopy of excited states involving particle-hole excitations across the N=50 gap

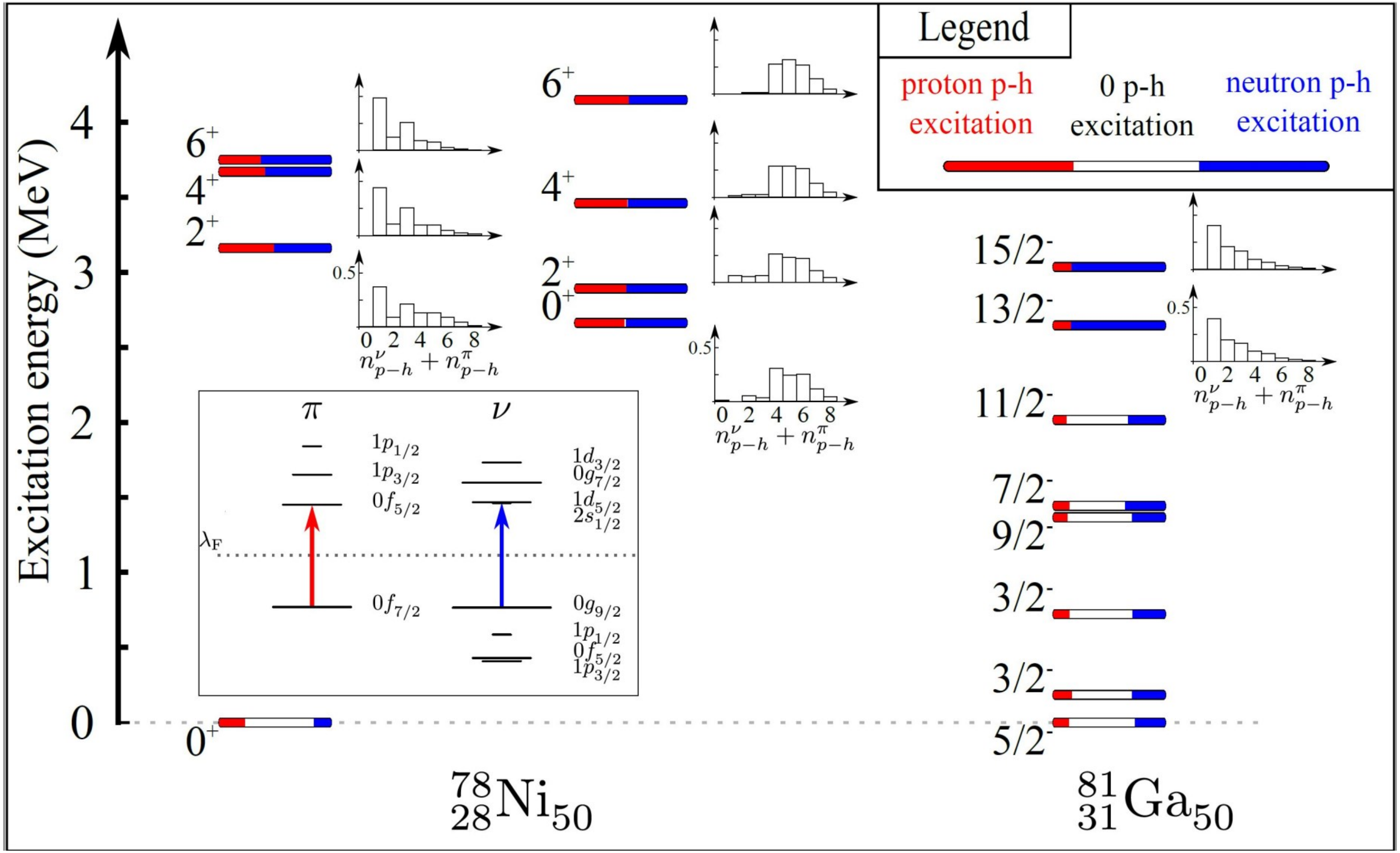
PFSDG-U interaction
F. Nowacki
PRL117, 272501







