Level structure of odd–odd At isotopes near the neutron midshell and first implementation of SIGMA in Jyväskylä focal plane

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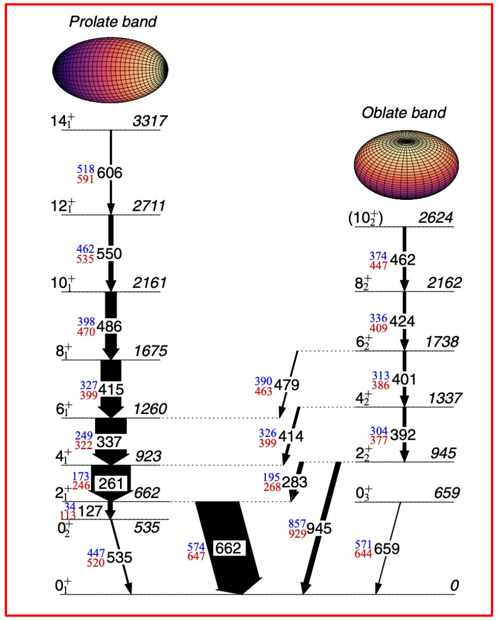
Introduction

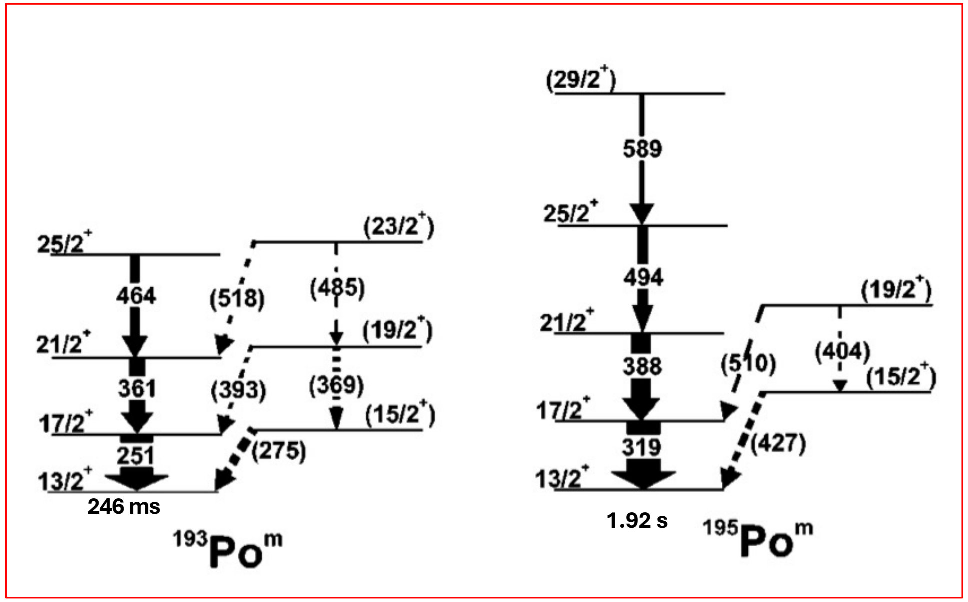
The neutron-deficient nuclei in the Pb region

Presence of deformation-driving intruder orbitals
→ shape co-existence

Presence of unique-parity orbitals →Long-lived isomers
The lowest unique-parity states in the odd-A nuclei in Pb(Z=82) region are often **isomeric- arising from ($\nu i_{13/2}$)**



^{186}Pb (*J. Ojala et al., Commun Phys 5, 213 (2022)*)



Andreyev et al., PRC 66, 014313 (2002)

Introduction: Odd Z nuclei in A~ 190 region

Neutron deficient odd mass Bi (Z = 83), At (Z = 85) isotopes

Change of ground state configuration :

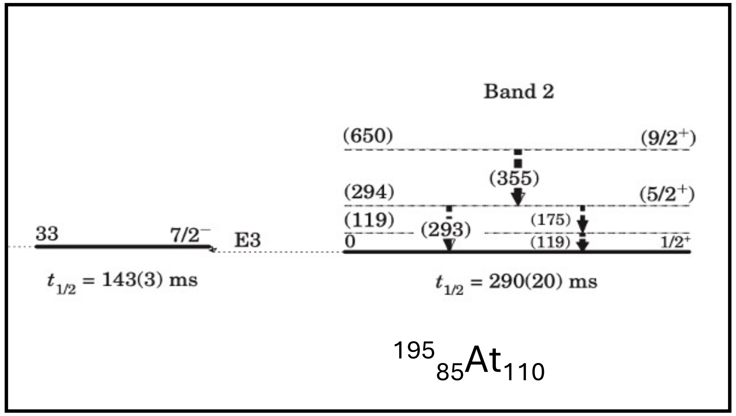
Neutron number decreases towards the mid-shell

