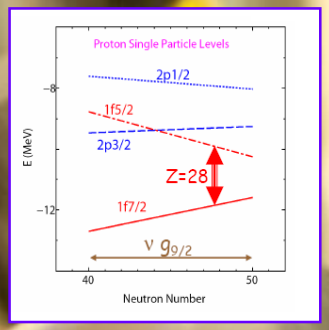
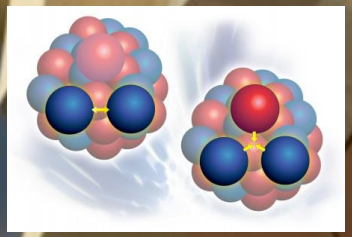
High Resolution γ-ray Spectroscopy in Exotic Nuclei: AGATA@GANIL

Nuclear Chemistry
Gordon Research Conference

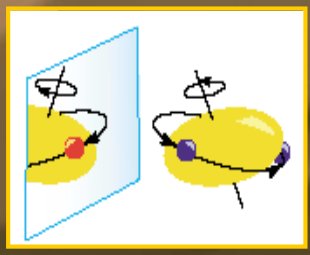
Shell evolution far from stability





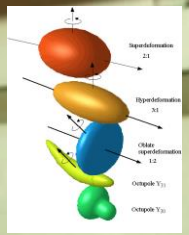
Three-body forces

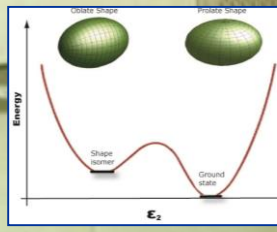
Isospin symmetry breaking



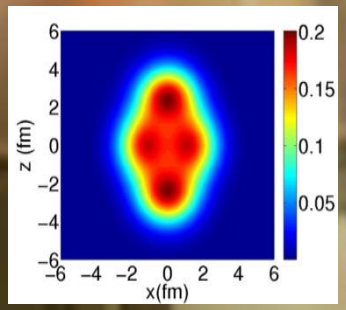
High-resolution gamma-ray spectroscopy is an optimum tool to study detailed nuclear structure properties and investigate how they emerge from fundamental interactions.

Nuclear shapes and coexistence

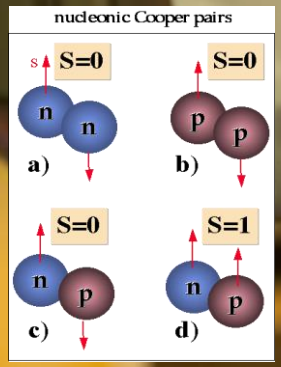




clusterization

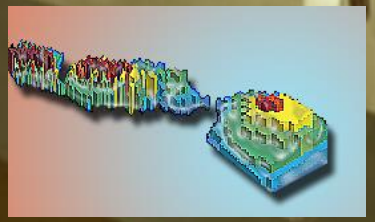


p-n pairing



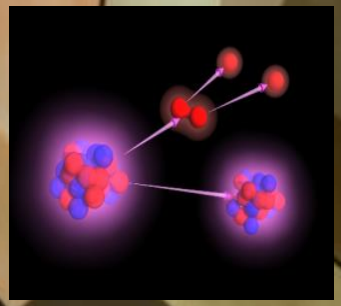
Measuring discrete γ-ray transitions from 20 keV to 20 MeV with 1‰ energy resolution and 30-40% P/T

Super heavy elements



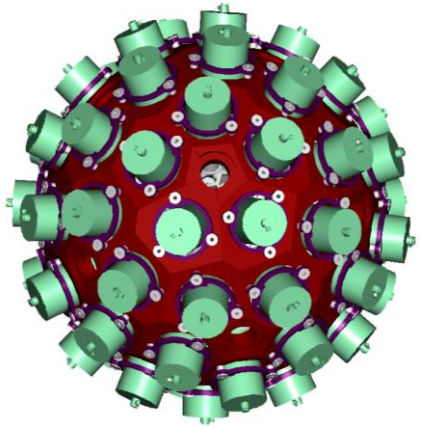


Nuclear Astrophysics



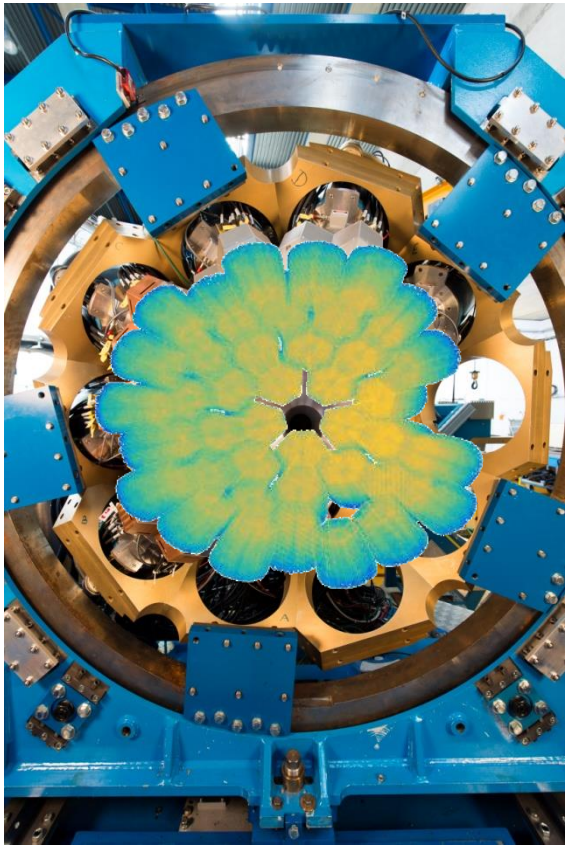
Coupling to the continuum

The AGATA project



- 180 (60 triple-clusters) 36-fold segmented crystals
- Amount of germanium: 362 kg
- Solid angle coverage: 82 %
- Singles rate >50 kHz
- Efficiency: 43% (M_γ=1) , 28% (M_γ=30)
- Peak/Total: 58% (M_γ=1), 49% (M_γ=30)
- Angular Resolution: ~1º

41 detectors on-line in 2019

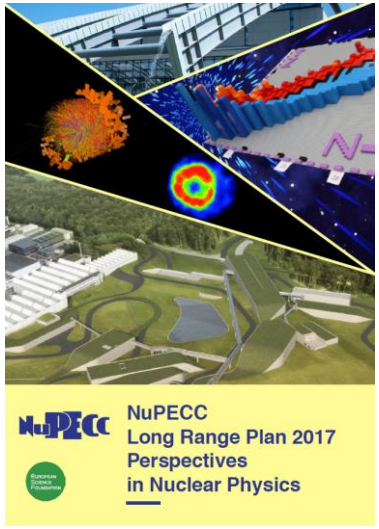


AGATA@GANIL

The project timeline is to complete the 4π by 2030

Combination of:

- ❑ segmented detector
- ❑ pulse-shape analysis
- ❑ tracking the γ rays
- ❑ digital electronics

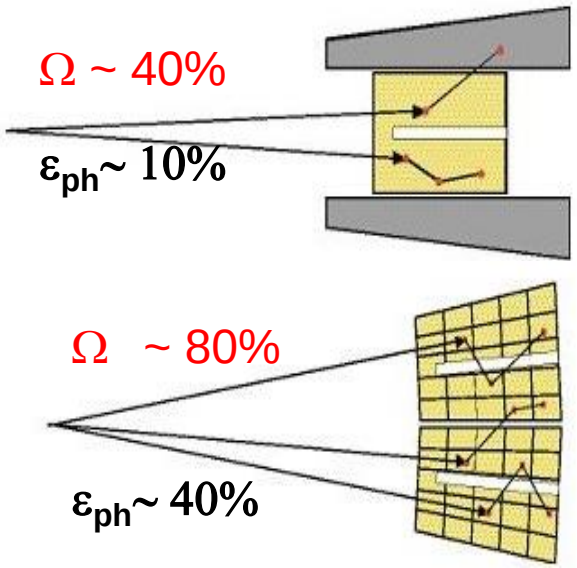


S. Akkoyun, et al, NIMA 669, 26-58 (2012)

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

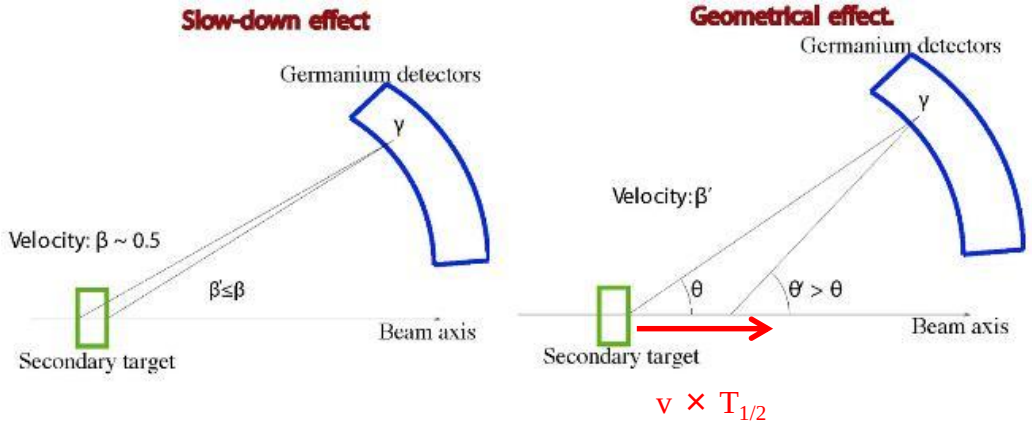
Tracking array

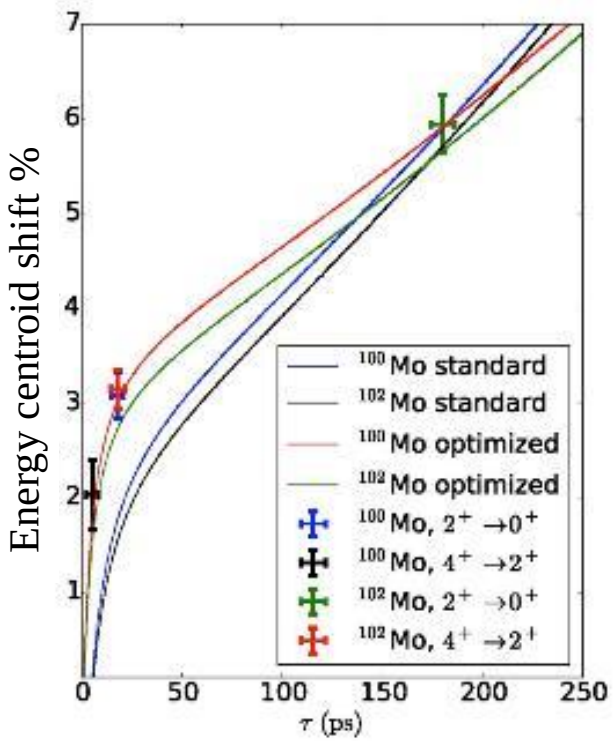
- Large solid angle
- Position sensitive mode using PSA
- Large P/T using tracking for γ-ray reconstruction

Tracking Arrays

Improved Doppler Correction capabilities

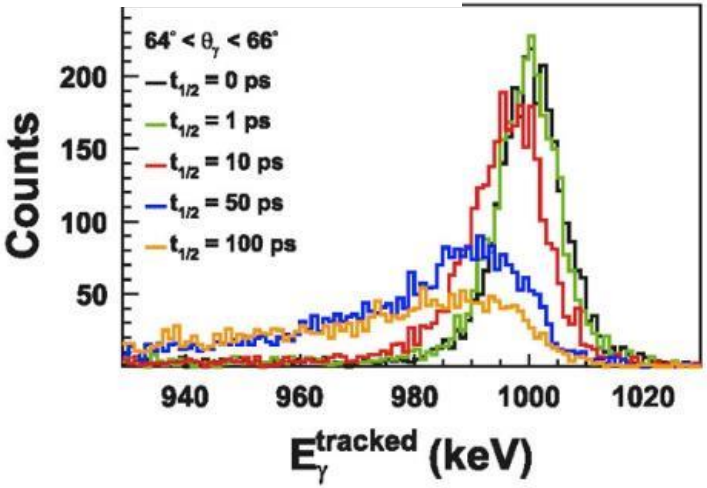
In-Flight Geometrical Line-Shape





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

MC simulations β=0.5

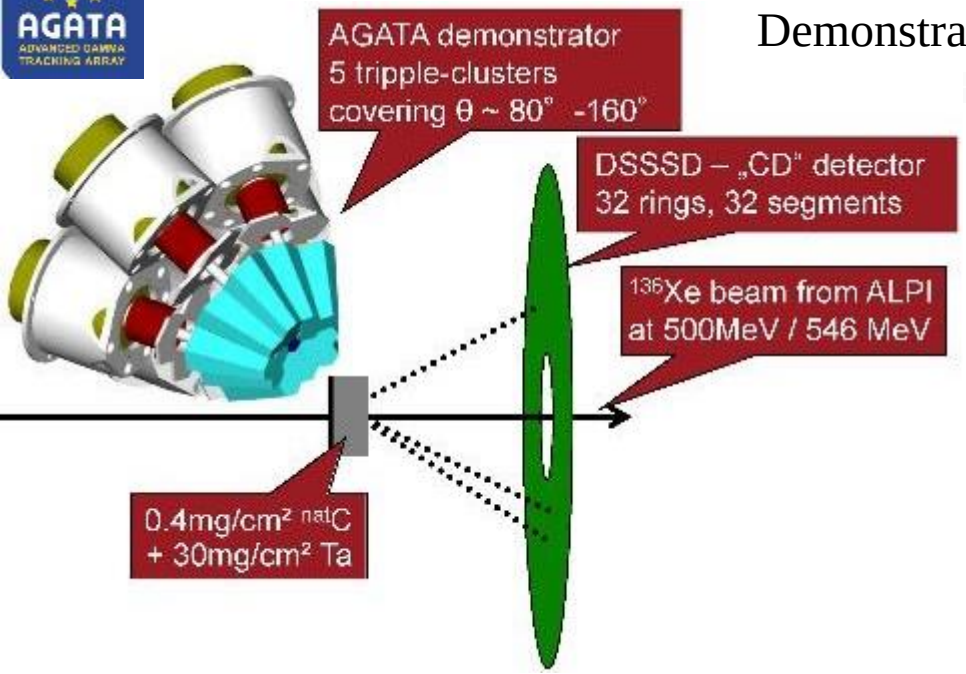


- New "DSAM-like" technique based on the position sensitivity and the Doppler correction.
- Possible to measure down to 1 to 10 ps lifetimes with relativistic RIBs.

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

Continuous-Angle DSAM

Firstly used with the AGATA – Demonstrator at LNL

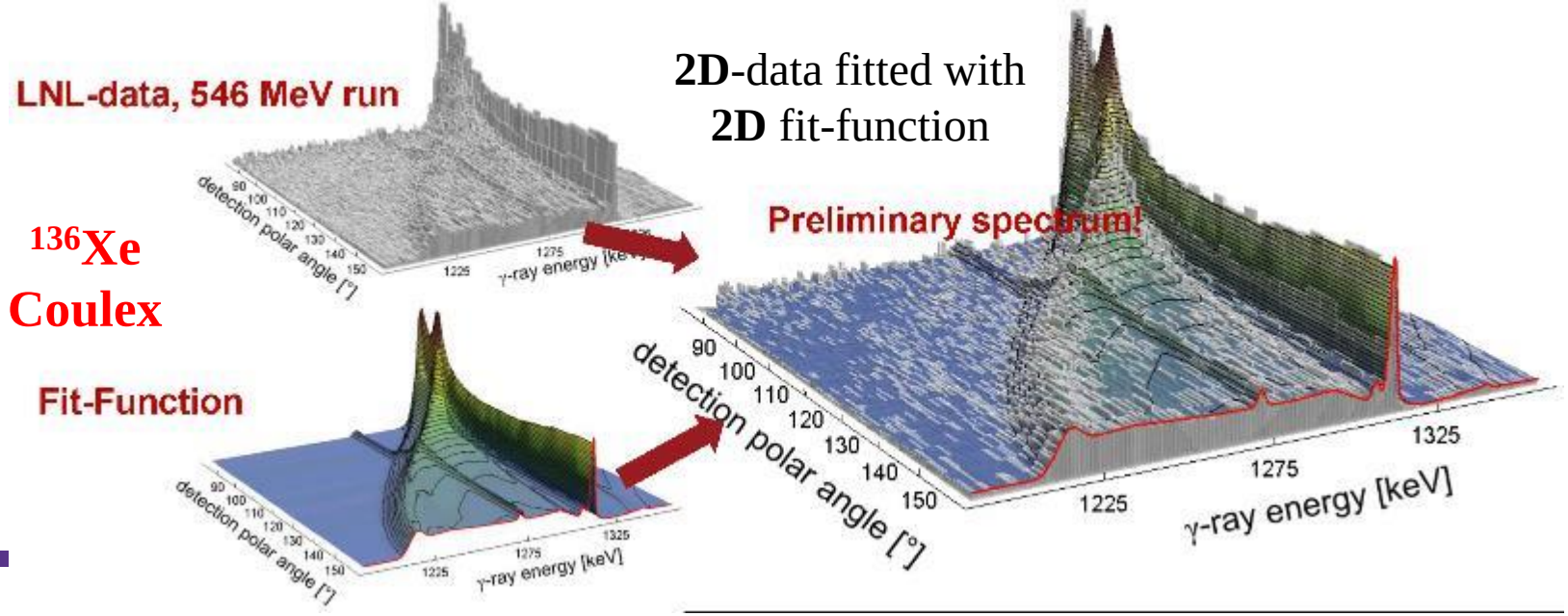


The continuous-angle DSAM represents an advancement of the ‘‘conventional’’ DSAM.

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.