^{81}Ga – Three valence protons coupled to N = 50 neutron-core excitations

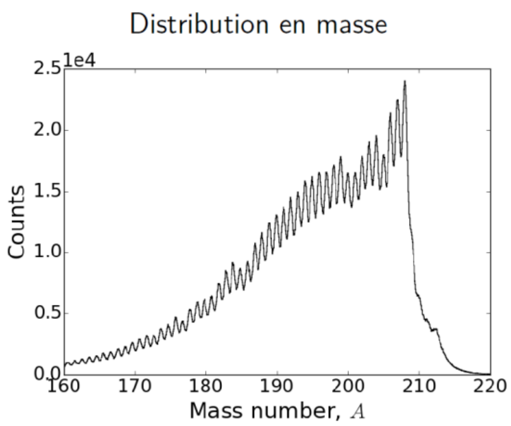


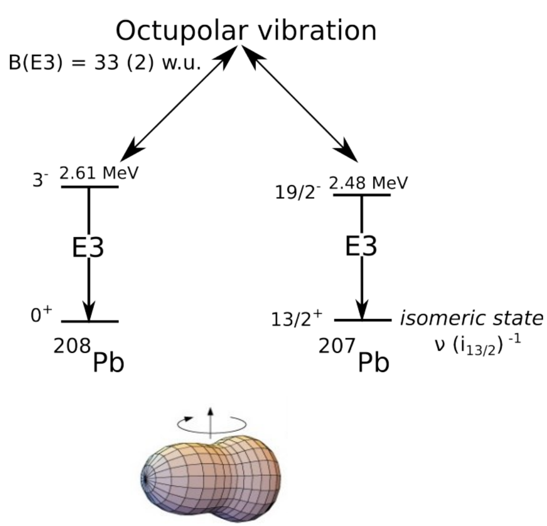
PFSDG-U interaction F. Nowacki PRL117, 272501

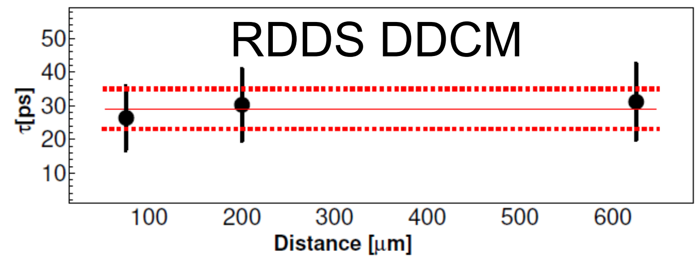
J. Dudouet et al., Submitted to Phys. Rev. Lett

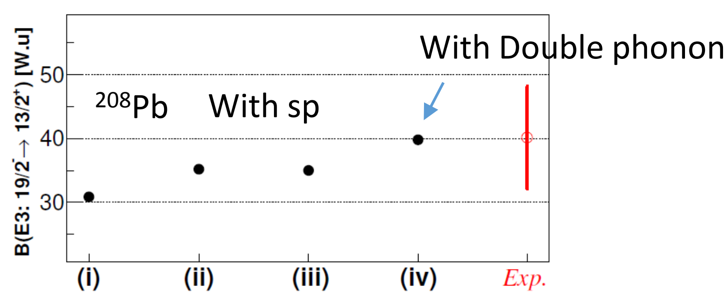
Evidence of octupole-phonon at high spin in ^{207}Pb : Study of the octupole phonon in the ^{208}Pb region.

- Case of the ^{207}Pb : 1 neutron hole in ^{208}Pb
- The first excited states of ^{207}Pb are part of the $\nu p^{-1}_{1/2} \times 3^-$ multiplet with slightly reduced B(E3) with respect to ^{208}Pb due to the $p_{1/2}$ blocking effect
- The $\nu(i_{13/2})^{-1}$ state band structure : strong coupling effect of the $i_{13/2}$ and $f_{7/2}$: enhanced B(E3) with respect to ^{208}Pb









D. Ralet, E. Clément et al, submitted to PLB

D. Ralet et al., Phys.Scr. 92, 054004 (2017)

GANIL AGATA-NEDA-DIAMANT Campaign:

2018: 5 Runs

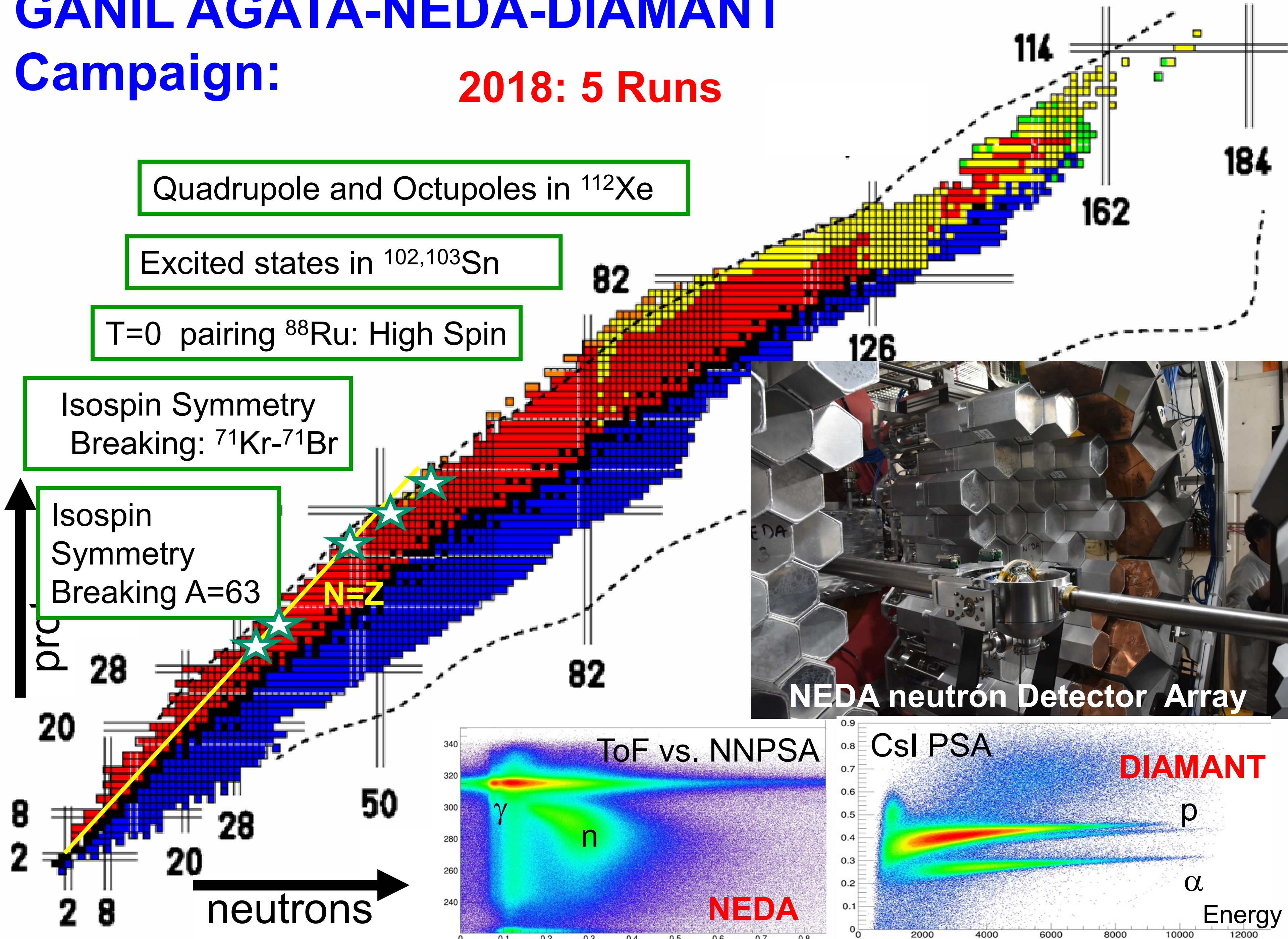
Quadrupole and Octupoles in ^{112}Xe

Excited states in $^{102,103}Sn$