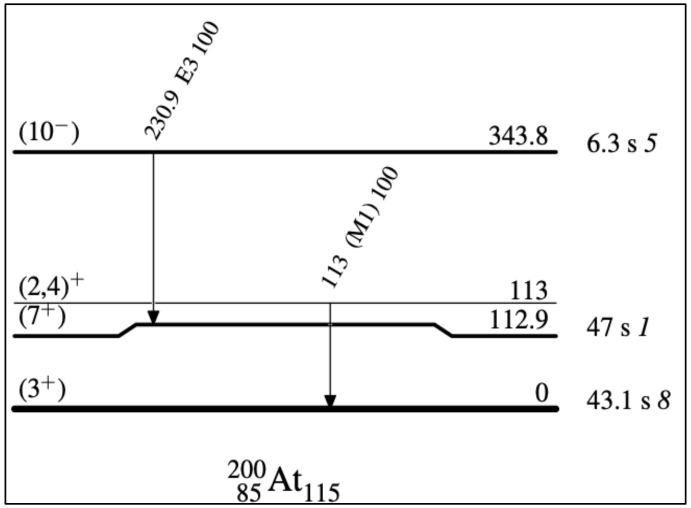
- Heavy mass nuclei → 9/2$^-$ ground state ($\pi h_{9/2}$)
- Light mass nuclei → 1/2$^+$ ground state ($\pi s_{1/2}^{-1}$)

→ Interpreted as the change of nuclear shape from spherical or near spherical to oblate

Neutron deficient odd-odd Bi (Z = 83), At (Z = 85) isotopes

- The effect of mid-shell neutron coupling with the protons
- Several possible configurations : multiparticle and multi-hole coupling across the shell closure
- In the neutron-deficient nuclei –
  - 3$^+$ → α–decaying ground state
  - 7$^+$, 10$^-$ → 2 α-decaying states – interconnected by E3

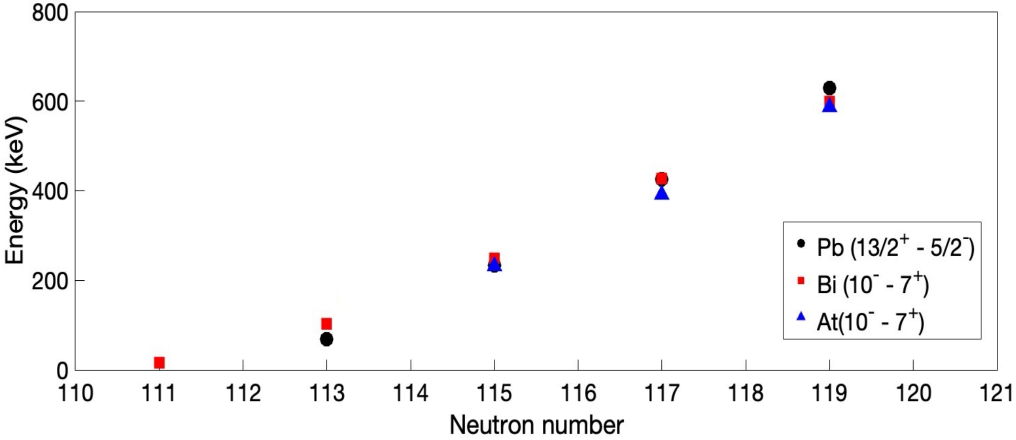




M. Nyman et. Al., PRC 88, 054320 (2013)

M. Huyse et. al., PRC 46, 1209 (1992)

Physics motivation for studying odd-odd neutron deficient At isotopes



The $10^- \rightarrow 7^+$ *E3* transition energy of odd-odd Bi, At isotopes
($13/2^+ \rightarrow 5/2^-$) Exc. Energy difference of odd Pb isotopes

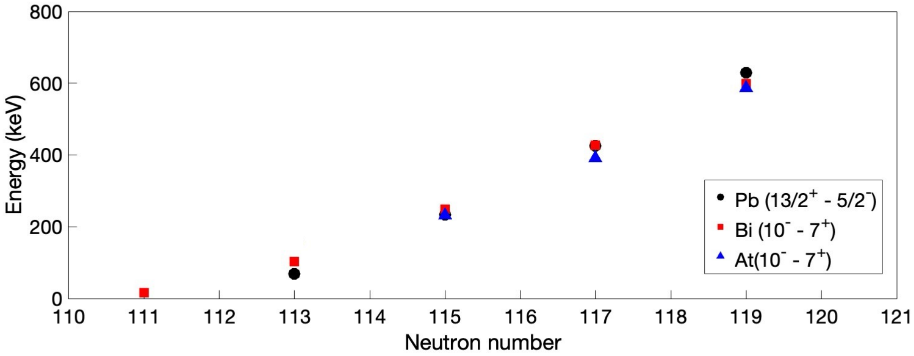
→ Proton coupling only acts as spectator