Ch. Stahl et al, PRC 92 (2015) 044324
Ch. Stahl et al, CPC 214 (2017) 174

2D-data fitted with **2D** fit-function

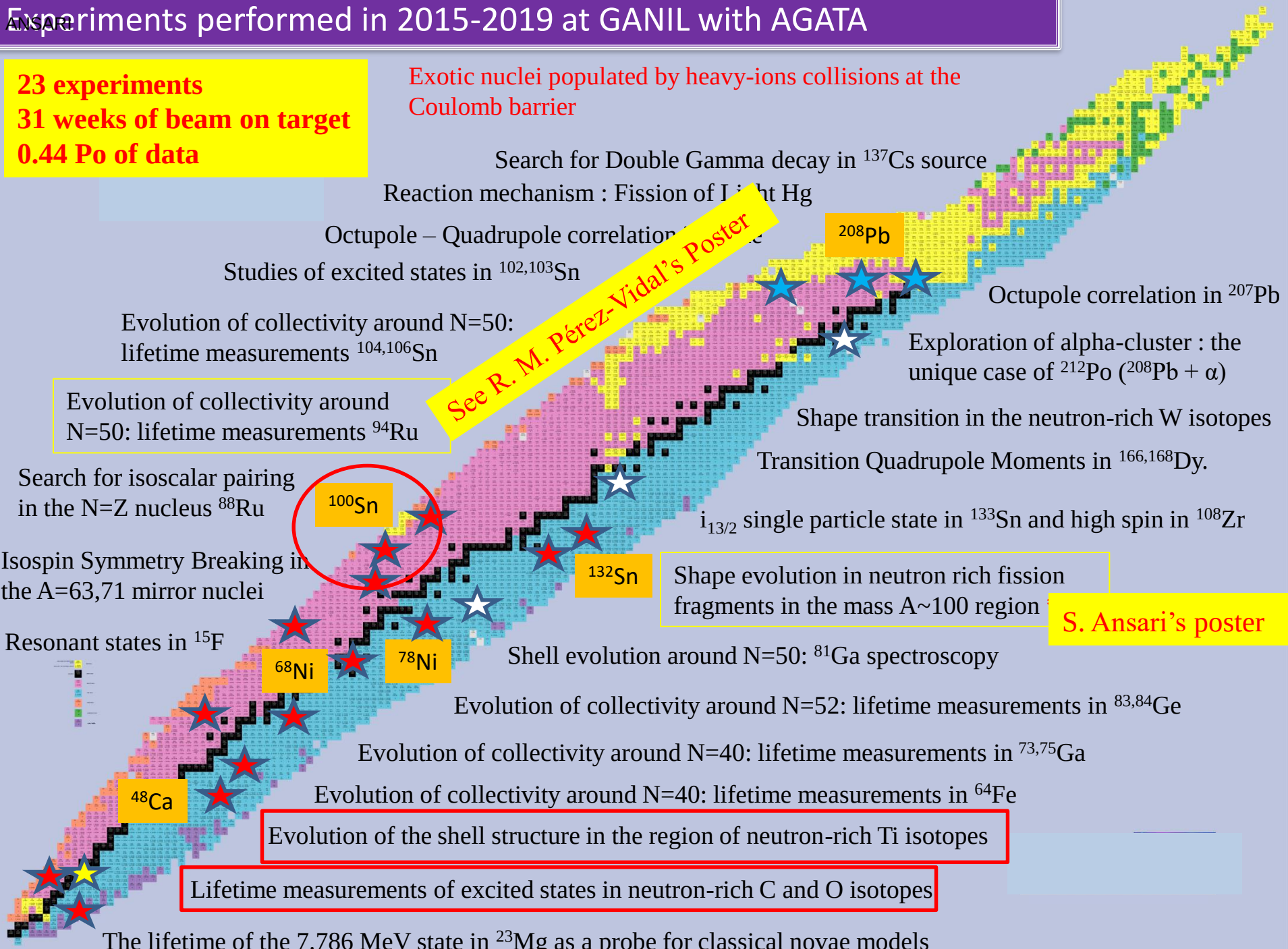


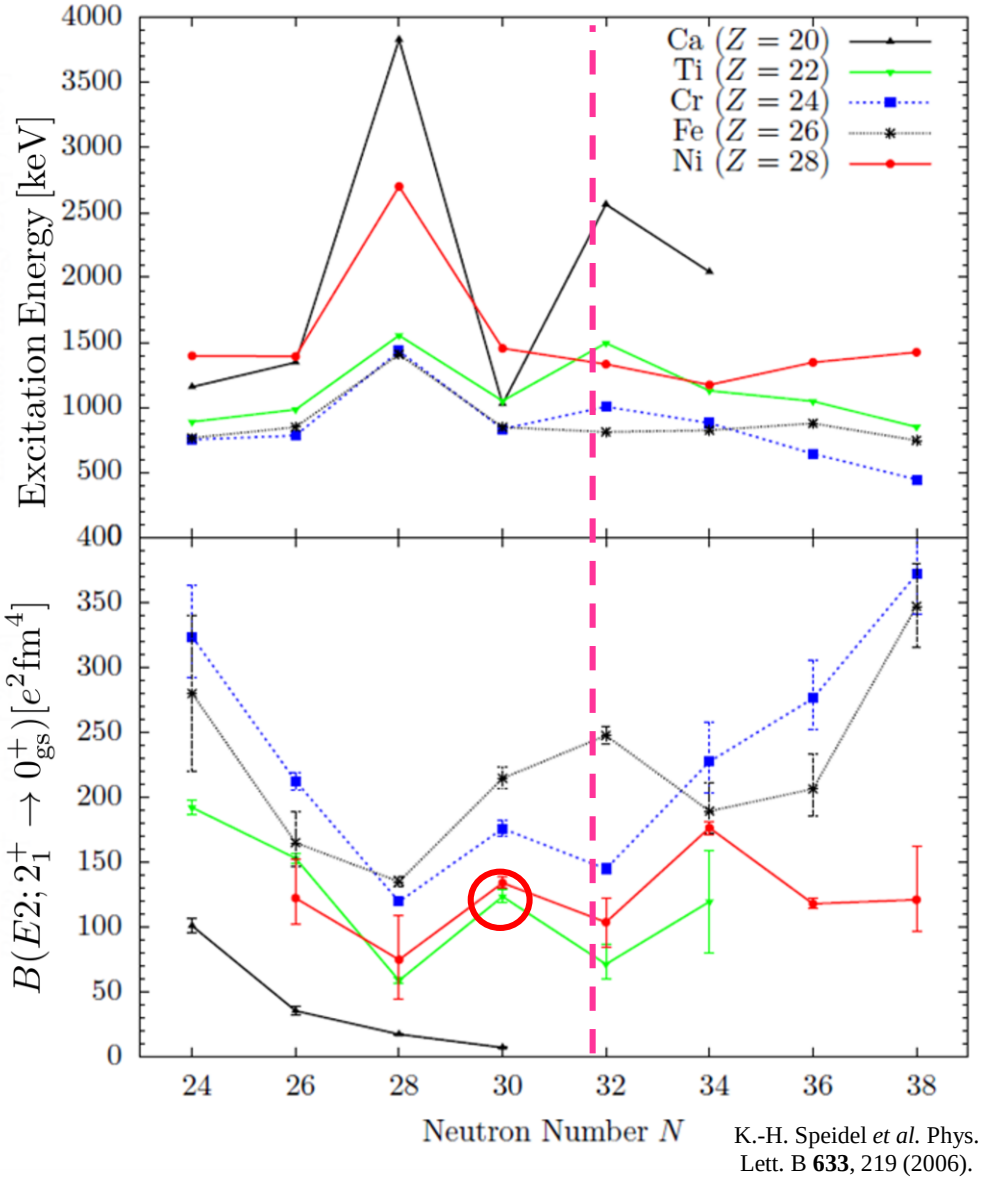
Experiments performed in 2015-2019 at GANIL with AGATA

ANSARI

23 experiments
31 weeks of beam on target
0.44 Po of data

Exotic nuclei populated by heavy-ions collisions at the Coulomb barrier





K.-H. Speidel *et al.* Phys. Lett. B **633**, 219 (2006).

Subshell closure at N=32?

- Phase transition from predominant collective structures in ^{58}Fe to a neutron subshell closure towards ^{52}Ca
- Staggering of the B(E2) values in the Ti isotopes

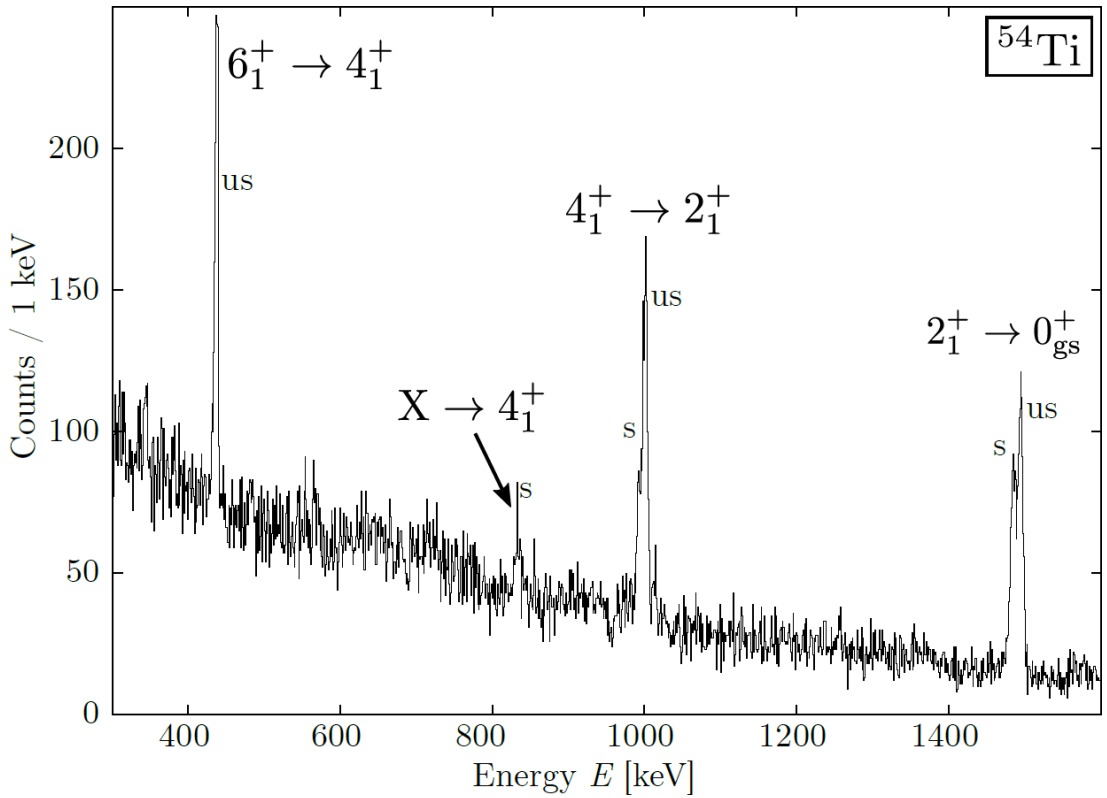
- Subshell closure at N=32 for higher spins in Ti
- What are the consequences for the evolution in neighboring nuclei ?
- How Shell Model calculations reproduce these systematics ?

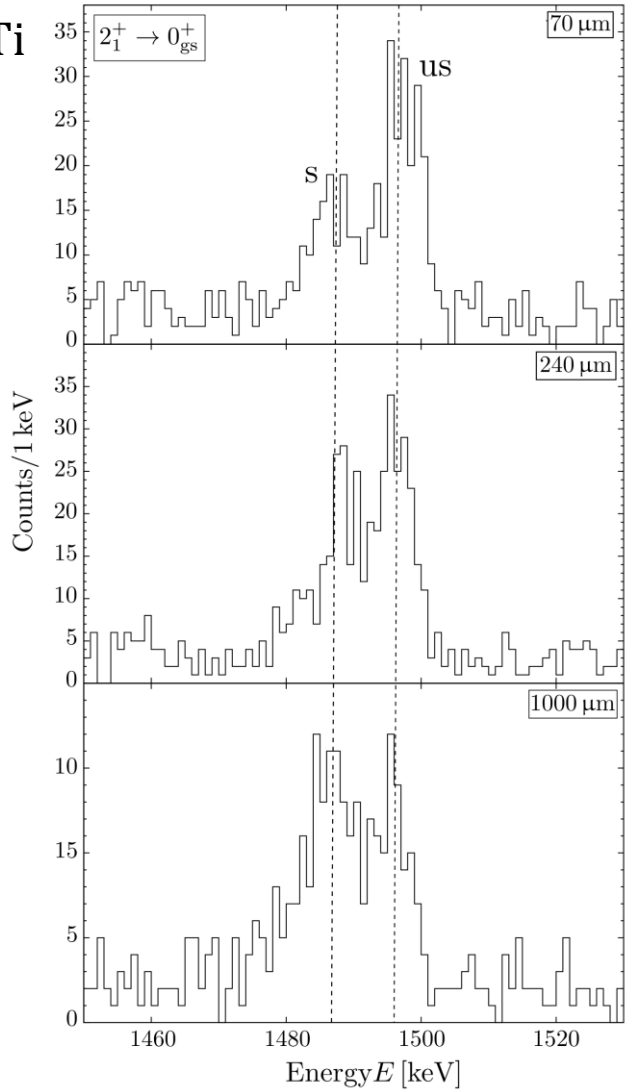
New B(E2) measurement in 2^+, 4^+, 6^+ states from their lifetime

A. Goldkuhle (IKP) et al, in preparation

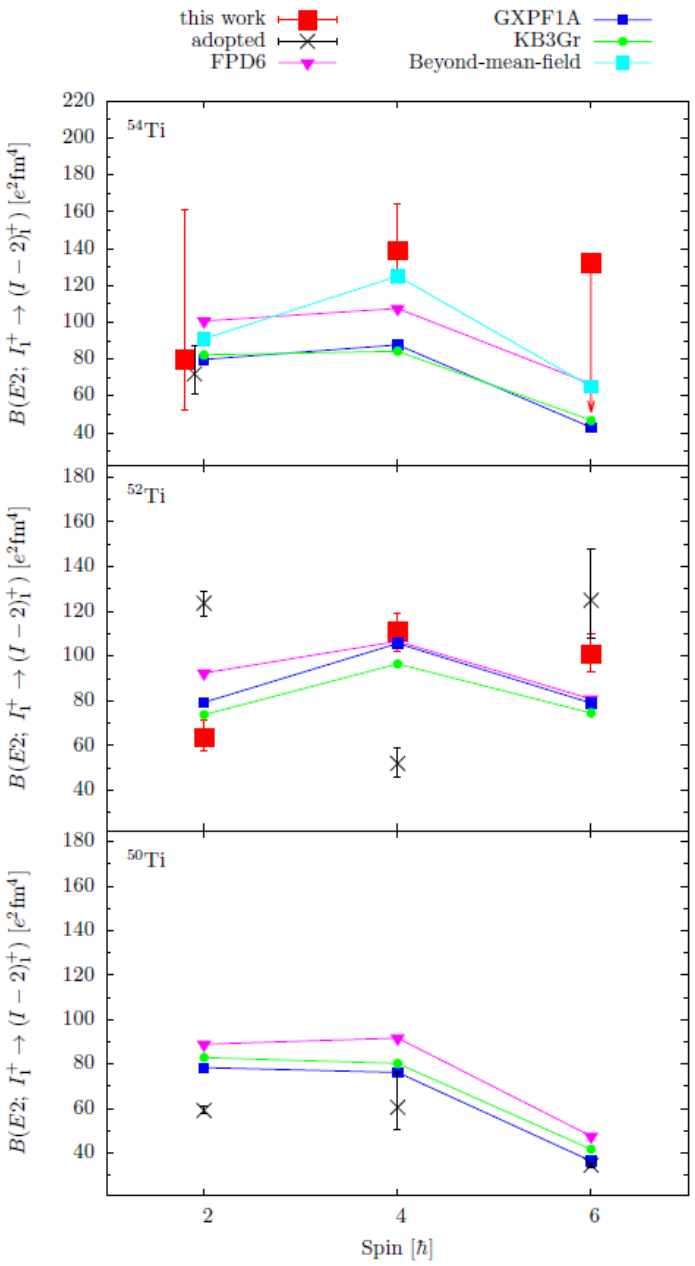
- Reaction: Multi-nucleon transfer reaction $^{50}Ti(^{238}U, xx)^{46-56}Ti$

Target: ^{50}Ti @ 1,2mg/cm² with ^{nat}Cu backing
Degrader: ^{nat}Mg @ 3,1 mg/cm²





A. Goldkuhle (IKP) et al, in preparation



Experimental results

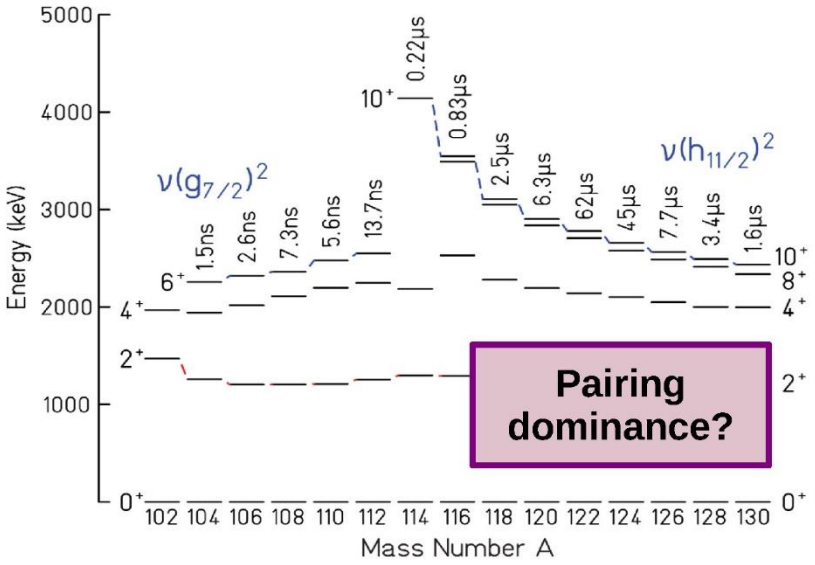
- 4 lifetime information in ^{54}Ti: 3 for the first time
- 3 lifetime information in ^{52}Ti: opposite behavior to previous measurement
- 5 preliminary lifetime information in ^{53}Ti determined for the first time

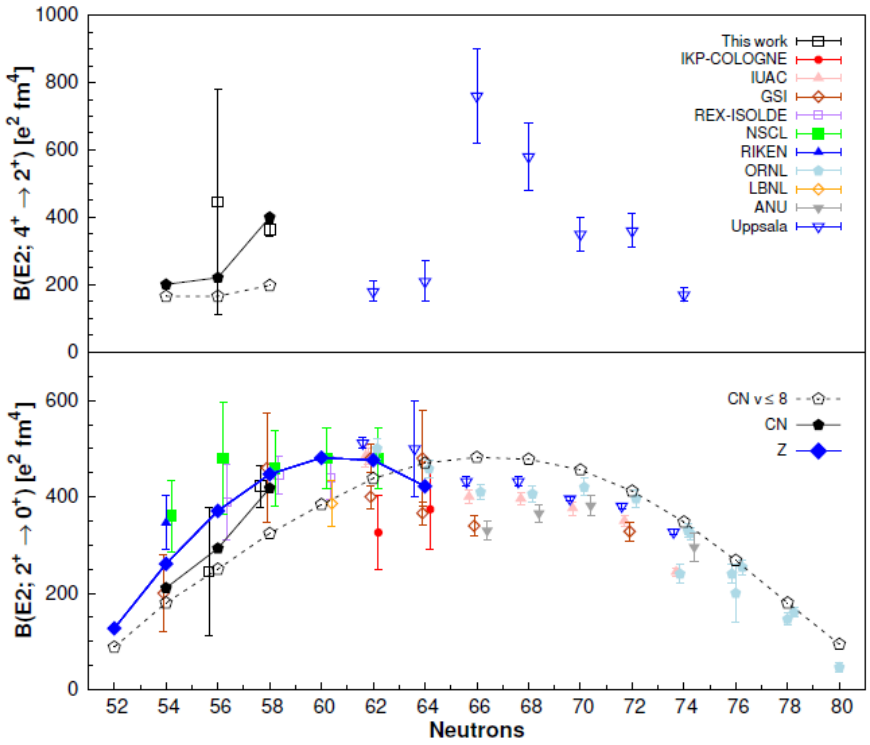
Interpretation

- Shell model calculations reproduce the trend in ^{50,52,54}Ti
- New result in ^{52}Ti: Opposite behavior to previous experimental results

A. Goldkuhle (IKP) et al, in preparation

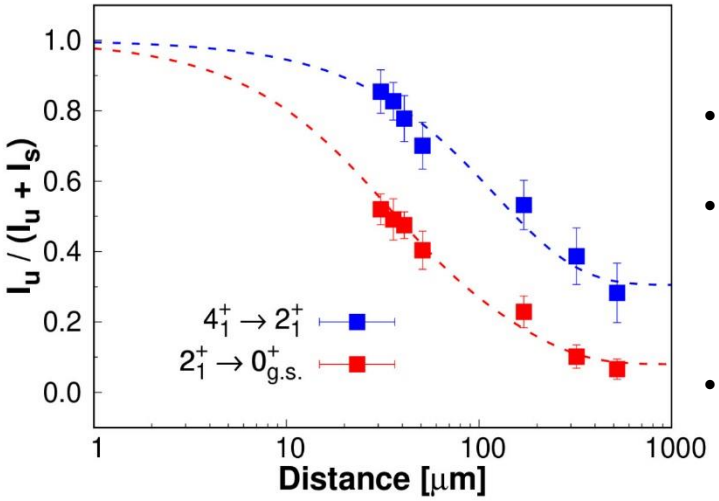
Lifetime Measurements in ^{106,108}Sn using MNT





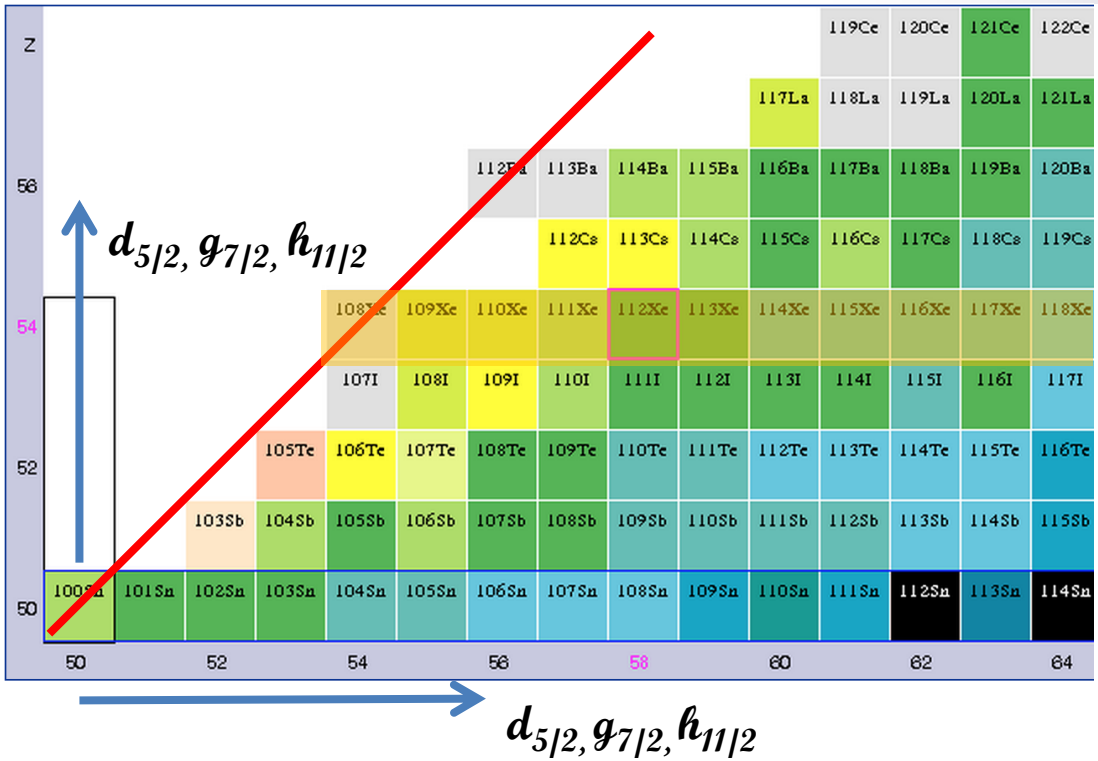
- **Direct population of the states**, avoiding the experimental limitations due to the "seniority" isomers
- **Complementary information** to Coulomb-excitation measurements
- Extend the investigation **above the 2_1^+** excited state