T=0 pairing ^{88}Ru: High Spin

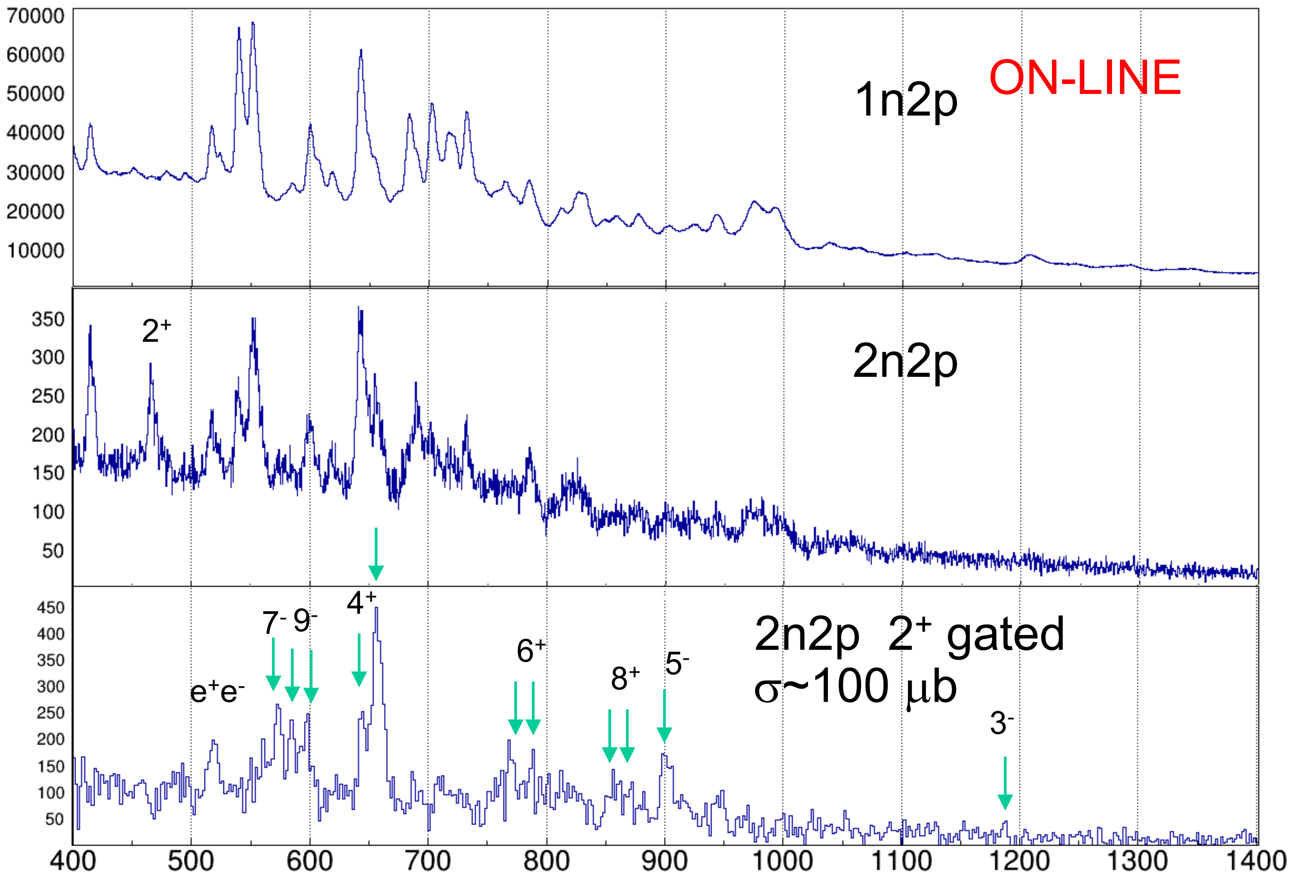
Isospin Symmetry Breaking: ^{71}Kr-^{71}Br