→ *E3* branch becomes fully internally converted

→ $\nu i_{13/2}$, $\nu f_{5/2}$ orbitals becomes lower in energy,

→ other low-lying spin multiplets

Physics motivation for studying odd-odd neutron deficient At isotopes



The 10^- → 7^+ *E3* transition energy of odd-odd Bi, At isotopes
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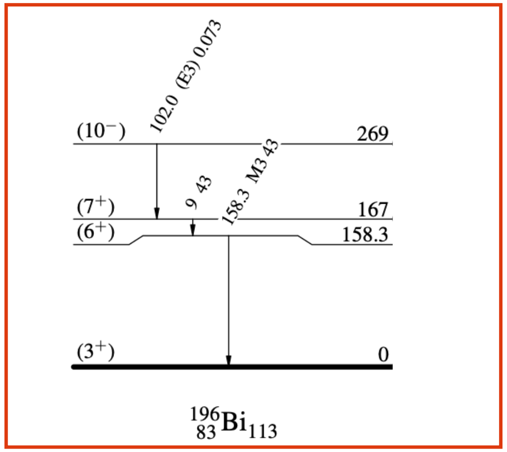
→ other low-lying spin multiplets

For ^{196}Bi, internal decay path of 10^- state already observed



P. Van Duppen et al, PRC 35, 5 (1992)

Internal decay path for the high-spin isomer states connecting to the 3^+ ground state

Search for the internal decay path of high-spin isomers of odd-odd exotic nuclei -^{198,196}At

Previous reported works on ^{196,198}At

Table of observed prompt γ-s

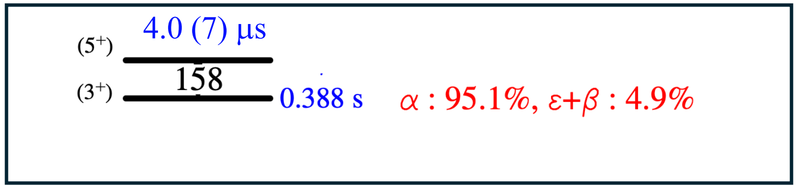
^{198}At		
	$\boxed{}$ 130.0(1)	64(9)
	$\boxed{136.7(2)}$	21(5)
	151.7(2)	20(7)
	155.5(9)	38(10)
	168.3(1)	33(6)
	173.7(2)	14(4)
	$\boxed{247.5(1)}$	54(8)
	$\boxed{279.1(2)}$	75(12)
	$\boxed{284.4(1)}$	100(14)
	304.9(5)	34(9)
	$\boxed{422.2(2)}$	17(6)
	486.5(4)	31(9)
	566.2(4)	42(11)
^{198m}At		
	$\boxed{136.2(2)}$	7(2)
	$\boxed{247.4(1)}$	30(5)
	$\boxed{279.1(3)}$	23(6)
	$\boxed{284.1(1)}$	81(10)
	413.3(2)	18(5)
	$\boxed{422.2(2)}$	53(9)
	551.9(1)	31(6)
	$\boxed{567.1(1)}$	100(14)

R-α tagged 3$^+$ ground state

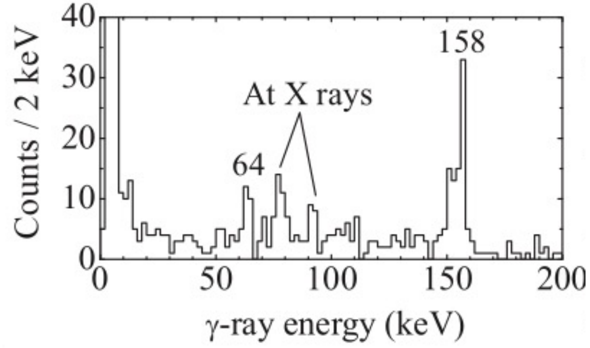
R-α tagged 10$^-$ state

R. B. E. Taylor et al., Phys. Rev. C 59, 673 (1999)

$^{196}_{85}$At$_{111}$



M.B. Smith et al., JPG Nucl. Part. Phys. 26(2000) 787



M. Nyman et al., PRC 88, 054320 (2013)

For ^{198}At (N = 113)