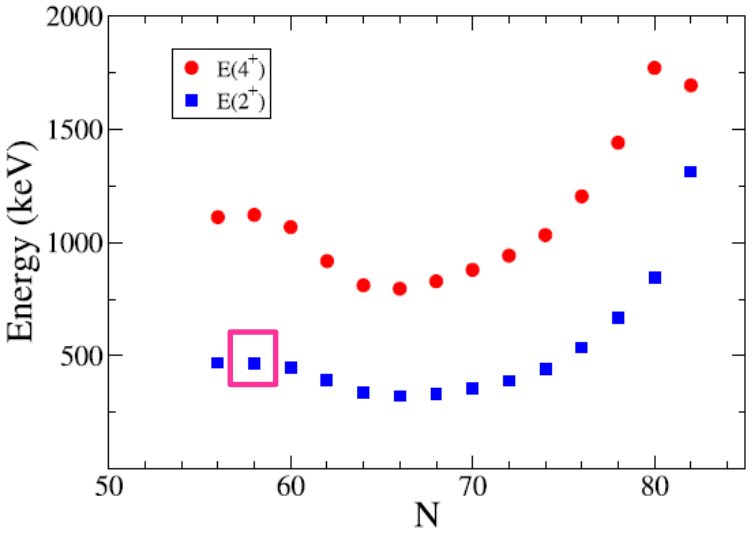
M. Siciliano (LNL) et al, submitted to PRL



- The first $4^+ \rightarrow 2^+$ transition strength in the neutron-deficient Sn.
- The precise measurement for ^{108}Sn sheds light on the proton excitation into the $g_{9/2}$ and $h_{11/2}$ (from CN un-truncated), or $g_{9/2}$ + pairing effect (Z)
- The recent MCSMC points to $g_{9/2}$ occupancy that vary with J and A, [T. Togashi et al PRL 121, 062501 (2018).], without comparison for the 4^+ strength

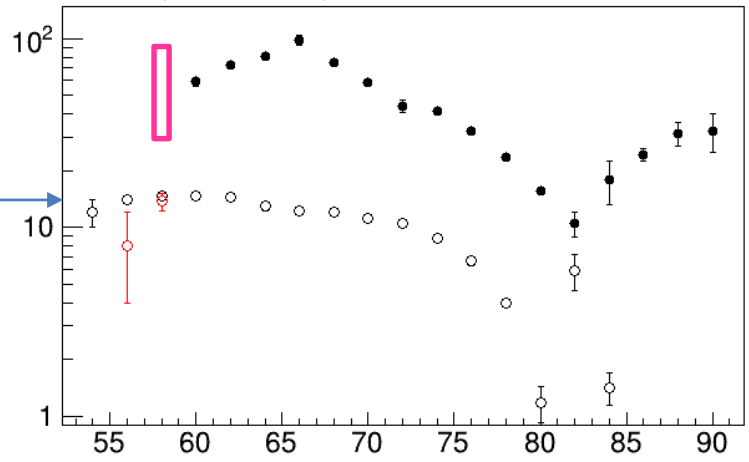
Shell evolution and collectivity using a ^{100}Sn core





M. Sandzelius et al Phys. Rev. Lett 99, 022501 (2007)

BE2($2^+ \rightarrow 0^+$) [Wu]

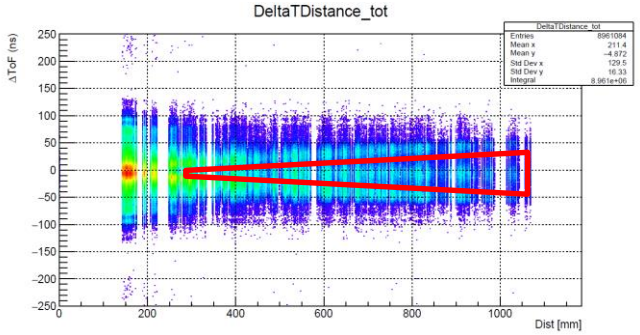


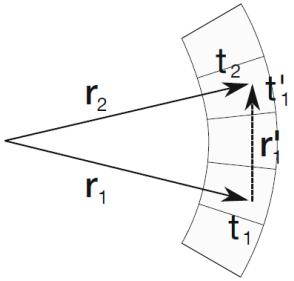
^{106,108}Sn

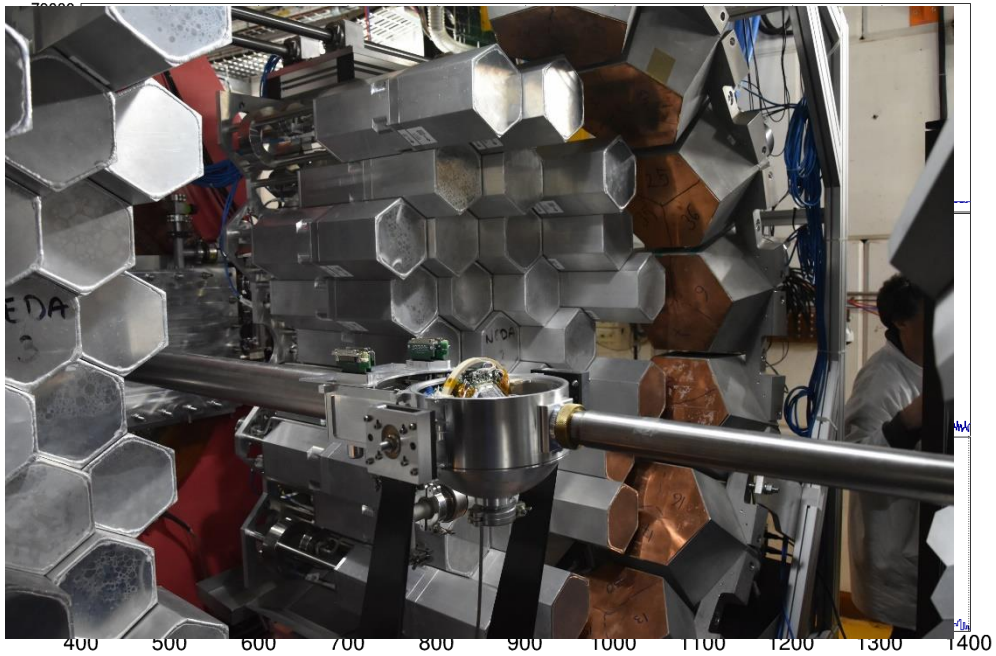
- Maximum of 2^+ and 4^+ excitation energies at N=82
- Maximum of collectivity at mid-shell
- Collectivity approaching N=50 ?

➢ Lifetime measurement in ^{112}Xe

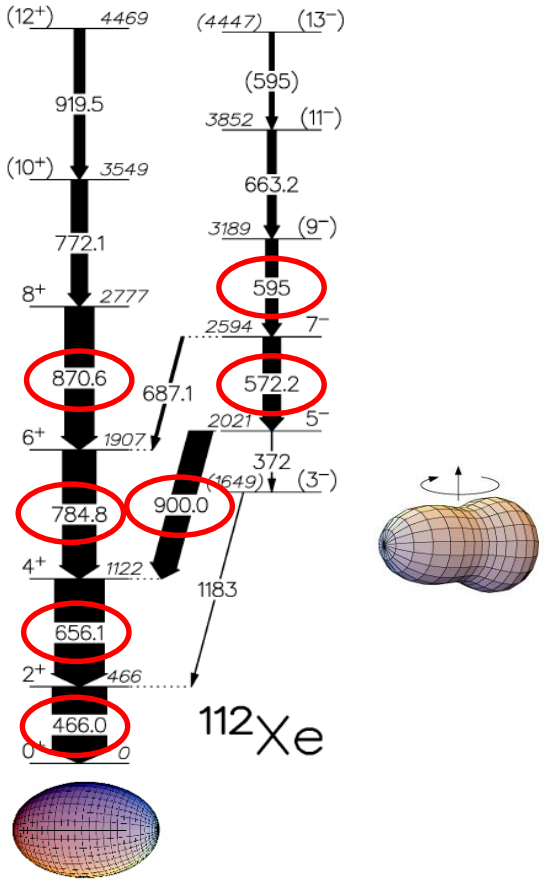
- ^{58}Ni(^{58}Ni, 2p2n)^{112}Xe @ 250 MeV, ~4pnA.
- Lifetime measurement using NEDA-AGATA-DIAMANT and the OUPS plunger in front of DIAMANT
- 9 plunger distances from 20 µm to 1.5 mm.
- 10 days experiments with ~30h per distances





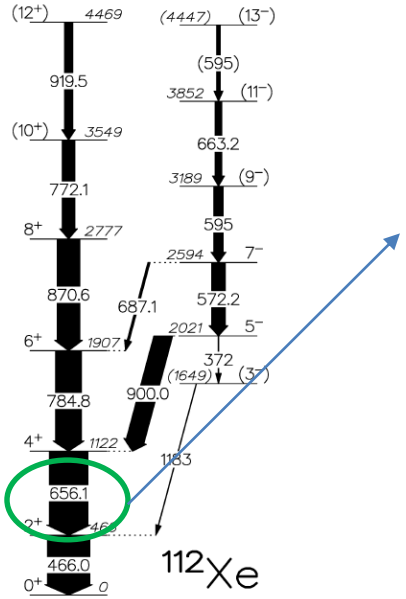


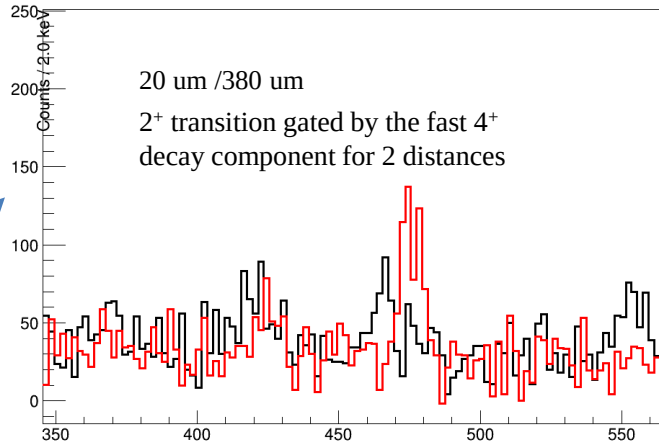
Transitions for which a decay curve was observed on-line

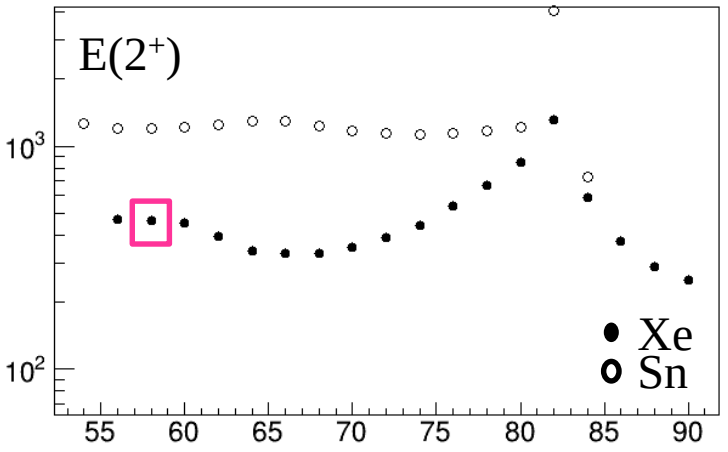


M. L. Jurado, D. Ralet, A. Goasduf, EC et al,
OUPS Plunger, J. Ljungvall et al, NIM A 679 (2012) 61-66. Degrader mode

J.F. Smith et al, Phys. Lett. B 523, 13 (2001)





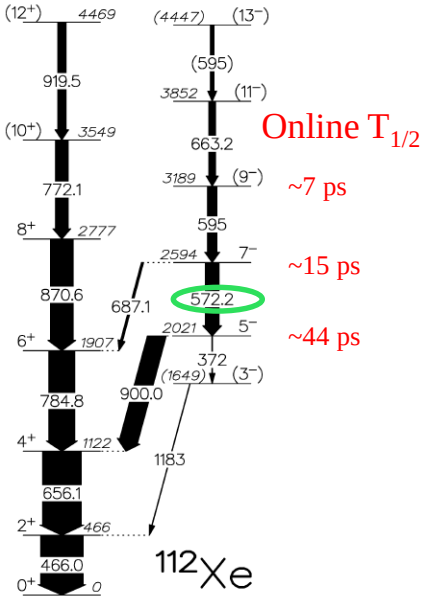


Based on
Delion et al, Phys. F
Caurier et al PRC 8

it supports more the
proton excitation frc
of the T=0 pairing

M. L. Jurado (IFIC), et al, *under analysis*

Enhanced octupole correlation due to the interaction of $\Delta L=3$, $\Delta J=3$, inverse parity : $d_{5/2}$ and $h_{11/2}$

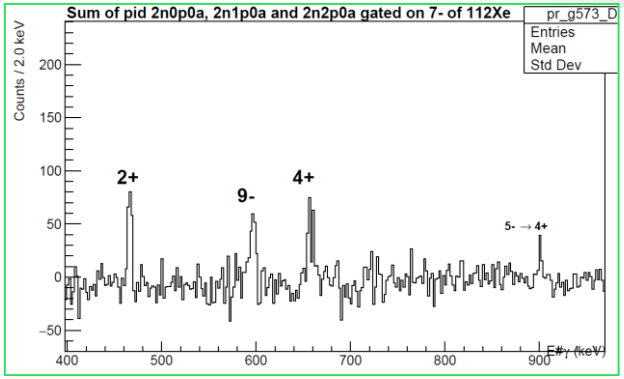


Online $T_{1/2}$

~7 ps

~15 ps

~44 ps



- ✓ The Lifetime of the 5^- is determined
- ✓ The E3 decay from the 5^- seems very weak and requires a careful analysis

B(E1 $5^- \rightarrow 4^+$)* ~ 1.3 10^{-5} e^2fm^2 (~0.9 10^{-5} wu)

*Assuming 100% E1 decay as soon as, on-line, the E2 and E3 are obviously very weak

Low B(E1). Similar to 3^- E1 decay in ^{114}Xe. E1 probe for octupoles ?

Carrefull analysis to be done to discover the E2/E1/E3 branching ratio to get the B(E3)

The ^{114}Xe case (G. De Angelis et al., Physics Letters B 535 (2002) 93–102)

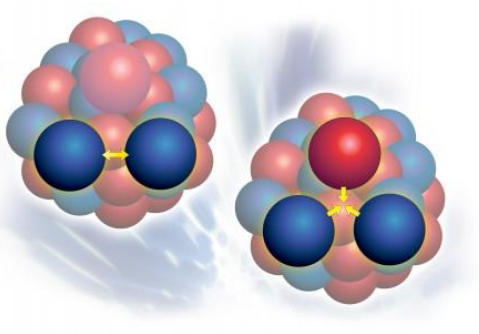
E_X (keV)	I_i^π ($\hbar$)	E_γ (keV)	I (%)	I_f^π ($\hbar$)	Eλ	$B(E\lambda)$ e^2 fm^{2L}	$B(E\lambda)$ [W.u.]
450	2^+	450.1(2)	100	0^+	E2	2066	62(4)
1069	4^+	618.5(2)	100	2^+	E2	1452	44(4)
1623	3^-	554.7(2)	36.9(5)	4^+	E1	$11.3(32) \times 10^{-5}$	$7.4(21) \times 10^{-5}$
1623	3^-	1172.8(3)	61.9(4)	2^+	E1	$2.0(5) \times 10^{-5}$	$1.3(4) \times 10^{-5}$
1623	3^-	1623(1)	1.2(3)	0^+	E3	$5.9(20) \times 10^4$	77(27)
2000	5^-	211.4(4)	6.9(4)	6^+	E1	$1.6(2) \times 10^{-4}$	$1.1(2) \times 10^{-4}$
2000	5^-	376.7(2)	91.3(5)	3^-	E2	$352(44) \times 10$	107(13)
2000	5^-	1549.1(5)	1.8(4)	2^+	E3	$527(132) \times 10^2$	68(17)

M. L. Jurado (IFIC), et al, *under analysis*

Lifetime in n-rich O and C

M. Ciemala , S. Leoni, B. Fornal, et al.,

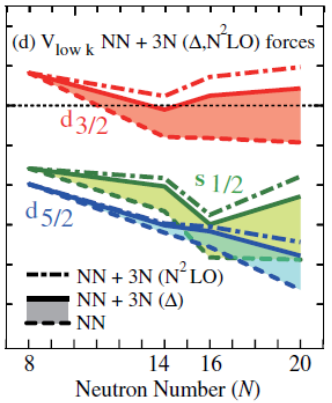
Lifetime measurement in the non-yrast excited states of neutron rich C and O isotopes. Branching ratio and E2/M1 using the PARIS LaBr3 array

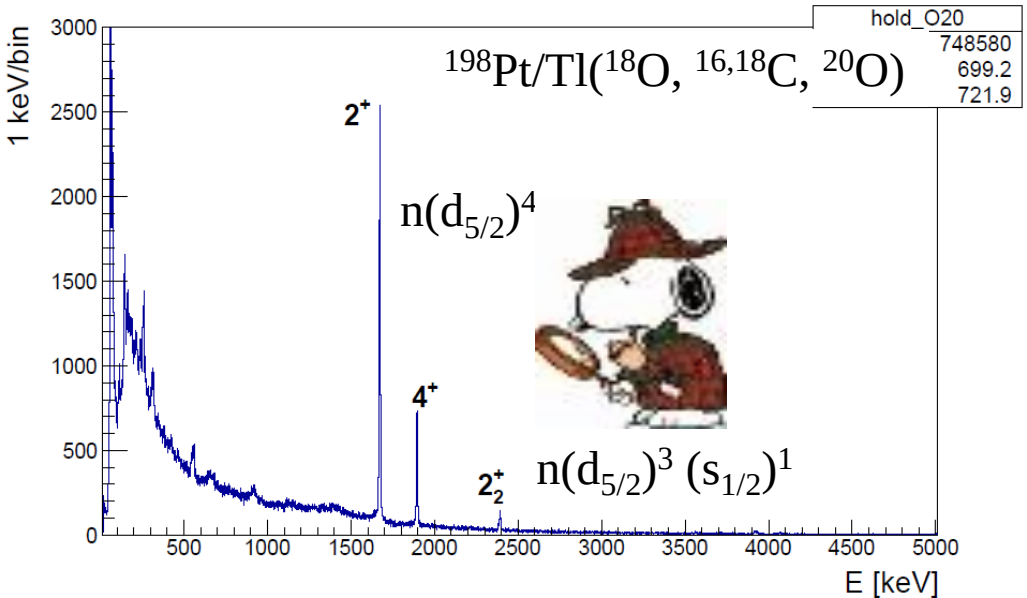


The 2^+_2 state corresponds to a neutron $(d_{5/2})^3(s_{1/2})^1$ configuration

C. R. Hoffmanu et al .PRC **85**, 054318 (2012)

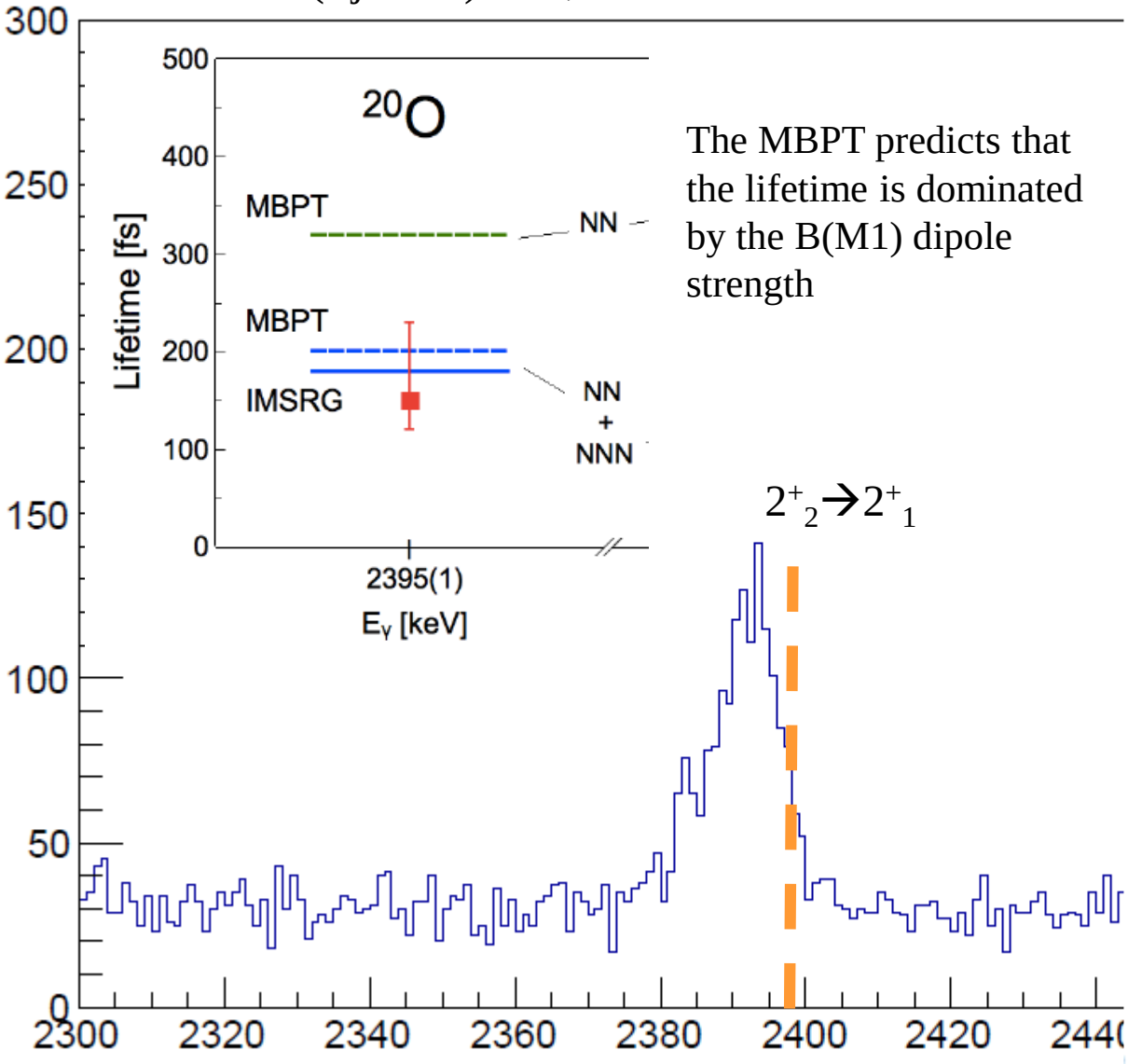
T. Otsuka PRL 105, 032501 (2010)