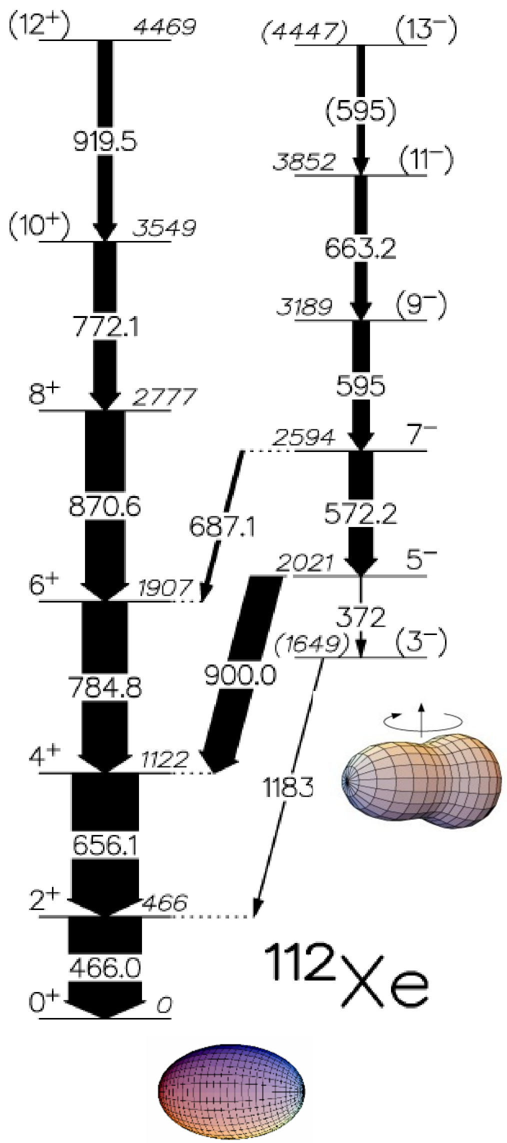
Isospin Symmetry Breaking A=63



The NEDA setup in the ^{112}Xe run: the 2n selectivity

RDDS Lifetime measurement ^{58}Ni+^{58}Ni at 250 MeV Beam Energy





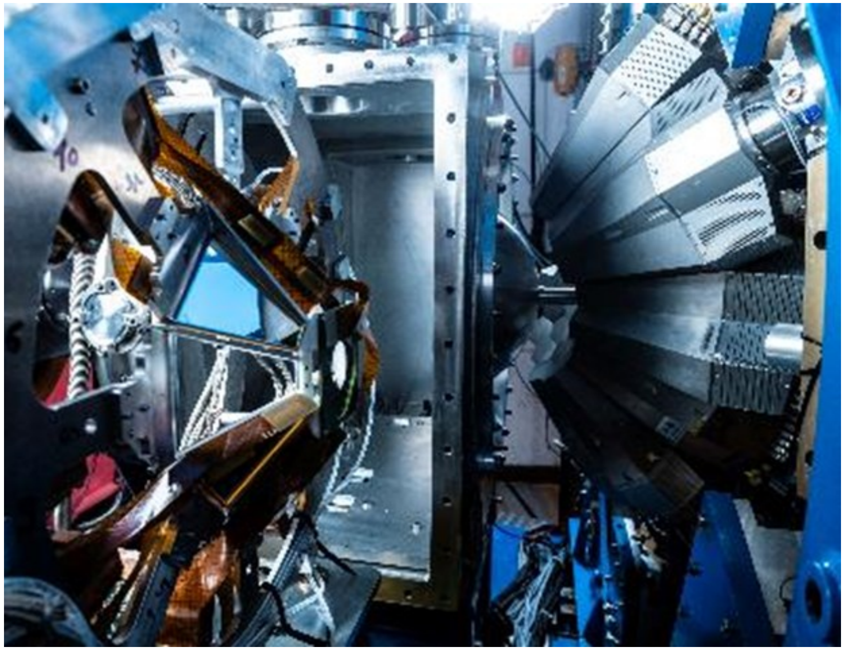
M. L. Jurado, E.Clement, D.Ralet, J.J.Valiente-Dobon, A.Gadea et al, OUPS Plunger, J. Ljungvall et al, NIM A 679 (2012) 61-66. Degrader mode

Outlook

- The GANIL campaign is proceeding now with SPIRAL1 beams in the AGATA+ MUGAST+VAMOS++ Setup.

- The campaign at GANIL will continue until 2021.

- In 2022 AGATA will start a new campaign at LNL with stable beams and will continue with SPES beams when available



Thanks' to all the AGATA Collaborators

Thank You For Your Attention!