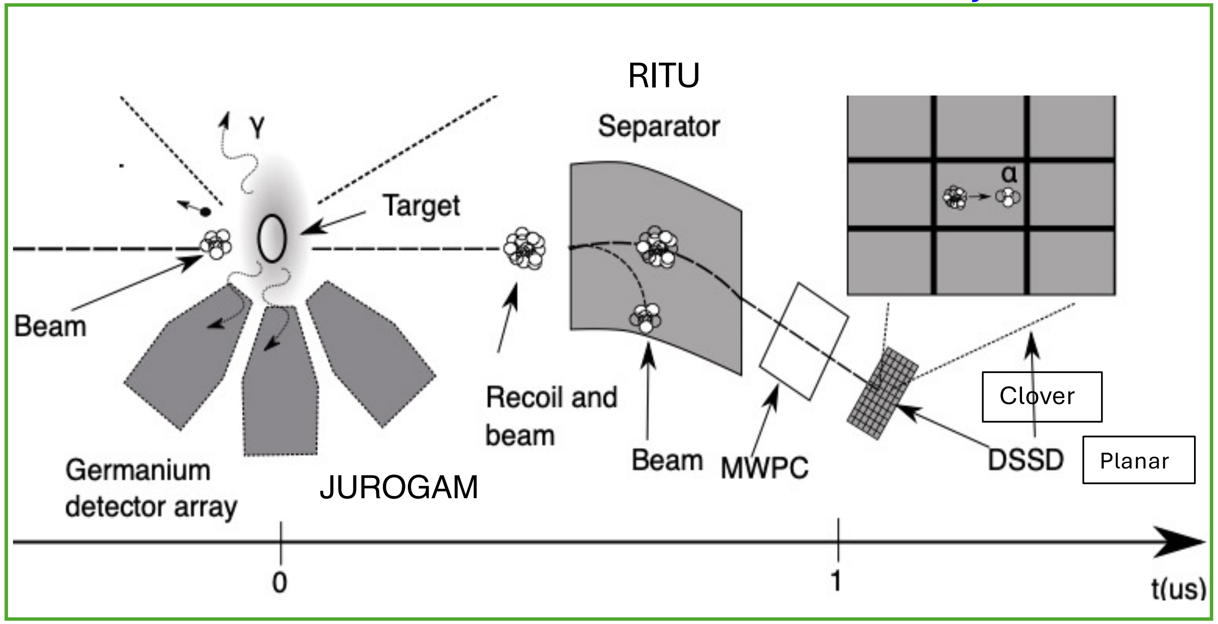
➢ Internal decay path for 10$^-$ state exist which connects to 3$^+$ state

For ^{196}At (N = 111)

→ Both 64 & 158 keV transition belong from the from the same cascade following from one isomeric state

Experimental details for ^{198}At

Accelerator Laboratory of the University of Jyväskylä

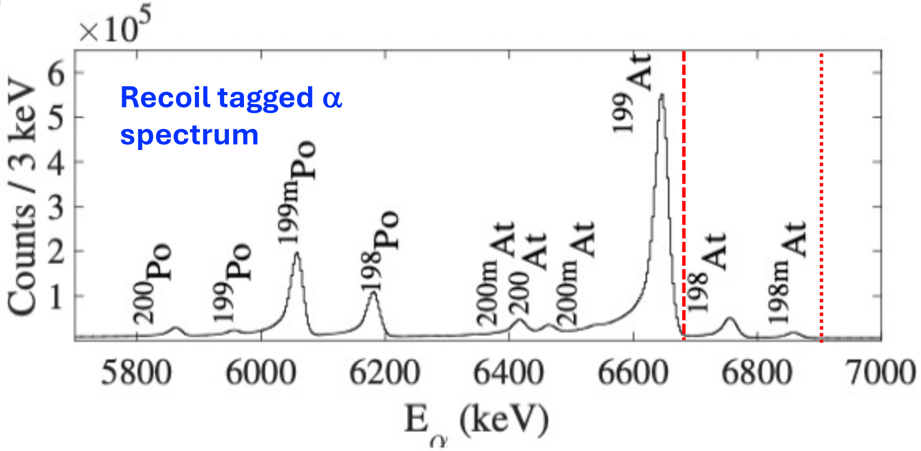


- Recoil products separated using Gas filled recoil Separator -RITU
- Implanted recoils in DSSD
- Correlated with subsequent α-decay

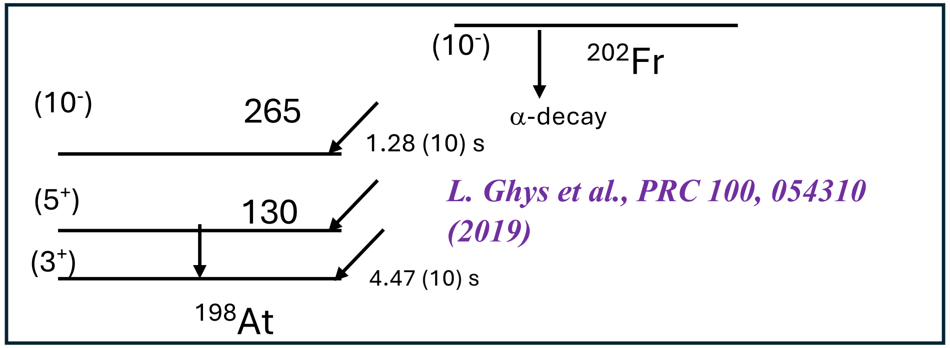
→ Recoil-decay tagging (RDT)