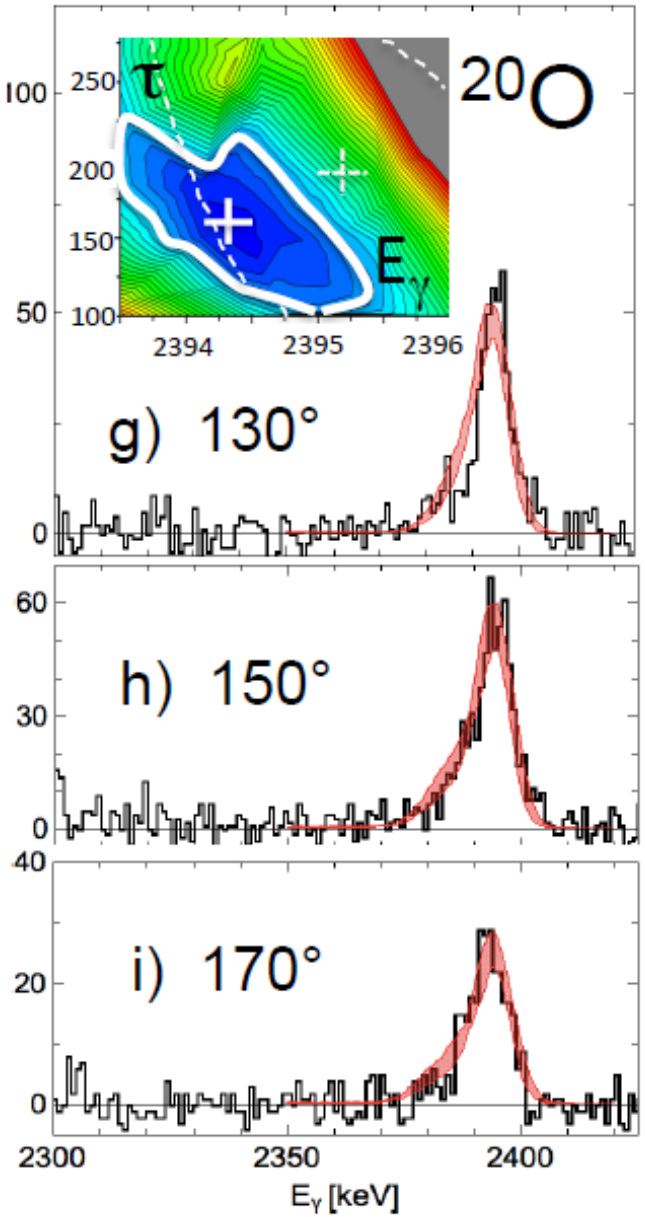


Nucleus	Excited state	Interactions: lifetime τ [ps] (*ab initio* NN)	Interactions: lifetime τ [ps] (*ab initio* NN+ NNN)	Interactions: mixing ratio δ (E2/M1) for $2^+_2 \rightarrow 2^+_1$ (*ab initio* NN)	Interactions: mixing ratio δ (E2/M1) for $2^+_2 \rightarrow 2^+_1$ (*ab initio* NN+NNN)	Experiment τ [ps]
^{16}C	2^+_1	24	24			11.4(10) - 18.3(50)
	2^+_2	**0.23**	**0.08**	**0.30**	**0.08**	< 4
^{18}C	2^+_1	19.4	20			22.4(3.5)
	2^+_2	**2.2**	**1.1**	**0.02**	**0.04**	< 4.6
^{20}O	2^+_1	10,3	11,7			10.70(40)
	2^+_2	**0.32**	**0.20**	**0.24**	**0.04**	-
^{22}O	2^+_1	**0.40**	**0.46**			0.69(28)
	2^+_2	**0.064**	**0.043**	**0.33**	**0.05**	-

M. Ciemala (ifj-PAN)et al , to be submitted to PRL

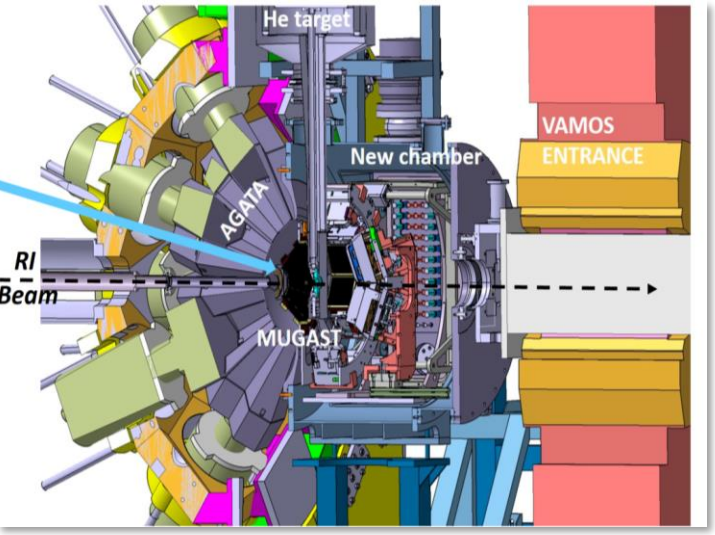


The MBPT predicts that the lifetime is dominated by the B(M1) dipole strength



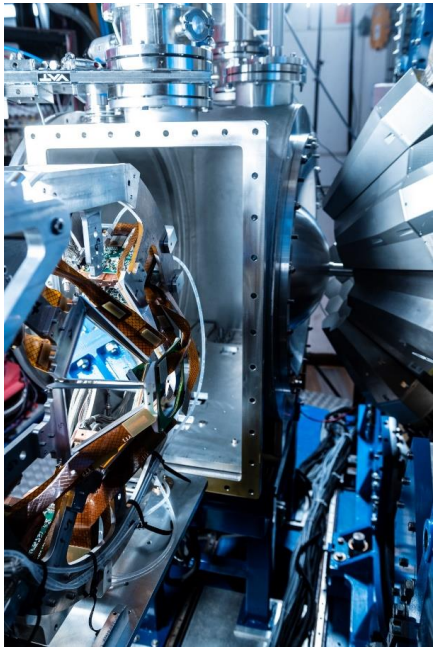
MUGAST campaign 2019-2020

Nucleons transfer spectroscopy using the SPIRAL1 ISOL beams



Nuclear Astrophysics: spectroscopic factors of relevant resonances for nucleosynthesis studies in radiative capture reactions: (^{6}Li,d), (^{3}He,d), (d,p)

Shell evolution:
spectroscopic factors, s.p. energies (d,p), (t,p), (^{3}He,n)
n-p pairing, clusterization



First successful SPIRAL1 exp in April : “Resonant state in ^{15}F” **

** *See François De Oliveira’s presentation on Wednesday morning*

Conclusions

The AGATA array is operated since 2014 at GANIL and will be transferred in summer 2021 to LNL – Legnaro

AGATA at GANIL is used to performed high resolution γ-ray spectroscopy in exotic nuclei produced in heavy-ions collision at the Coulomb barrier

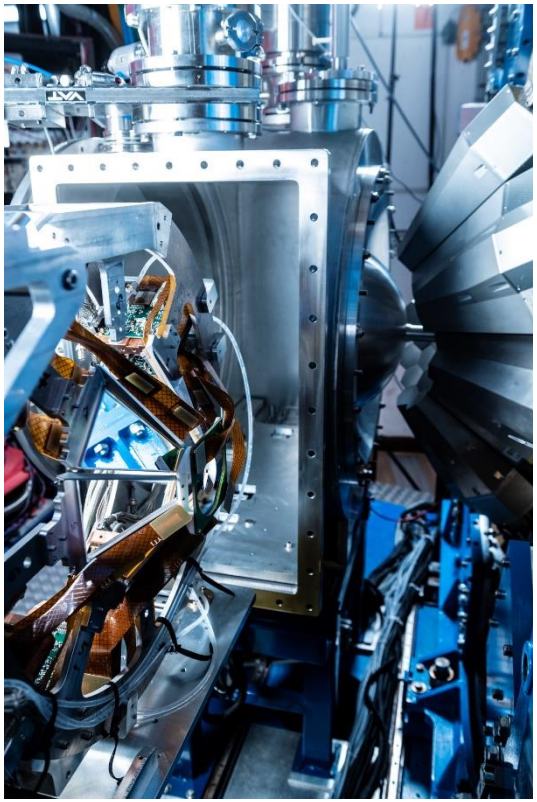
Unpublished results in ^{52,54}Ti, ^{106,108}Sn, ^{112}Xe, ^{20}O have been presented with a specific focus on lifetime measurements

The new lifetime measurements result for states with $J>2_1^+$ are :

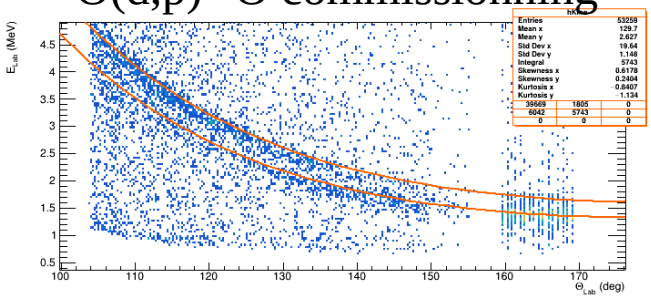
- New values for ^{52}Ti presenting now bell shape compatible with SM
- New B(E2) up to the 6^+ state in ^{54}Ti at the N=32 shell closure
- High precision measurements in ^{108}Sn underline the role of proton excitation above Z=50
- New reduced transition probabilities in ^{112}Xe
- New indication that the 3-body term of the nuclear interaction plays a major role in the structure of n-rich Oxygen isotopes

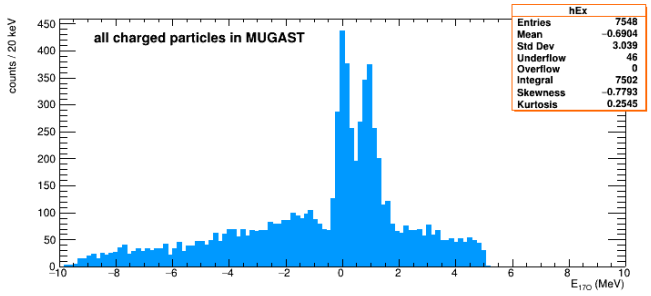
First successful SPIRAL1-MUGAST experiment performed in April

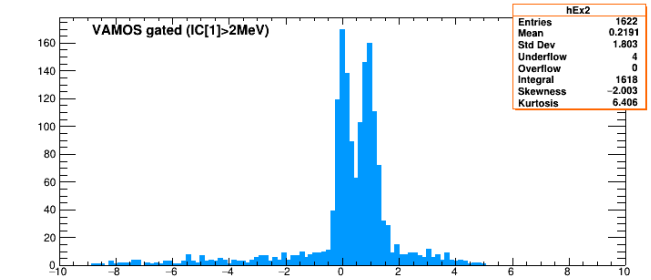
MUGAST campaign 2019-2020

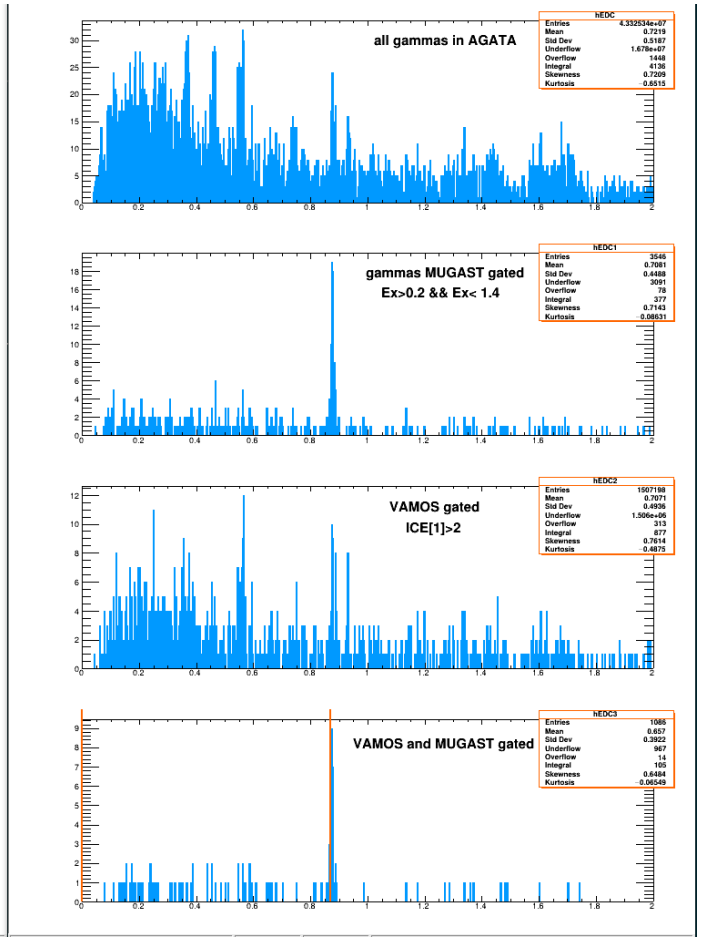


$^{16}O(d,p)^{17}O$ commissionning







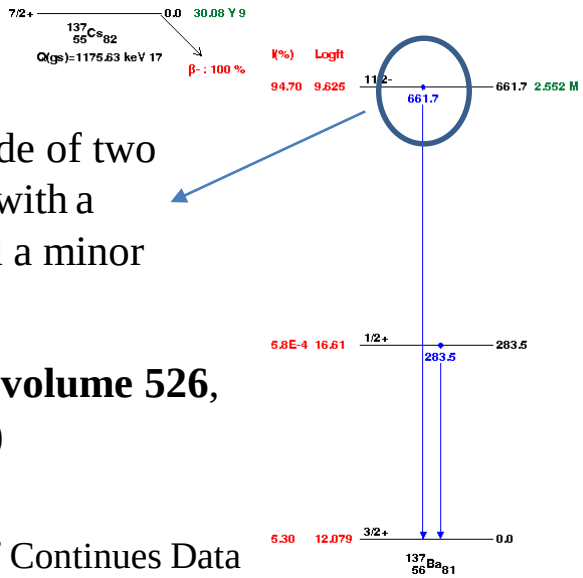


867 keV:: 152Eu= 7.7(2)%. 870 keV ^{17}O = 7.8%. Geant4 = ~8%

First successful SPIRAL1 exp (e744) in April : “Resonant state in ^{15}F”

Double Gamma decay

D. Brugnara, A. Goasduff, JJ Vailente-Dobon et al.



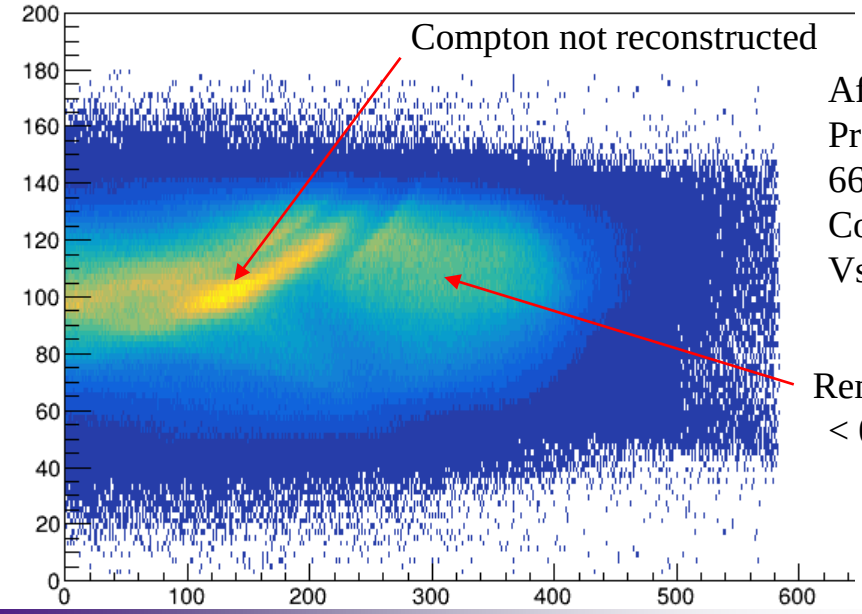
Can decay as a cascade of two gamma ($P \propto 2\ 10^{-6}$) with a dominant M2-E2 and a minor E3-M1 contribution

C. Walz et al., *Nature* **volume 526**, pages 406–409 (2015)

The main point is to discriminate the real double gamma event candidates on top of the "background" of the Compton scattering.

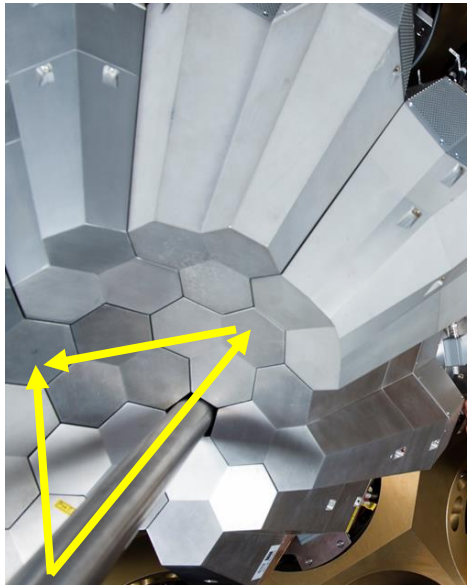
"Tracking" should be able to reconstruct the Compton scattering and leave only candidate for the double events … Proof of principle ?