UNIÓN EUROPEA
Cofinanciado por el Fondo Europeo de Desarrollo Regional
Una manera de hacer Europa

Supported by MINECO, Spain
Grant n. FPA2017-84756-C4

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

CSIC
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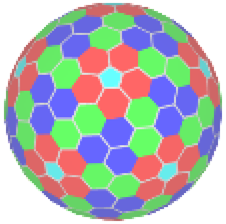
The AGATA Collaboration



>40 Institutions
>350 Collaborators

Bulgaria:	**Univ. Sofia**
Finland:	**Univ. Jyväskylä**
France:	**GANIL Caen, IPN Lyon, CSNSM Orsay, IPN Orsay, CEA-DSM-DAPNIA Saclay, IPHC Strasbourg, LPSC Grenoble**
Germany:	**GSI Darmstadt, TU Darmstadt, Univ. zu Köln, TU München**
Hungary:	**ATOMKI Debrecen**
Italy:	**INFN-LNL, INFN and Univ. Padova, Milano, Firenze, Genova, Napoli**
Poland:	**NINP and IFJ Krakow, SINS Swierk, HIL & IEP Warsaw**
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**

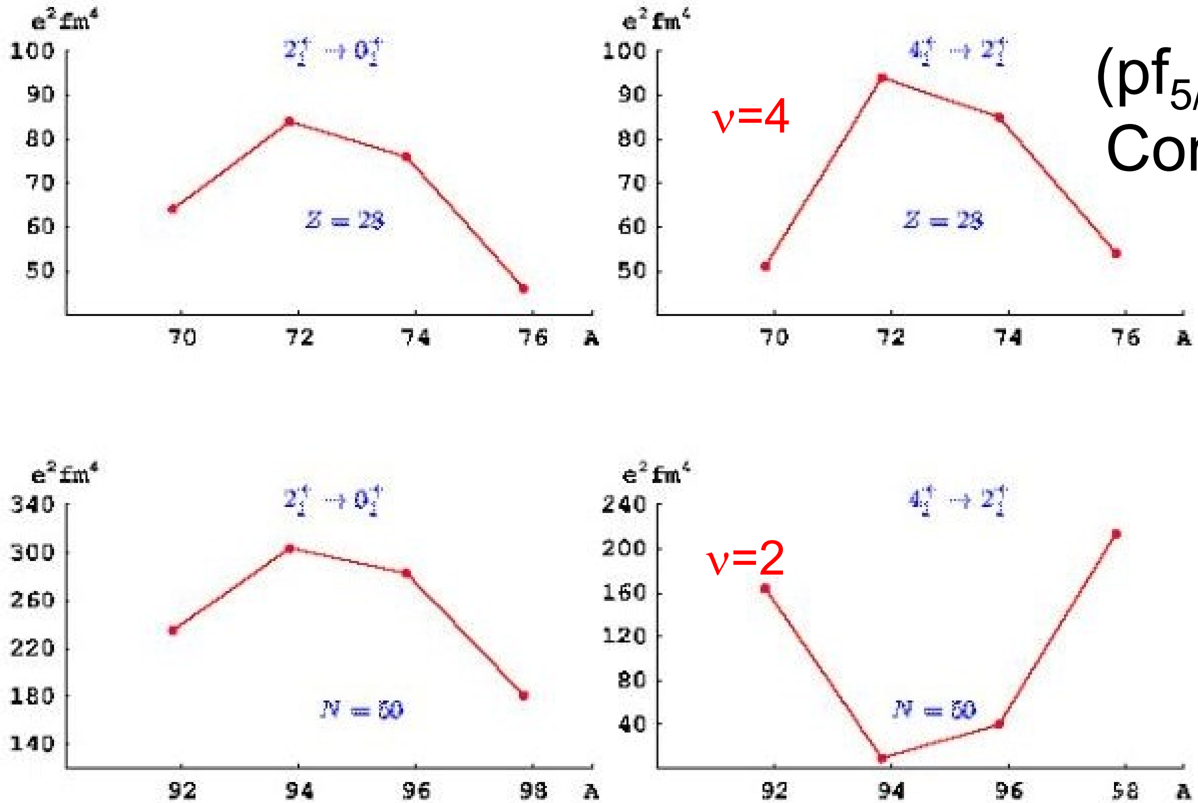
Investigation of the Seniority Conservation in the $\pi g_{9/2}$ shell

$p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ model space

$(pf_{5/2})^{12}_{0+}(g^{n}_{9/2})_J$ Configurations

Z=28

N=50



A.F. Lisetskiy et al., Eur. Phys. J. A 25, s01, 95 (2005)
A.F. Lisetskiy et al,. Phys. Rev.C 70, 044314 (2004).