	E_α	b_α	$T_{1/2}$	Counts
3^+	6750 (4)	90%(10)	4.47 (10) s	3.9 x 10^5
10^-	6852 (4)	84%(16)	1.28(10)s	1.3 x 10^5

- ✓ **Reaction: ^{165}Ho(^{40}Ar, 7n)^{198}At**
- ✓ Beam energy: 205 MeV
- ✓ Beam intensity : 9 pnA
- ✓ Target thickness : 350 μg/cm^2
- ✓ Beam-Time: ≈ 10 days



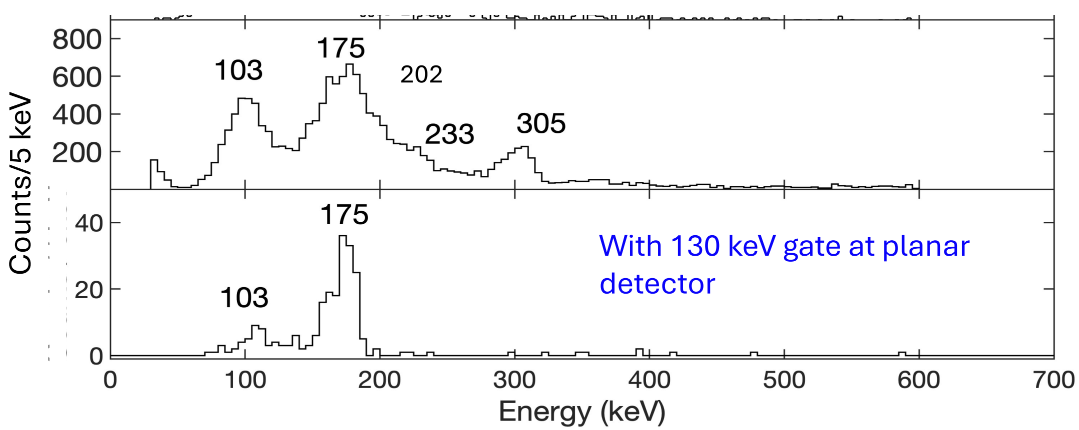
Results: Conversion electron and delayed γ-s in the focal plane



L. Ghys et al., PRC 100, 054310 (2019)

Recoil implantation → Internal Conversion from 10⁻ state → 3⁺ ground state α-decay

Recoil correlated conversion electron spectra Observed in DSSD



DSSD Conversion electron spectrum

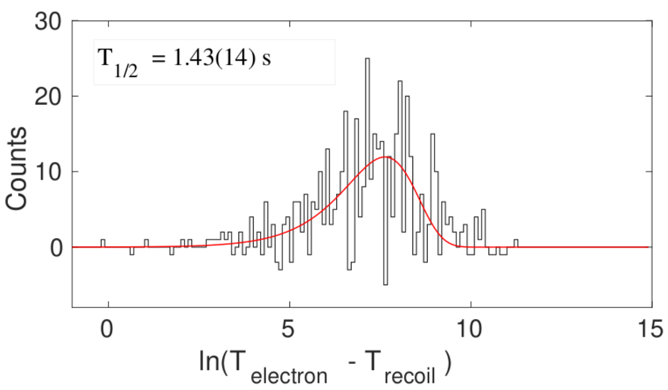
Recoil implantation

followed by Internal conversion , atomic relaxation

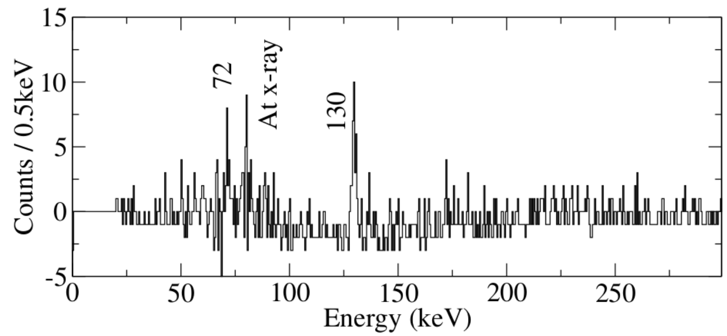
- **103 – 103 L+M+....**
- **175 – (103 +72) L+M+....**
- 202 – (130+72) L+M+....
- 233- (130+103) L+M+....
- 305- (103+130+72) L+M+....