30-31 May 2018 : 49h of Continues Data



After Tracking – OFT Std
Prompt Track1+Track2 =
661 ± 1.5 keV, nbTrack=2
Compton Angle (Track1,Track2)
Vs Diff (ETrack1, ETrack2)

Remain to be understood in details
< 0.007% of events



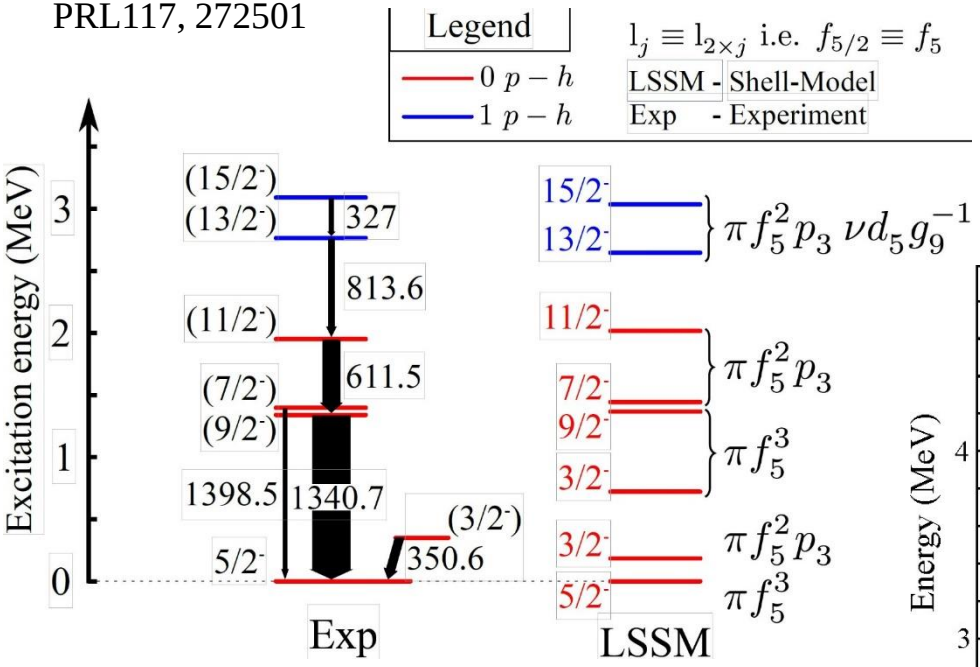
^{137}Cs

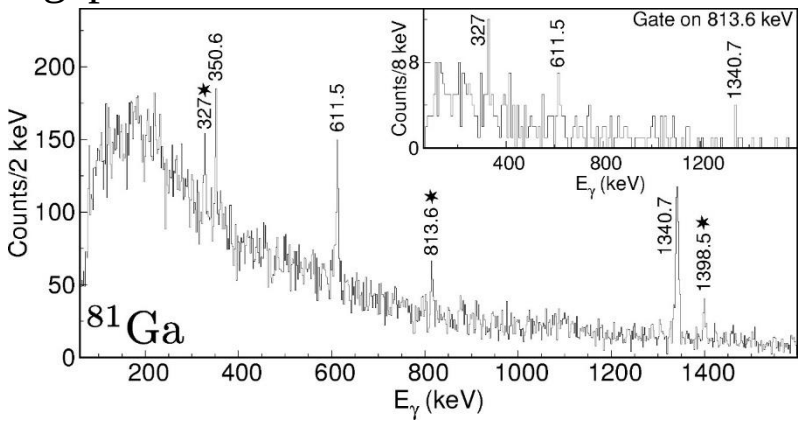
^{81}Ga – Three valence protons coupled to N = 50 neutron-core excitations

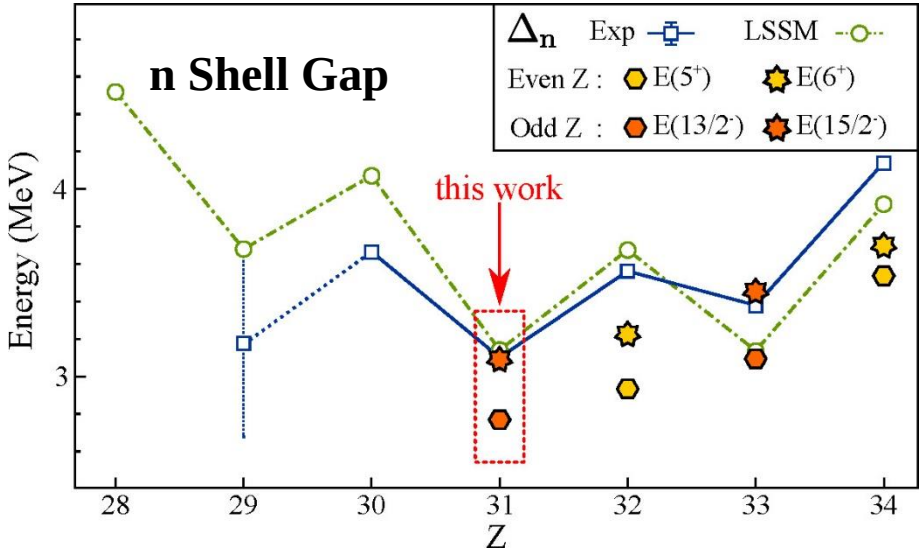
J. Dudouet et al., Submitted to Phys. Rev. Lett

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

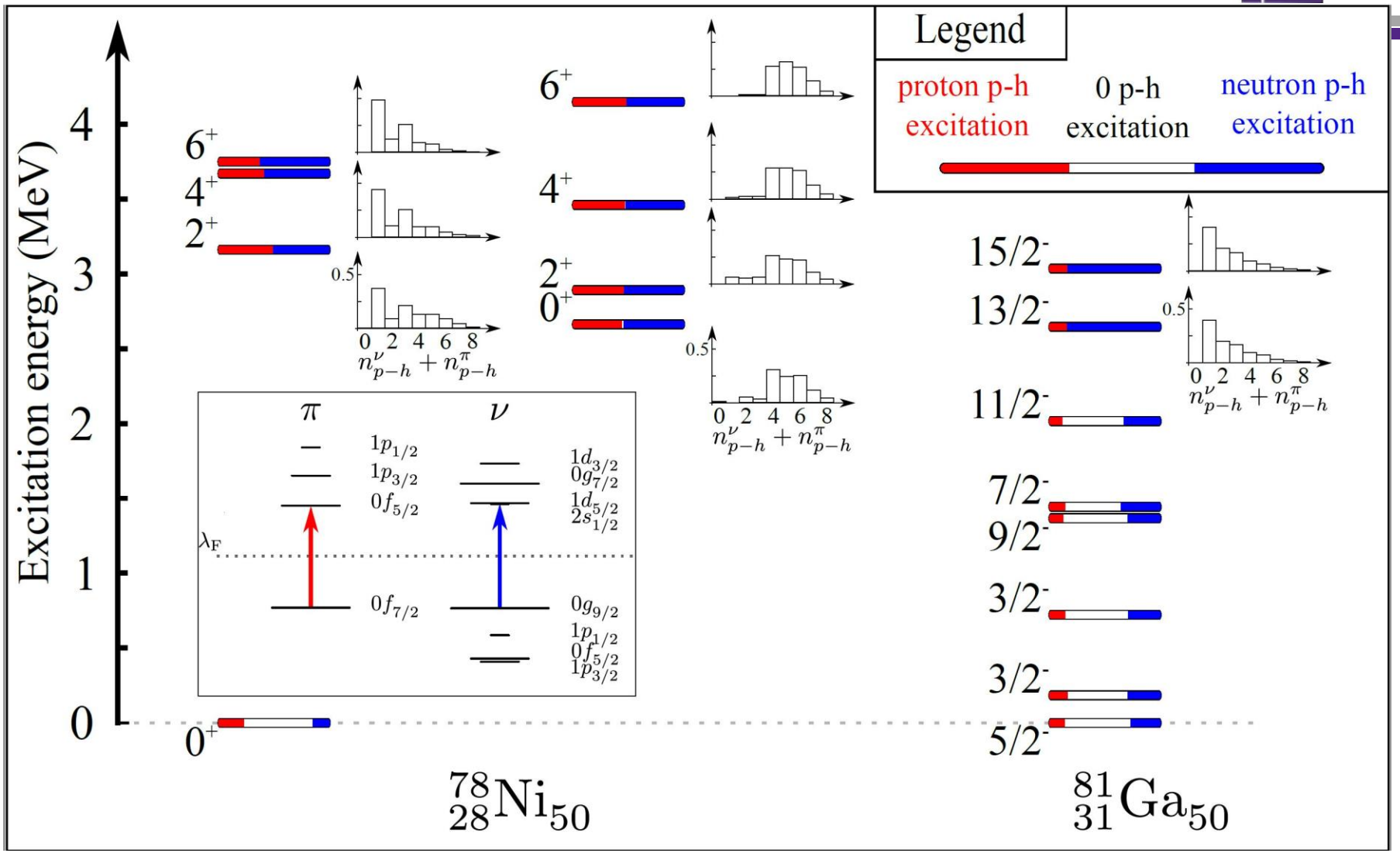
PFSDG-U interaction
F. Nowacki
PRL117, 272501







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

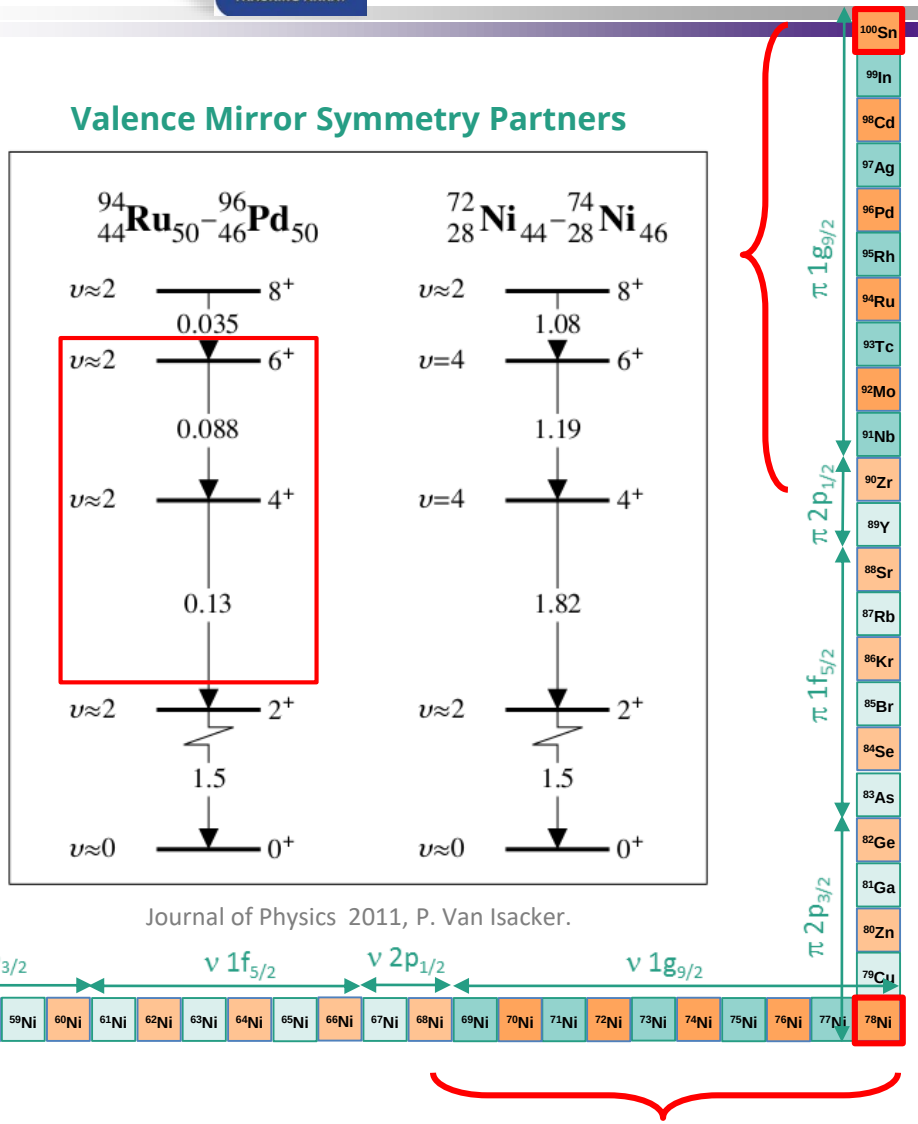


PFSDG-U interaction F. Nowacki PRL117, 272501

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

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

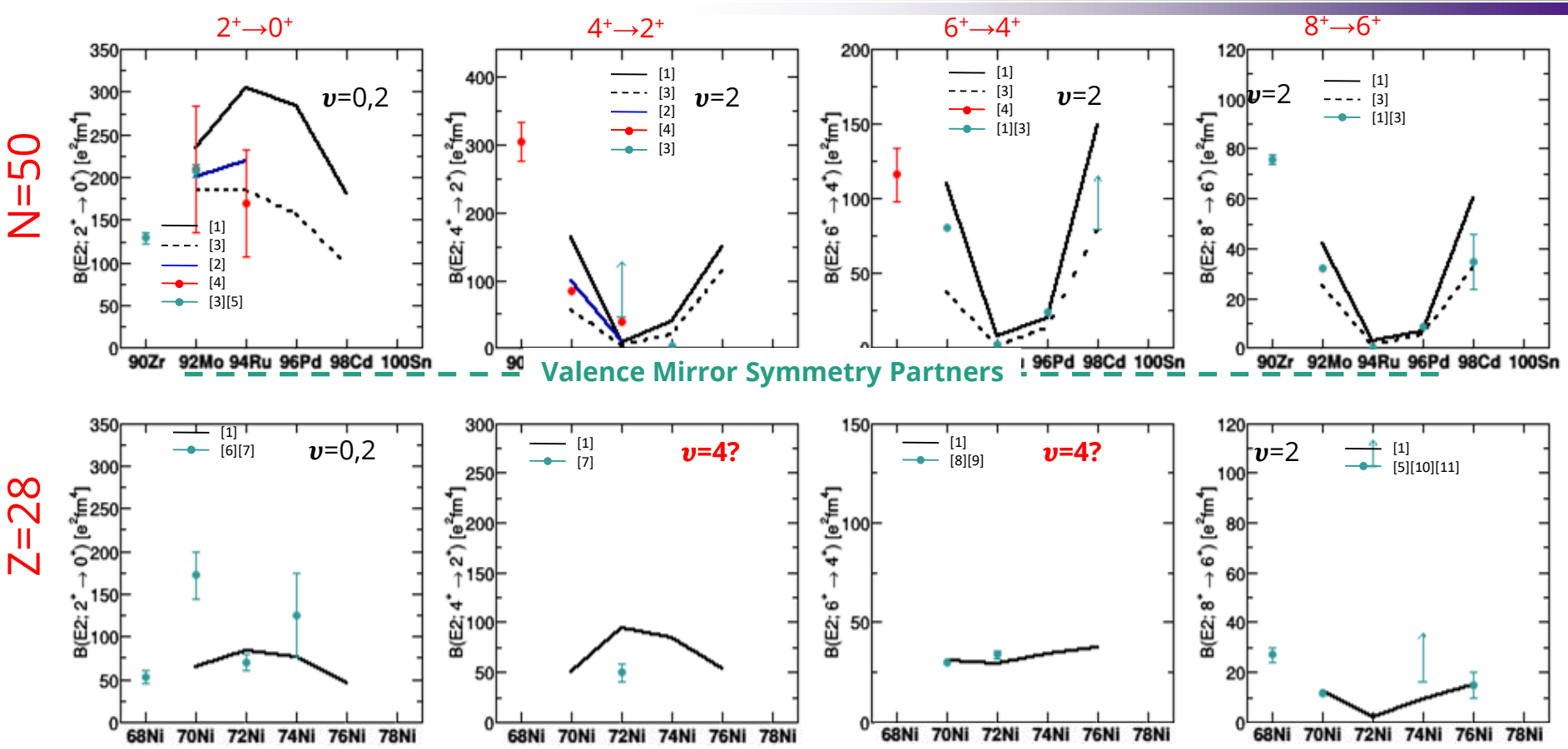
- Shell Model orbitals for valence along N=50 are the same as for valence along Z=28
- Same nuclear structures for Valence Mirror Symmetry Partners (?)
- Indeed similar 2^+ and 4^+ excitation energy towards ^{100}Sn and ^{78}Ni
- Effective two-body interaction is very different along $g_{9/2}$ near ^{100}Sn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



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)

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

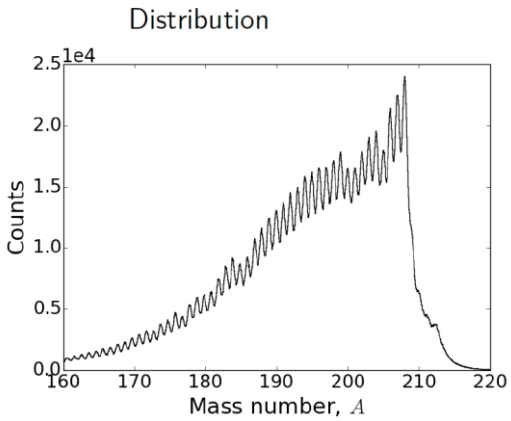
R.Perez-Vidal, A.Gadea, C.Domingo-Pardo (IFIC) et al, in preparation

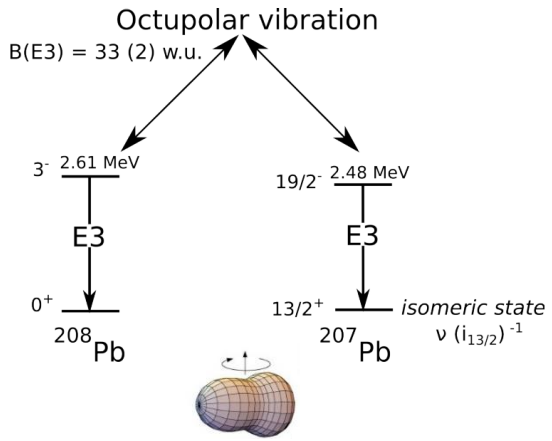


[1] A.F. Lisetskiy et al. PRC 2004
[2] A. Gargano Private communication
[3]H. Mach et al. PRC 2017
[4]R.M. Pérez-Vidal et al. This work
[5]NNDC
[6] T. Marchi et al PRL 2014
[7] K. Kolos et al PRL 2016
[8] C.J. Chiara et al PRC 2015
[9] A.I. Morales et al. PRL 2018
[10] M. Sawicka et al PRC 2003
[11]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

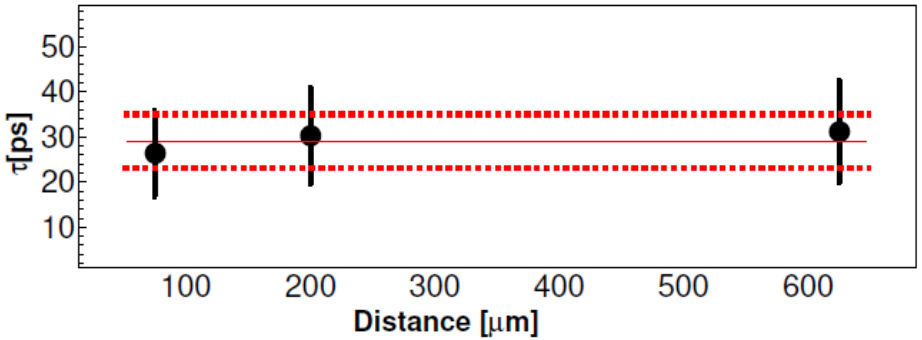
Seniority is well preserved in the N=50 isotones along the $(\pi g_{9/2})^n$ excitations