not observed @130 keV gate

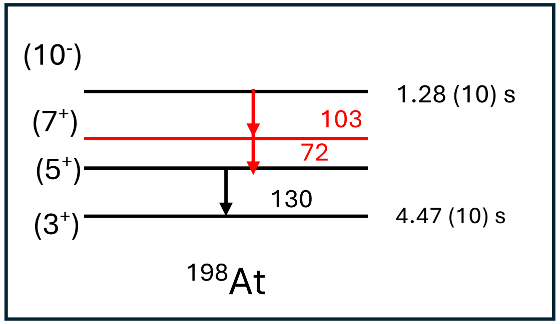
Delayed γ-s observed in focal plane Clover with Recoil-e-α tag



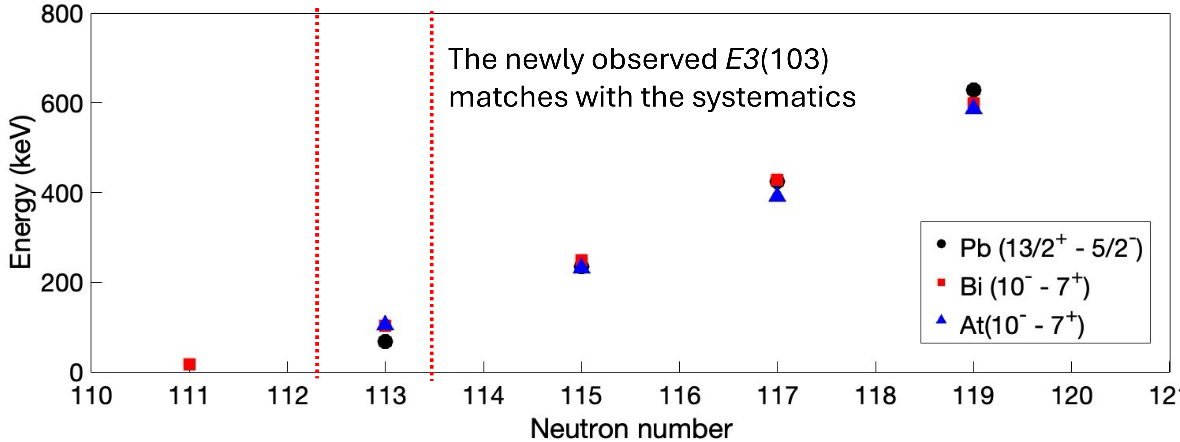
Logarithm of time difference between recoil implantation and c.e decay



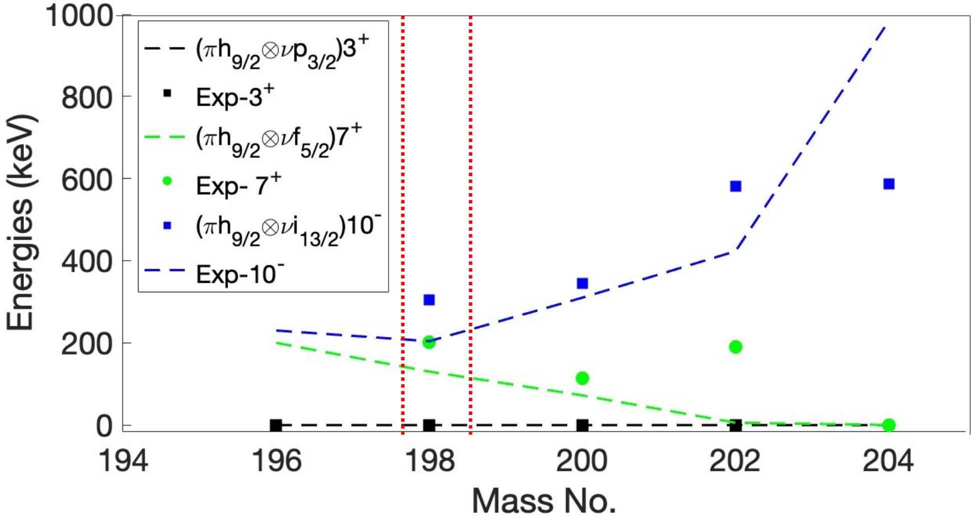
Results: First observation of an internal decay branch from 10^- state of ^{198}At



New level scheme of ^{198}At



- The $10^- \rightarrow 7^+$ *E3* transition energy of odd-odd Bi, At isotopes
- ($13/2^+ \rightarrow 5/2^-$) Exc. Energy difference of odd Pb isotopes



Interpretation of the experimental energy levels

The energies of the low-lying states → single-particle type

- Estimated from (j_p+j_n) of nearby Po & At isotopes
- Compared with the experimental energies reported for 3^+, 7^+ and 10^- states for odd-odd At isotopes
- ^{198}At values match well with the calculation

Experimental details

Accelerator Laboratory of the University of Jyväskylä

- ✓ **Reaction: ^{165}Ho(^{36}Ar, 5n)^{196}At**
- ✓ Beam energy: 186 MeV
- ✓ Beam intensity : 20 pnA
- ✓ Target thickness : 350 μg/cm^2
- ✓ Cross section: ≈ 30 μb
- ✓ Beam-Time: ≈ 10 days

- ➢ Recoil products separated using Gas filled recoil Separator -RITU
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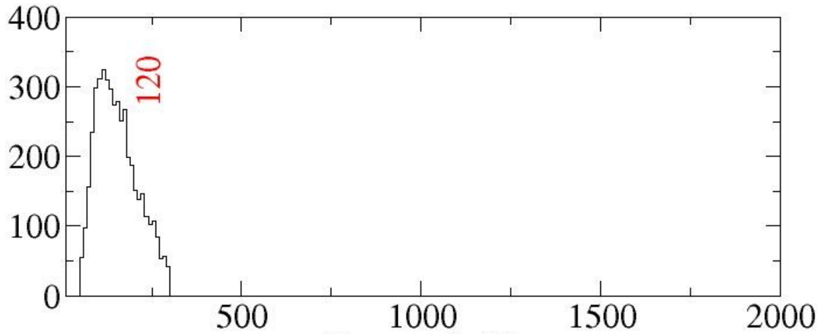
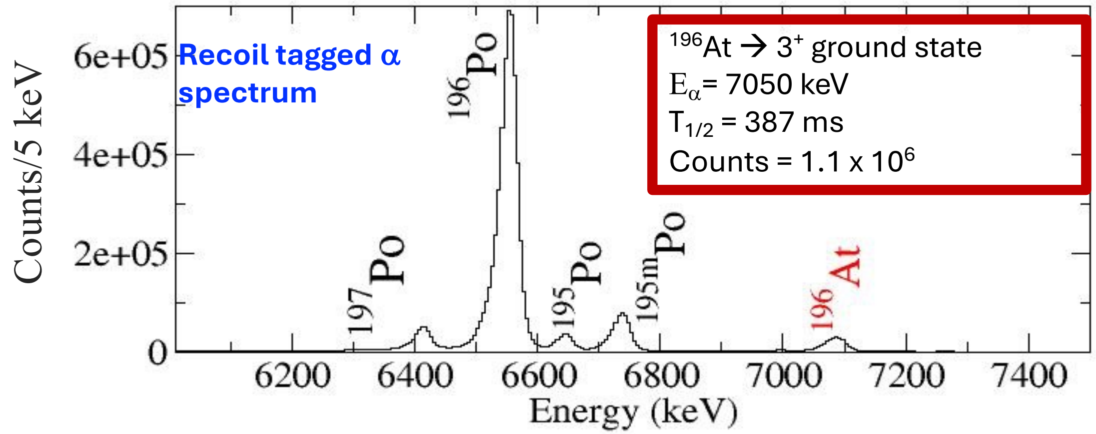
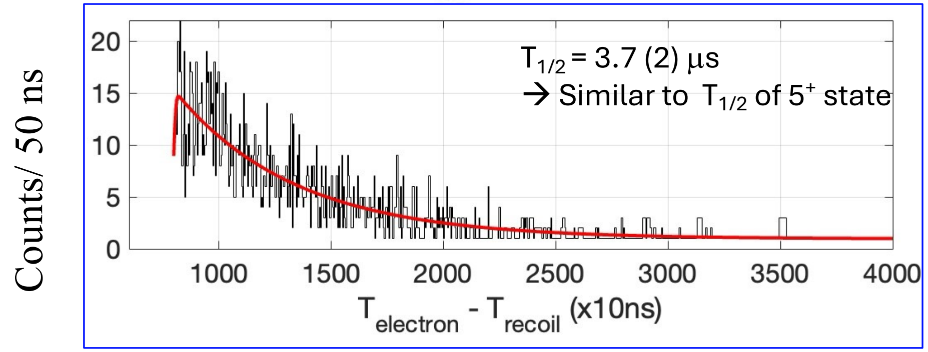
- ➢ Correlated with subsequent α-decay→ Recoil-decay tagging(RDT)

Recoil correlated conversion electron spectrum followed by ^{196}At α-decay



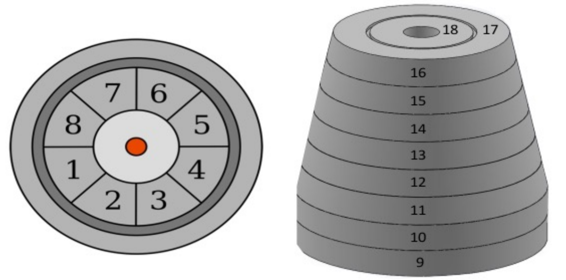


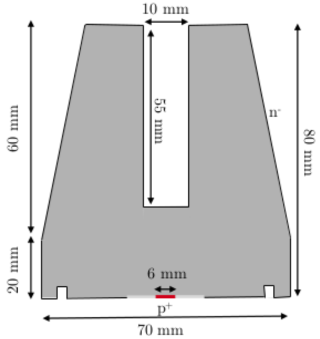


Existence of internal decay path of high-spin isomer which connects to the ground state
Further analysis is still in progress !!