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

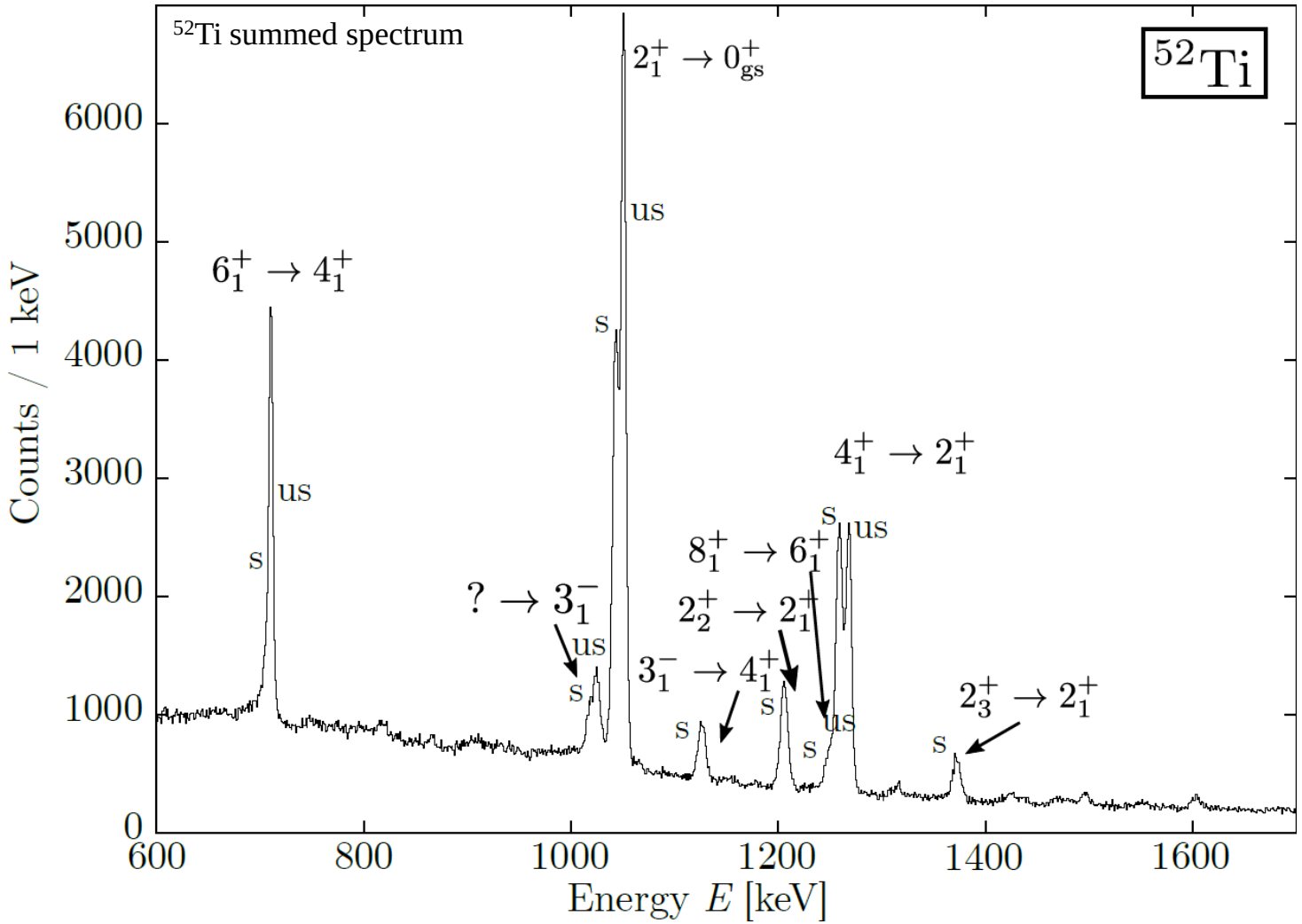


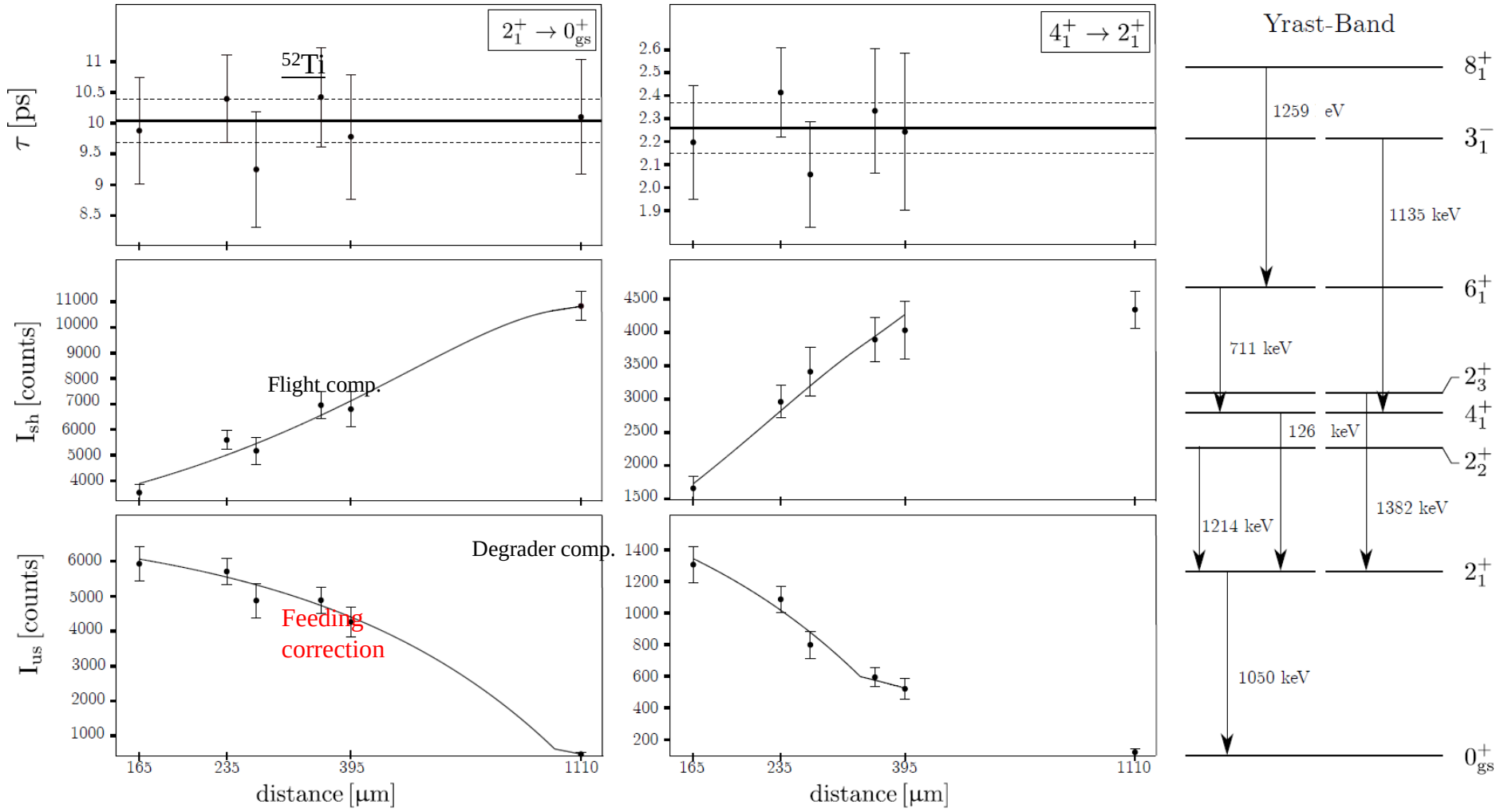


- Case of the ^{207}Pb : 1 neutron hole in ^{208}Pb
- The first excited states of ^{207}Pb are part of the $\nu p^{-1}_{1/2} \otimes 3^-$ multiplet with slightly reduced B(E3) with respect to ^{208}Pb due to the $p_{1/2}$ blocking effect
- The $\nu(i_{13/2})^{-1}$ state band structure : strong coupling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

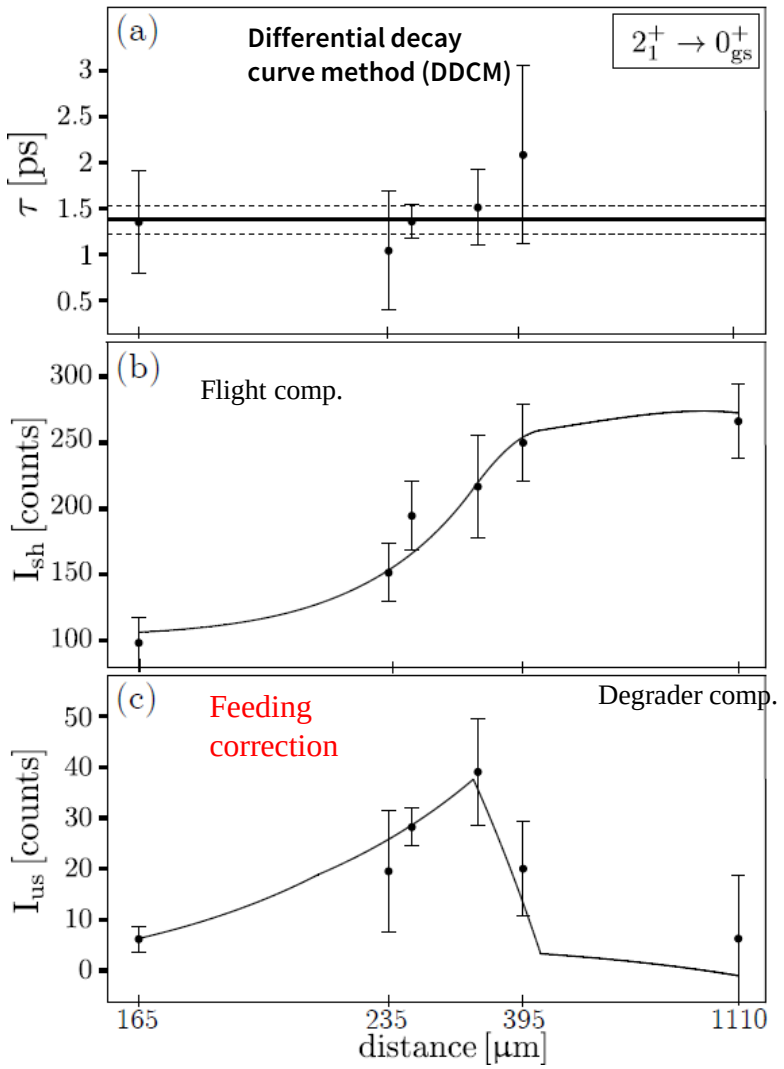


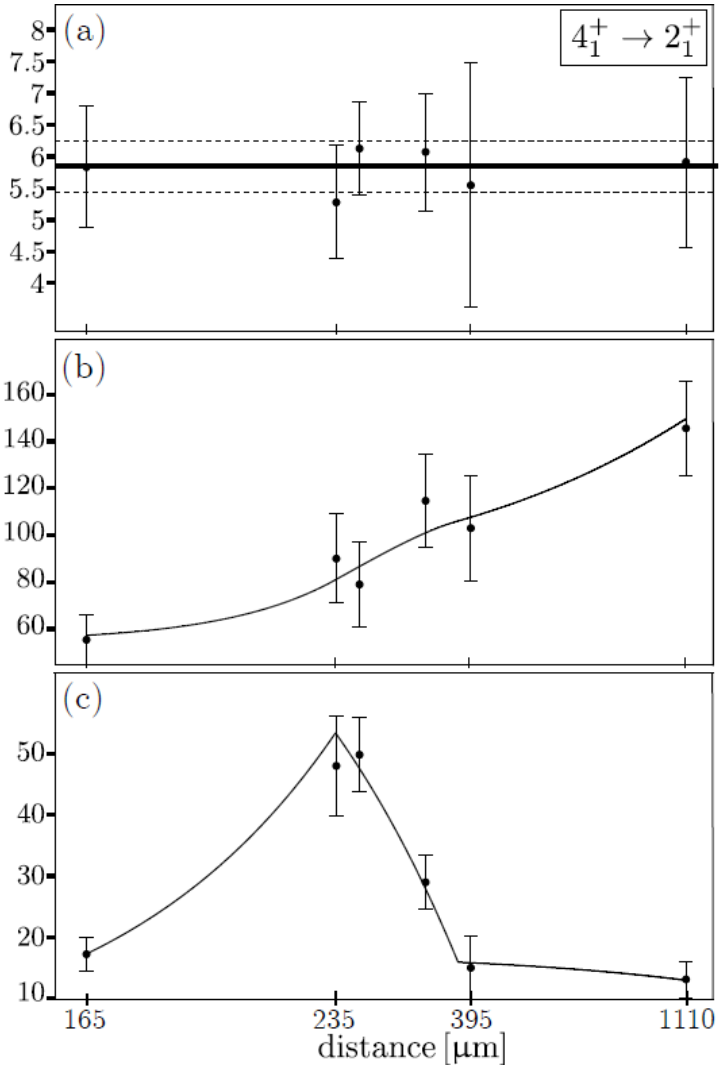
D. Ralet, E. Clément et al, submitted to PLB
D. Ralet et al., Phys.Scr. 92, 054004 (2017)

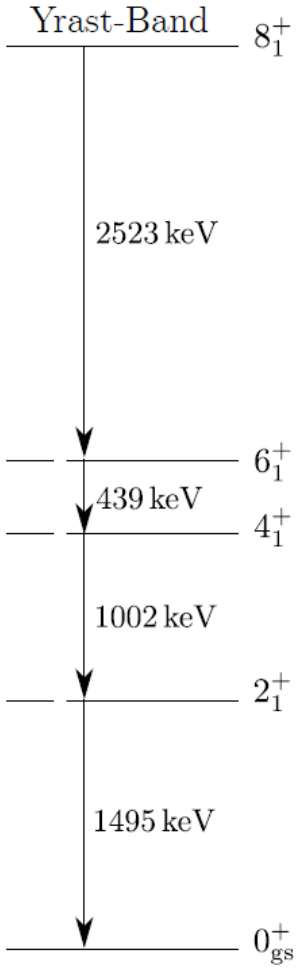

^{52}Ti summed spectrum
^{52}Ti
$2_1^+ \rightarrow 0_{gs}^+$
$6_1^+ \rightarrow 4_1^+$
$4_1^+ \rightarrow 2_1^+$
$8_1^+ \rightarrow 6_1^+$
$2_2^+ \rightarrow 2_1^+$
$? \rightarrow 3_1^-$
$3_1^- \rightarrow 4_1^+$
$2_3^+ \rightarrow 2_1^+$
us
s
Counts / 1 keV
Energy E [keV]
0
1000
2000
3000
4000
5000
6000
600
800
1000
1200
1400
1600


$2_1^+ \rightarrow 0_{gs}^+$
^{52}Ti
$4_1^+ \rightarrow 2_1^+$
τ [ps]
I_{sh} [counts]
I_{us} [counts]
Flight comp.
Degrader comp.
Feeding correction
distance [µm]
Yrast-Band
8_1^+
3_1^-
6_1^+
2_3^+
4_1^+
2_2^+
2_1^+
0_{gs}^+
1259 eV
1135 keV
711 keV
126 keV
1382 keV
1214 keV
1050 keV

^{54}Ti







A. Goldkuhle (IKP) et al, in preparation

^{54}Ti

	Lifetime [ps]		B(E2) [e^2fm^4]	
$I_1^+ \rightarrow (I-2)_1^+$	Present	Previous [1]	Present	Previous [1]
$2_1^+ \rightarrow 0_{g.s.}^+$	1.4(7)	1.53(27)	80^{+82}_{-27}	72^{+15}_{-11}
$4_1^+ \rightarrow 2_1^+$	5.9(9)	-	139^{+25}_{-18}	-
$6_1^+ \rightarrow 4_1^+$	≥ 380	-	≤ 132	-
$8_1^+ \rightarrow 6_1^+$	≤ 1.4	-	≥ 5.7	-

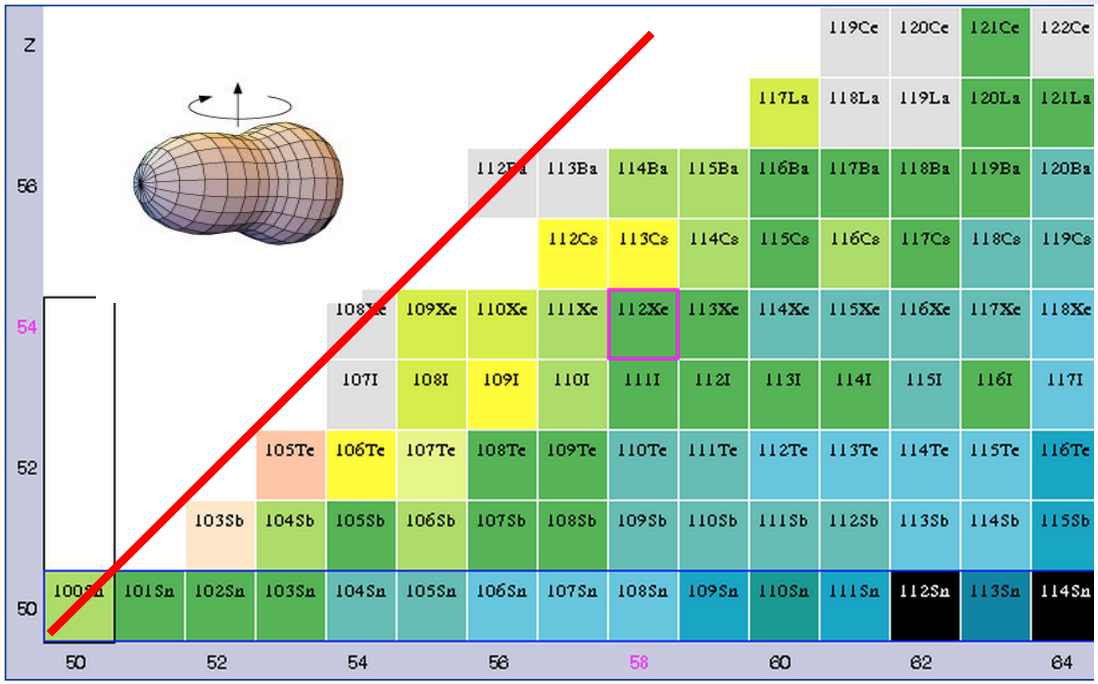
[1] D.-C. Dinca *et al.*, Phys. Rev. C 71, 041302 (2005).

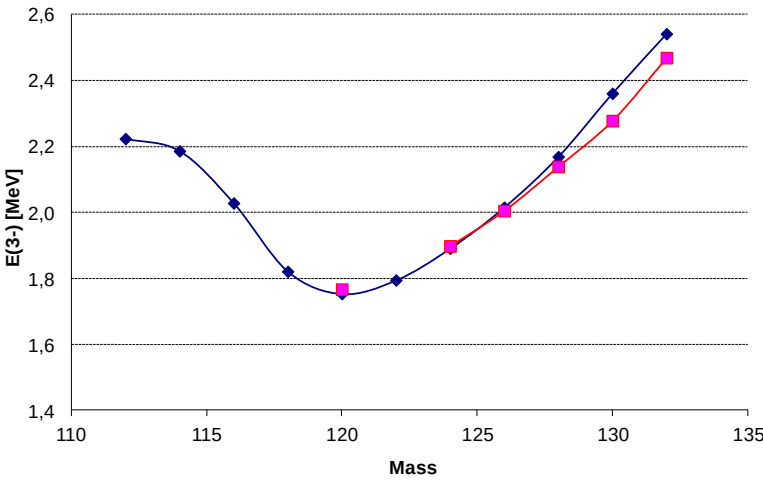
^{52}Ti

	Lifetime [ps]		B(E2) [e^2fm^4]	
$I_1^+ \rightarrow (I-2)_1^+$	Present	Previous [2]	Present	Previous [2]
$2_1^+ \rightarrow 0_{g.s.}^+$	10.1(4)	5.19(20)	63^{+8}_{-6}	124^{+5}_{-5}
$4_1^+ \rightarrow 2_1^+$	2.3(1)	4.76(58)	111^{+8}_{-9}	53^{+7}_{-6}
$6_1^+ \rightarrow 4_1^+$	45(1)	36.07(577)	100^{+9}_{-8}	125^{+24}_{-17}

[2] K.-H. Speidel *et al.* Phys. Lett. B **633**, 219 (2006).

A. Goldkuhle (IKP) et al, in preparation



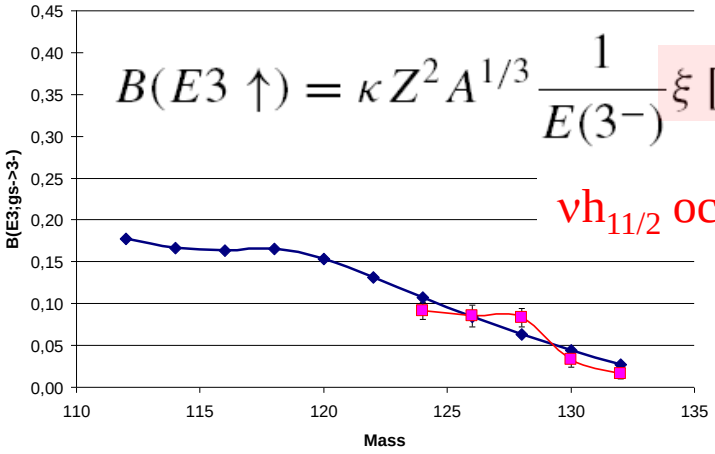


Collective octupole motion in such nuclei is strongly influenced by quadrupole softness

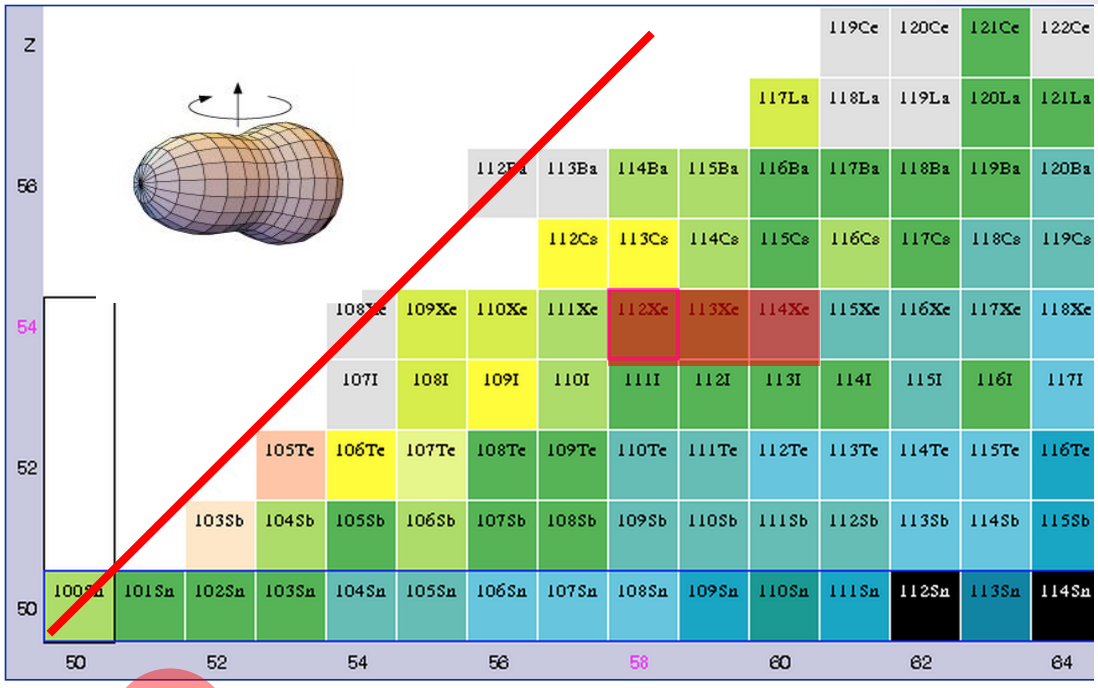
$$E(3^-) = E_0 - \frac{B^2}{E(2_1^+)}.$$

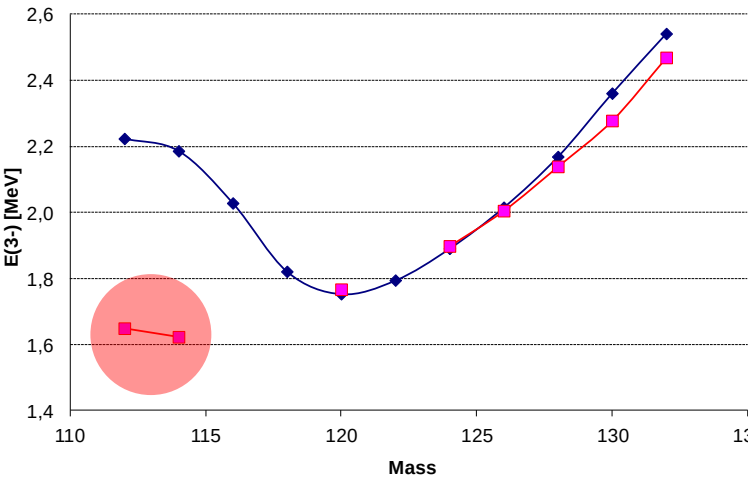
*[M. P. Metlay Phys. Rev. C **52**, 1801 (1995)]*

$$B(E3\uparrow) = \kappa Z^2 A^{1/3} \frac{1}{E(3^-)} \xi\ [e^2 b^3]$$

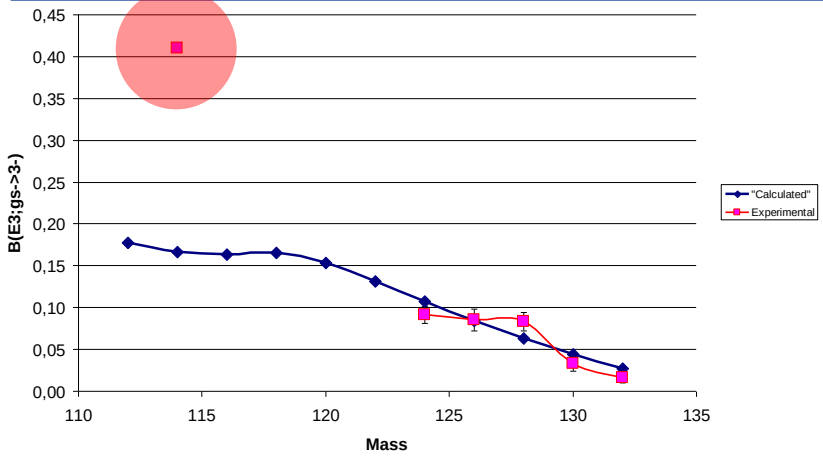


$\nu h_{11/2}$ occupancy



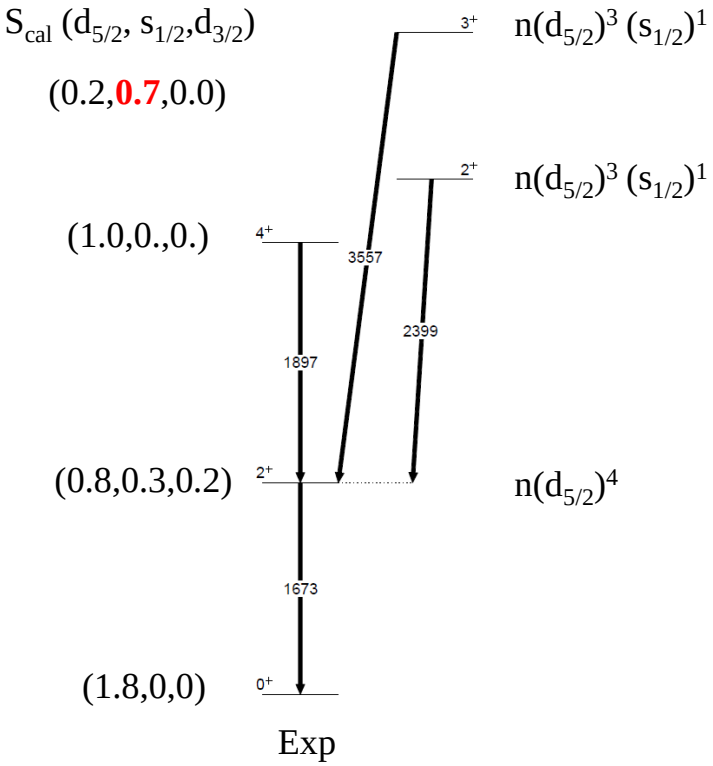


G. de Angelis et al., Phys. Lett. B 535 (2002) 93
J.F. Smith et al., Phys. Lett. B 523 (2001) 13.



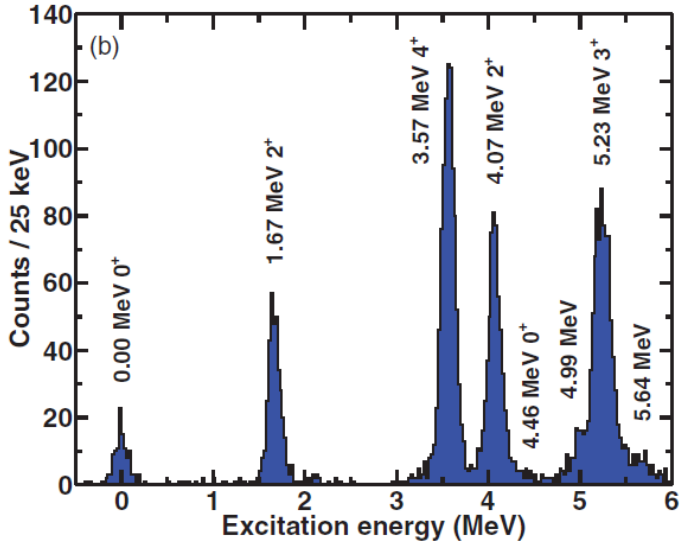
^{114}Xe : B(E3:3$^-$ → 0$^+$) = 77(27) W.u

Non –yrast states in ^{20}O



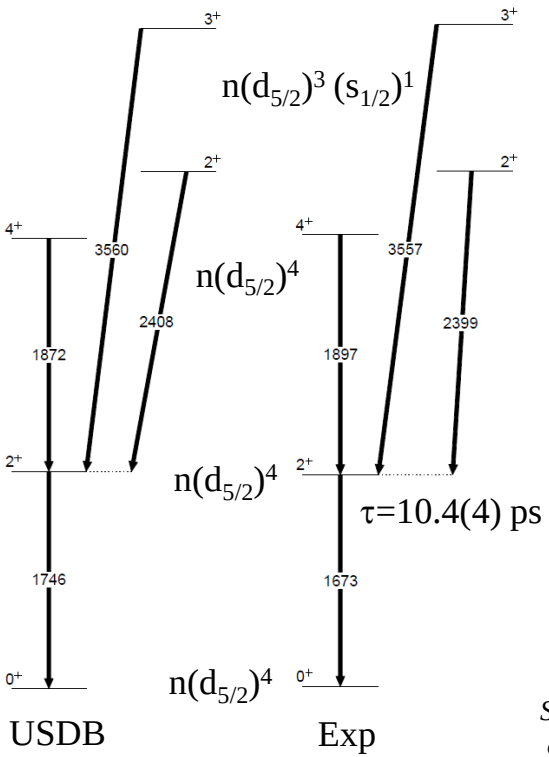
Neutron transfer reaction by *C. R. Hoffman et al .PRC* ***85****, 054318 (2012)* has shown that :

- Yrast 2^+ and 4^+ states are dominated by the natural $n(d_{5/2})^4$ configuration
- The 2^+_2 and 3^+ states are dominated by the $n(d_{5/2})^3(s_{1/2})^1$configuration



Theoretical S factors from SM calculations are in good agreement with the measured ones

Non –yrast states in ^{20}O



τ=27 fs

τ=180 fs

$d_{3/2}$ lowered by 2 MeV

τ=240 fs

τ=12 ps

$d_{3/2}$ lowered by 2 MeV

τ=11 ps

SM :M. Rejmund, Private communication USDB, A. Brown et al PRC, 74(3), 034315 (2006).

Abinitio
G. Hagen et al., PRL 108, 242501 (2012)

τ_{NN} = 320 fs

τ_{NNN} = 200 fs

τ_{NN} = 10.5 ps

τ_{NNN} = 11.7 ps

The 2^+_1 lifetime is not sensitive to the $d_{3/2}$ position

The 2^+_2 and 3^+ states lifetimes are sensitive to the $d_{3/2}$ contribution

- Placed phenomenological in SM calculations
- the 3-body interaction create repulsion in the ab-initio model

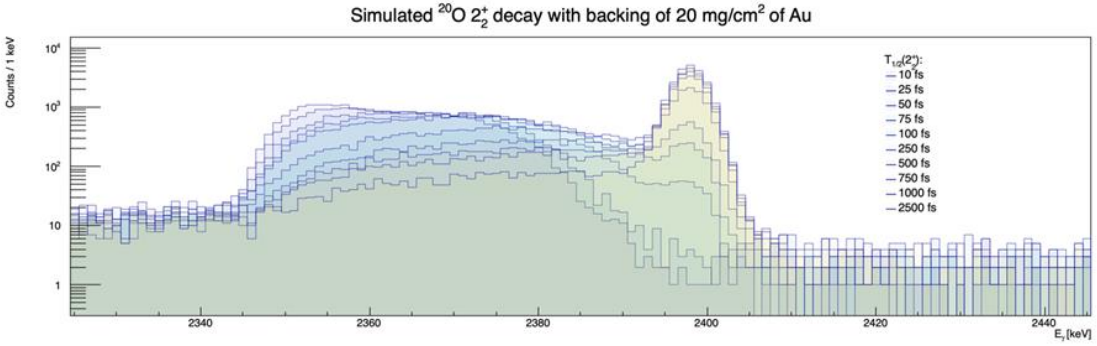
- A reduced splitting of the $s_{1/2}d_{3/2,5/2}$ increases the lifetime
- As an increased repulsion between the orbits reduces the lifetime

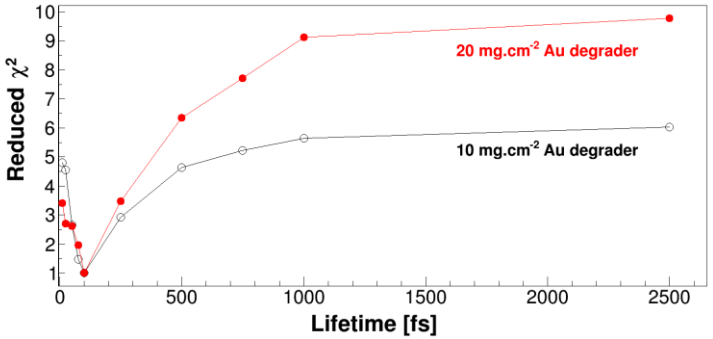
The lifetime of the 2^+_2 state is a sensitive probe for the $s_{1/2}d_{3/2,5/2}$ decomposition in neutron-rich O

Proposed experiment

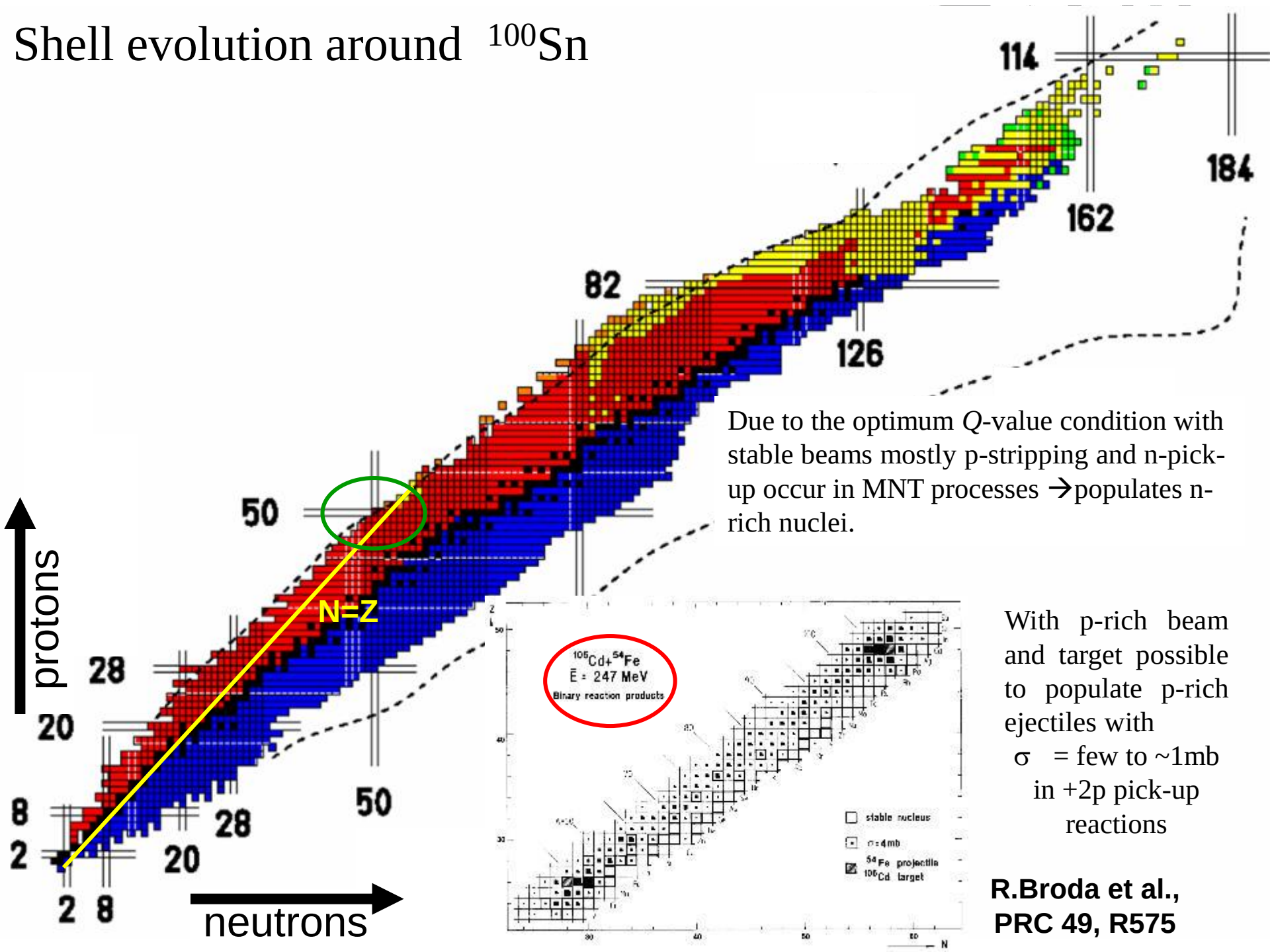
- Populating the relevant neutron states by the selective $^{19}O(d,p)^{20}O$ reaction
- ^{19}O beam from SPIRAL1 at 6.6 MeV/ and at 7. 10^4 pps
- DSAM dedicated target CD2 (0.3mg/cm²) + Au (20mg/cm²)
- ^{20}O to be identified in VAMOS and γ-ray in AGATA placed at backward angles
- The entry point is constrained by the proton spectroscopy in MUGAST
- Lifetime measurement of the 2^+_2 and 3^+ state, feeding free, by DSAM

- ✓ We do not probe directly the 3-body term (because it is impossible)
- ✓ We do not directly measure the relative position of the $s_{1/2} - d_{3/2,5/2}$
- ✓ But we measure an accurate and relevant quantity ($T_{1/2}$) which is sensitive to their relative spacing independently if it is the consequence of the 3-body term or a phenomenological approach
- ✓ Within an ab-initio framework it can be related to the 3-body contribution
- ✓ Within the SM approach, it can be related to the position of the single particle orbit





Shell evolution around ^{100}Sn



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

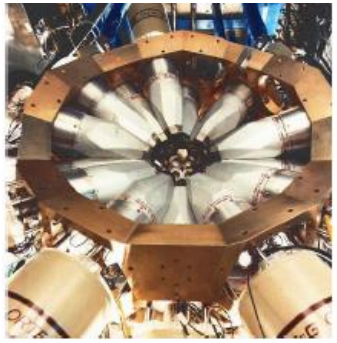
R.Broda et al., PRC 49, R575

Large arrays for γ-ray spectroscopy in Europe by European collaborations



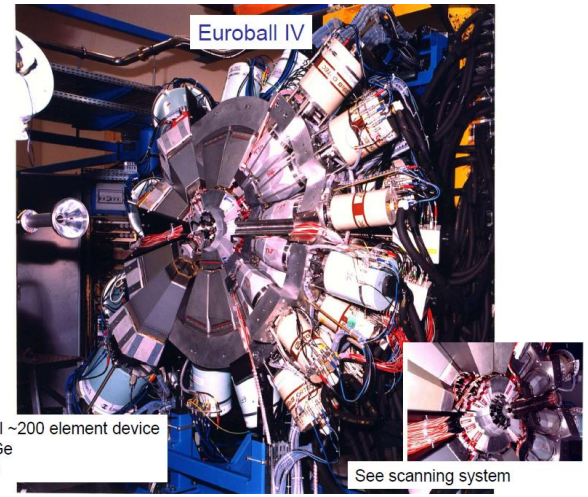
ESSA30

30 Detec. at Daresbury - 1987



Eurogam

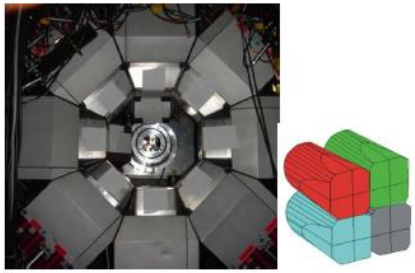
40-50 Detec. 90’



Euroball 100. Detec. 90’-2000



MINIBALL triple-clusters with 6 and 12 fold segmentation



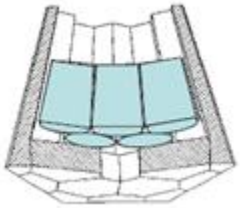
EXOGAM at GANIL with 4-fold segmented clovers

Strong collaboration with industry

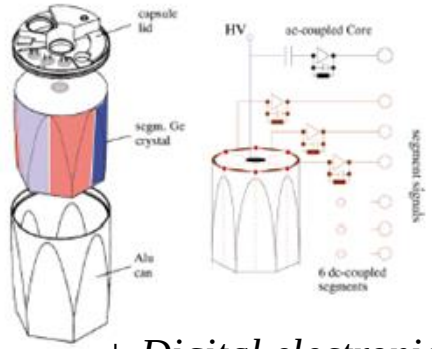


→ Composite detector to increase the photopeak efficiency

Cluster detector
7 crystals per detector
encapsulated detectors



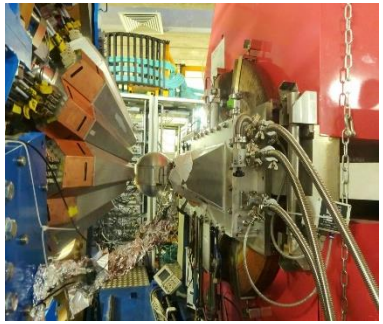
20-40 Detec. 2000-

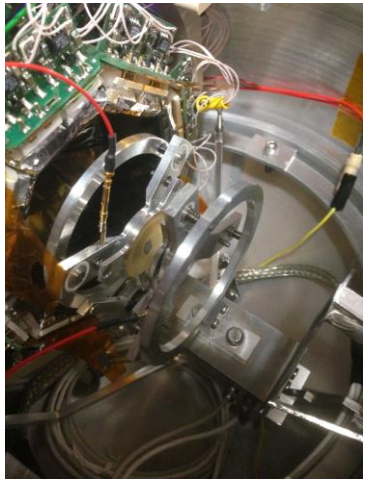


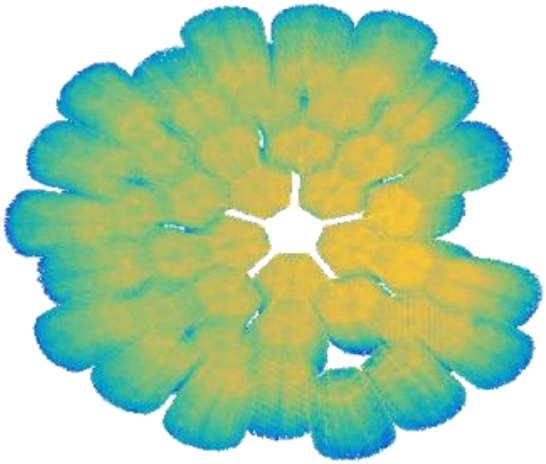
Segmentation of detectors
Improve granularity (reduce Doppler broadening)

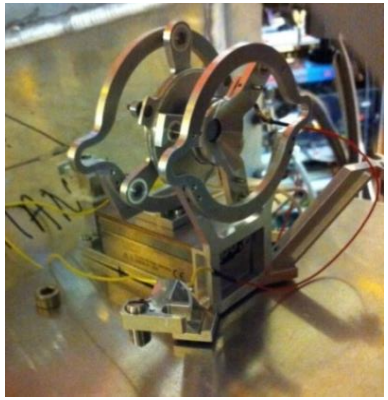
+ Digital electronic

The GANIL Campaign [2015-2021]

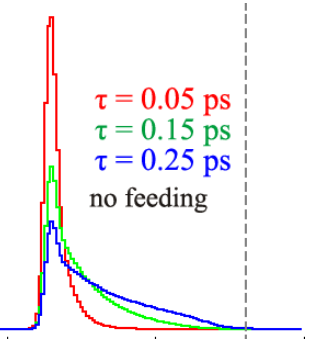




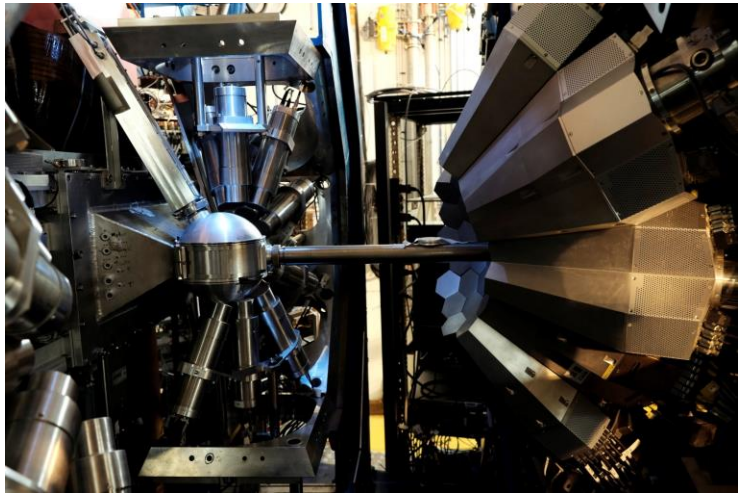




Lifetime measurements



2015-2017: 93% of performed experiments are lifetime measurements from fs to μs



E. Clément et al., NIMA 855, 1-12 (2017)
Y. H. Kim et al., Eur.Phys.J. A 53, 162 (2017)

FATIMA-PARIS detectors coupled to AGATA

Shell evolution below ^{68}Ni

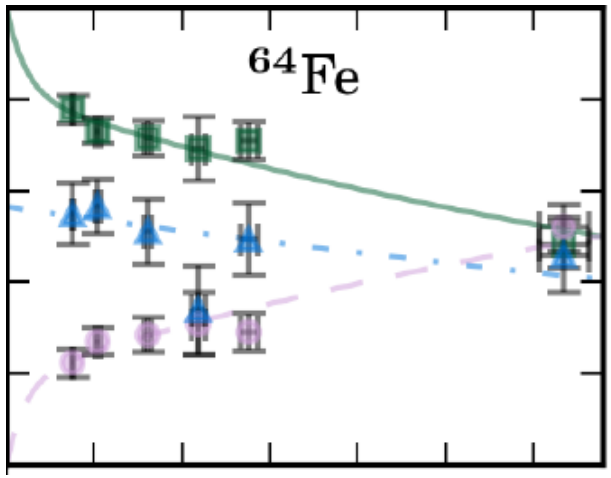
Interplay of the monopole terms of the interaction with multipole terms, like pairing and quadrupole, which determines the different phenomena we observe

Collecting spectroscopic data like transition probability constraining the theoretical description of the Island of inversion from N=28 to N=40 :

- What is the influence of the νg9/2 and νd5/2 orbits ?
- What is the influence of the proton excitations across Z=28 ?
- How collectivity change when decreasing the number of proton in the f7/2 orbital

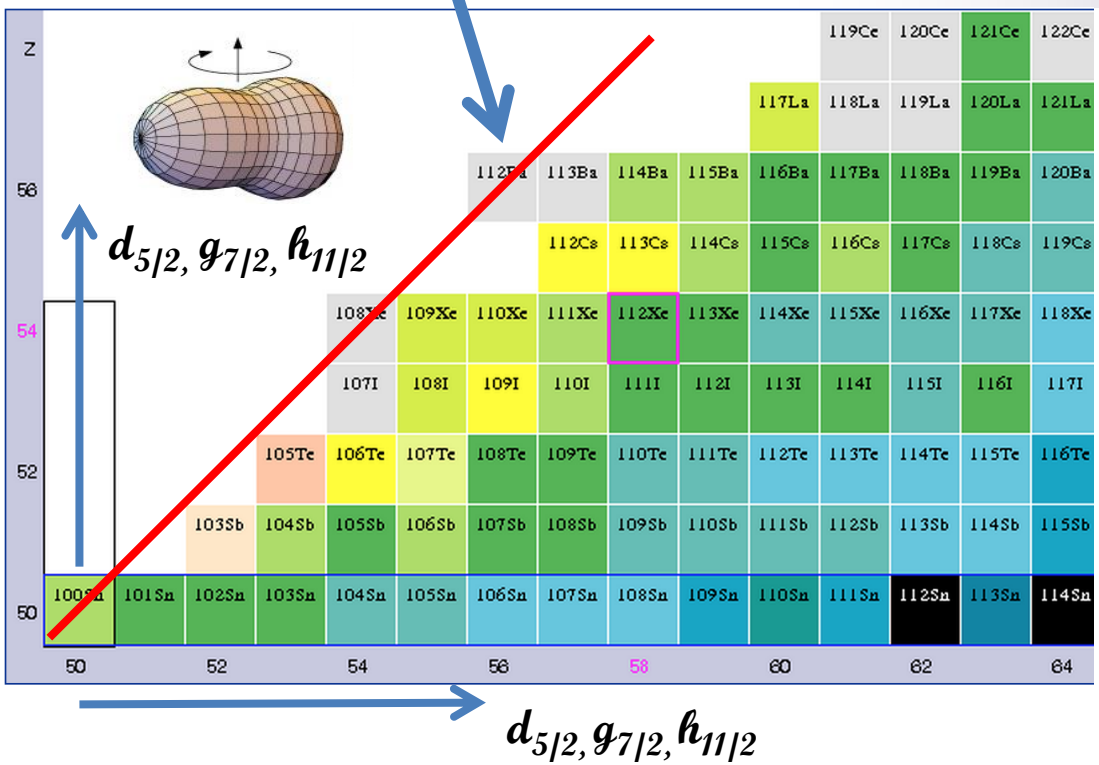


Lifetimes of the 4^+ states in $^{62;64}$Fe and the $11/2^-$ in $^{61;63}$Co and ^{59}Mn



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

^{112}Ba should corresponds to the best octupole N=Z=56 for p and n



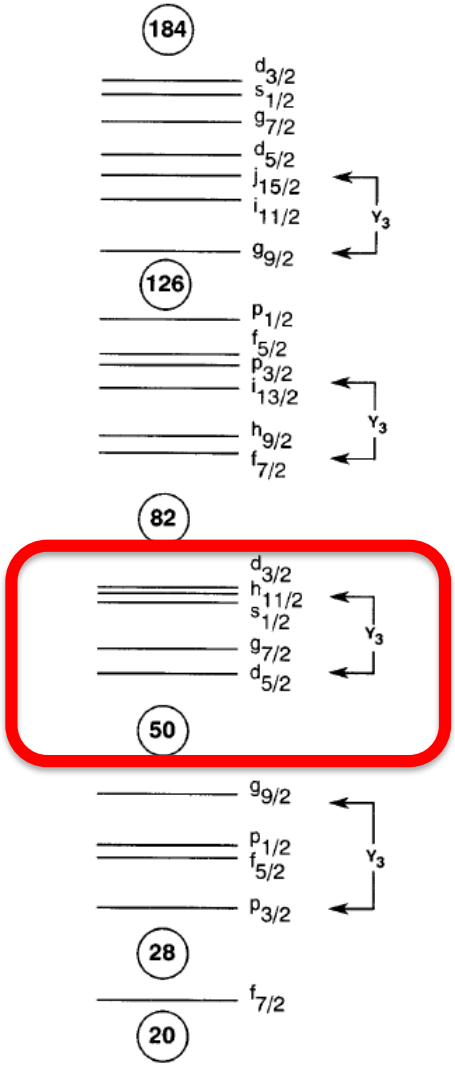


FIG. 4. Nuclear spherical single-particle levels. The most important octupole couplings are indicated.

Enhanced octupole due to the interaction of ΔL=3, ΔJ=3, inverse parity : $d_{5/2}$ and $h_{11/2}$

3^- states dominate by $d_{5/2} \times h_{11/2}$ orbital configuration

Removing neutron from the $h_{11/2}$ orbital gradually decreases the 3^- excitation energy and enhances the B(E3) value

	^{114}Xe	^{112}Xe	^{118}Ba
E (3-)$_{theo}$ (MeV) / Exp	1.84 /1.62	1.99/1.65	2.11
B(E3: 3- → 0+)$_{theo}$ W.u.	17	25	18.7
B(E3: 3- → 0+)$_{exp}$ W.u.	77(27)	-	-

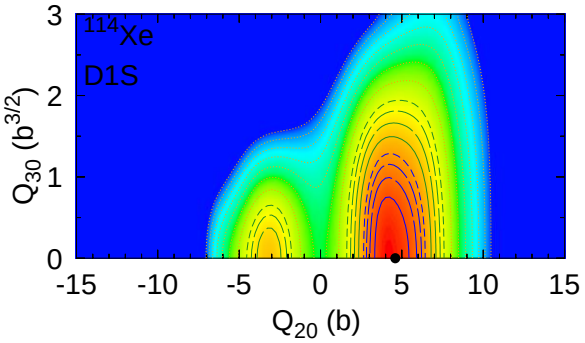
Factor 4.5

- The $h_{11/2}$-$d_{5/2}$ octupole in ^{146}Gd for protons is 37 W.u. reproduced by the same GCM HFB calculations

- Quadrupole-octupole coupling is a key contribution
  → Reproduces the Ra-Rn octupole transition strength
  L.M. Robledo and P.A. Butler, PRC 88 051302 (R) (2013)

- Q2-Q3 does not change the B(E3)

L.M. Robledo private communication



The large B(E3) might be due to the presence of an isoscalar the proton-neutron $\pi(\nu)\ d_{5/2}$ - $\nu\ (\pi)\ h_{11/2}$ term

Should increase toward N=Z

^{112}Xe : B(E3) = ?

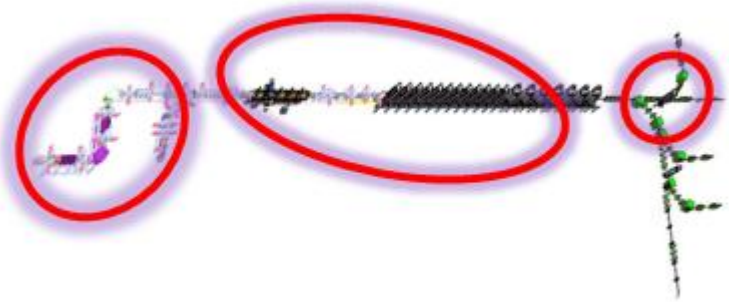
Shell evolution around proton shell closure

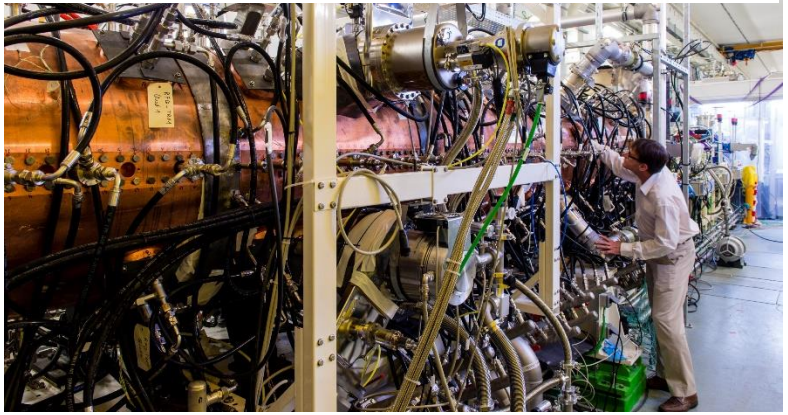
Interplay of the monopole terms of the interaction with multipole terms, like pairing and quadrupole, which determines the different phenomena we observe

- Characterizing the islands of inversion, formed near the magic numbers.
- Collectivity development with valence particle
- These are new regions of deformation with configurations involving intruder orbitals from the above main shell.
- While a signature of collective properties is given by the energy of the first excited states, their lifetimes allow a better understanding of their properties by comparison with LSSM calculations

GANIL Facilities

- The cyclotrons **will continue** to deliver **stable, high intensity** beams from ^{12}C to ^{238}U 4-3 months/year
- SPIRAL1 has delivered **post-accelerated RIB** after an important upgrade
- The start of the full LINAC accelerator commissioning with RF on July
- **First** experiment using the neutron beam around summer 2020
- The **S3 spectrometer** assembly has started in the cave. First Cryo-modules delivered, final cooling expected for 2021
- The **DESIR** hall construction contract signed



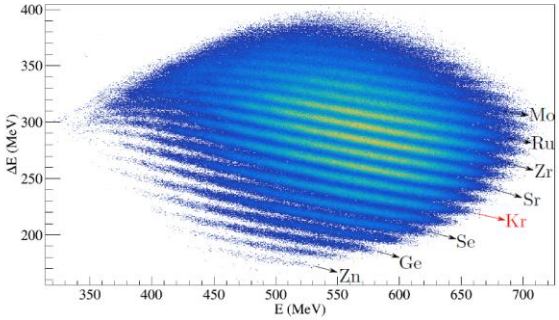


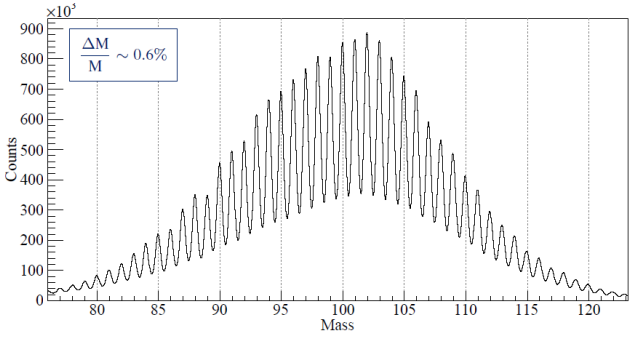


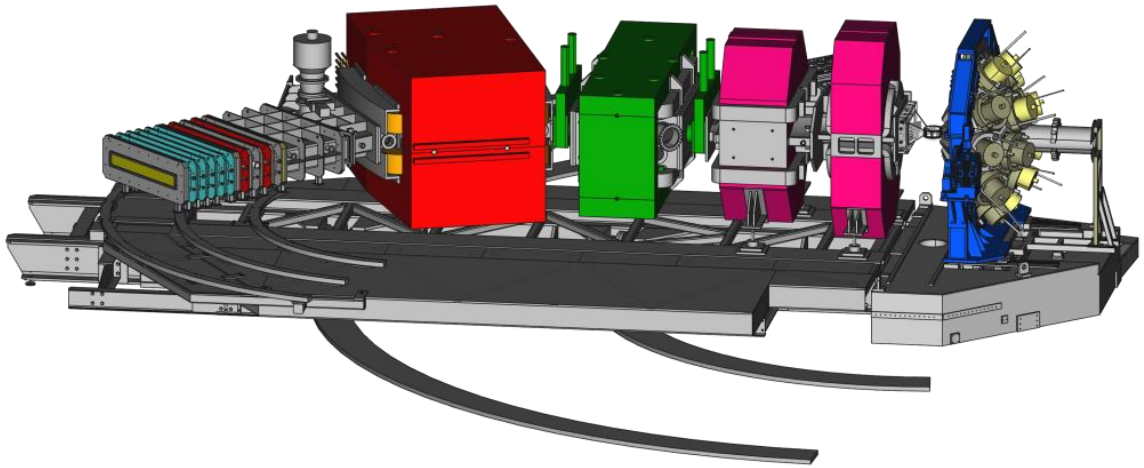
The GANIL Campaign [2015-2021]

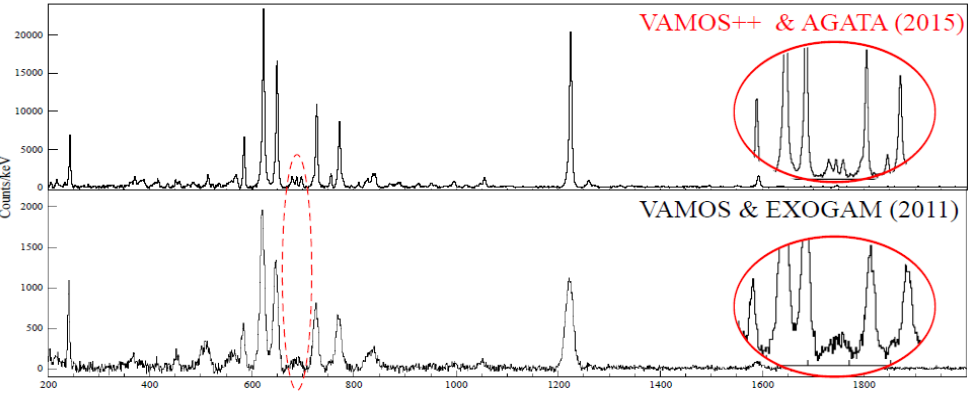
2015-2017 run VAMOS campaign

Courtesy J. Dudouet









- ✓Nucleons transfer
- ✓Fusion-fission
- ✓Transfer-fission

« States above the 2^+ are well populated »

E. Clément et al., NIMA 855, 1-12 (2017)
Y. H. Kim et al., Eur.Phys.J. A 53, 162 (2017)

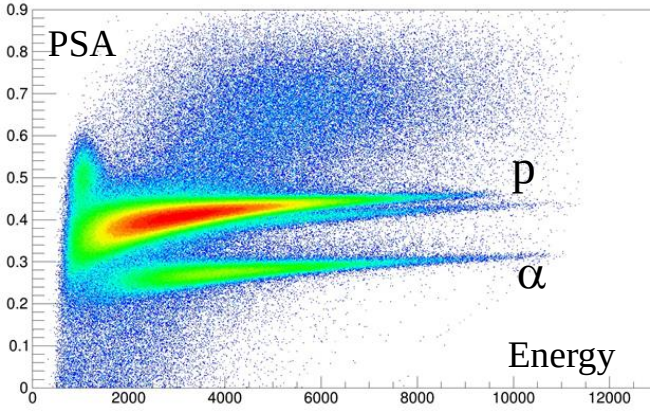
The GANIL Campaign [2015-2021]

2018 run NEDA campaign

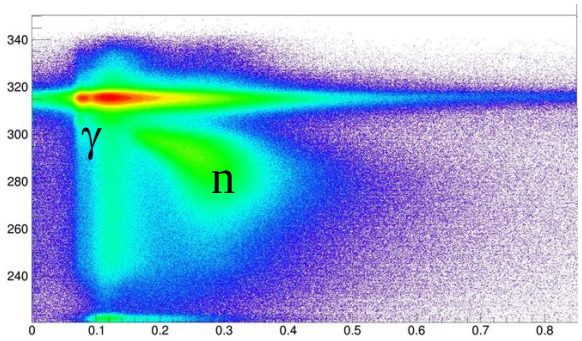
DIAMANT and NEDA in full digital system making use of the NUMEXO2 boards and coupled to AGATA with the AGATA GTS system

×20 increase in (nγ²) event rate readout compared to the NWALL-DIAMANT-EXOGAM system in VME-VXI.

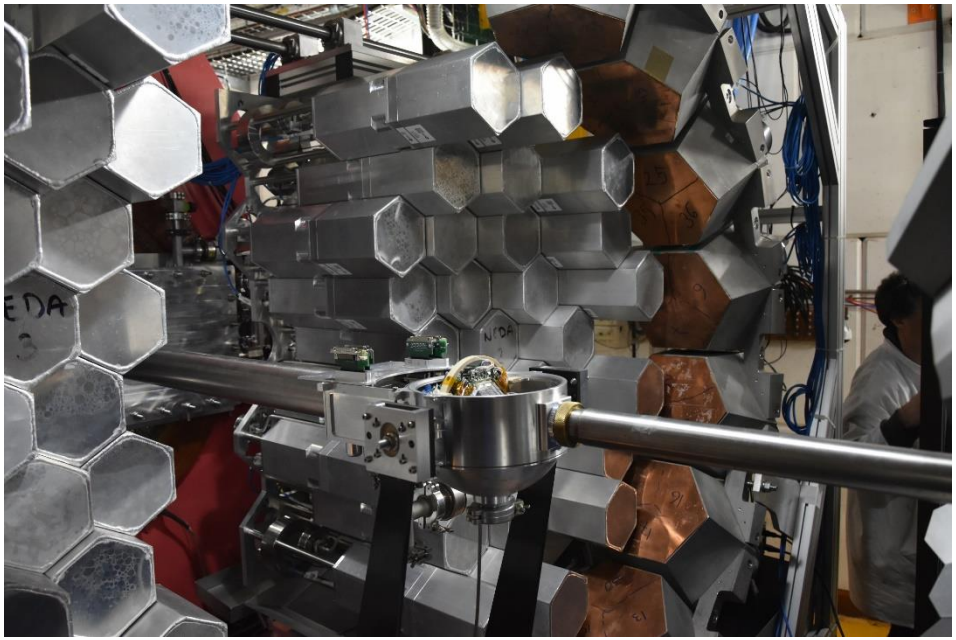
T. Huyuk et al, Eur. Phys. J. A (2016) **52**: 55 Page 5
E. Clément et al., NIMA 855, 1-12 (2017)
J. J. Valiente-Dobon et al, NIMA 927, 81-86 (2019)



Time of flight



PSA – Neural network



54 self produced NEDA detectors at forward angles and 14 NWALL detectors + plunger

~9% γ-efficiency at 1.4 MeV after tracking

>20% efficiency for 1 neutron

>35% efficiency for 1 proton

Tracking Arrays

Improved Doppler Correction capabilities

- Lifetime measurements are revisited

- ✓ Separation of both peaks for a larger solid angle even for small Δv → Combined with spectrometer and low recoil energy
- ✓ Use of thinner degrader for shorter lifetime