Installation of a new detector SIGMA in the focal plane

SIGMA (Segmented Inverted-coaxial GerMAnium) detector





Point-Contact technology + segmentation of outer contacts
Segmentation Scheme

- **1- 8 azimuthal segments,**
- **9-16 longitudinal segments**
- **2 concentric segments (17, 18)**
- **19 readout channels including the point contact(PC)**

P-type germanium
inverted-coaxial detector
Height – 80 mm
Diameter –70 mm
Volume ~ 240 cm^3

- The small size of the point contact - low capacitance – better energy resolution- 0.2% at 1.4 MeV
- Inverted Co-axial- much longer drift paths for the holes- ideal for good position resolution keeping the number of channels to lower

Applications of SIGMA

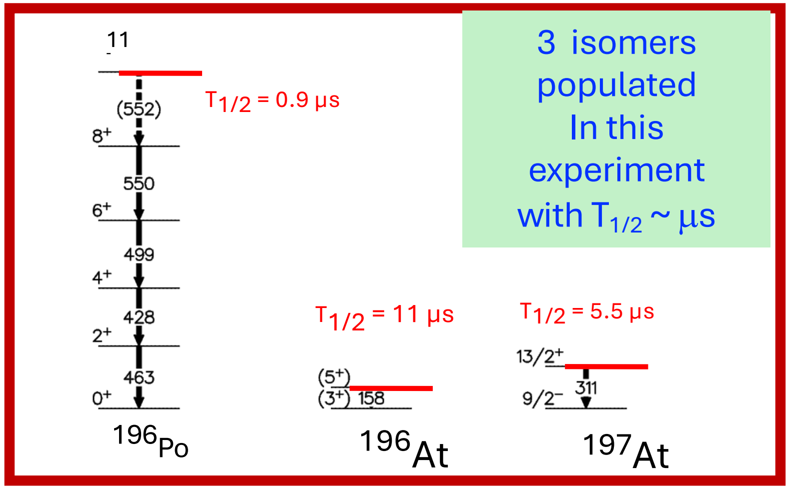
- **Spectroscopic gamma-ray imaging**
- **Tracking detector for decay experiments**

Applications of SIGMA in this experiment

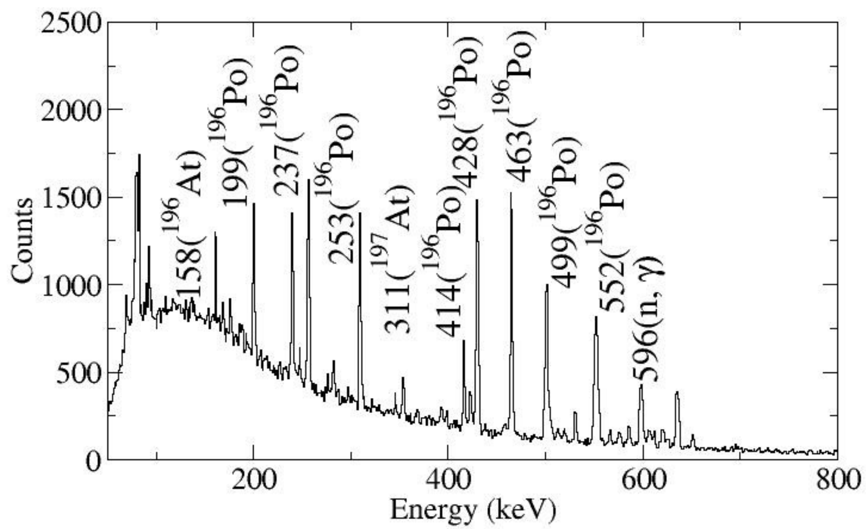
Commissioning experiment **SIGMA installed in the focal plane in place of one BeGe detector**

- Spectroscopic detector with promising energy resolution
- Gamma ray tracking and imaging device-
  - ✓ To track gamma rays back to the DSSD with Pulse Shape Analysis (PSA) technique
  - ✓ To correlate/veto-out the events generating from the isomeric decays of the implanted exotic ions.

SIGMA as spectroscopic detector

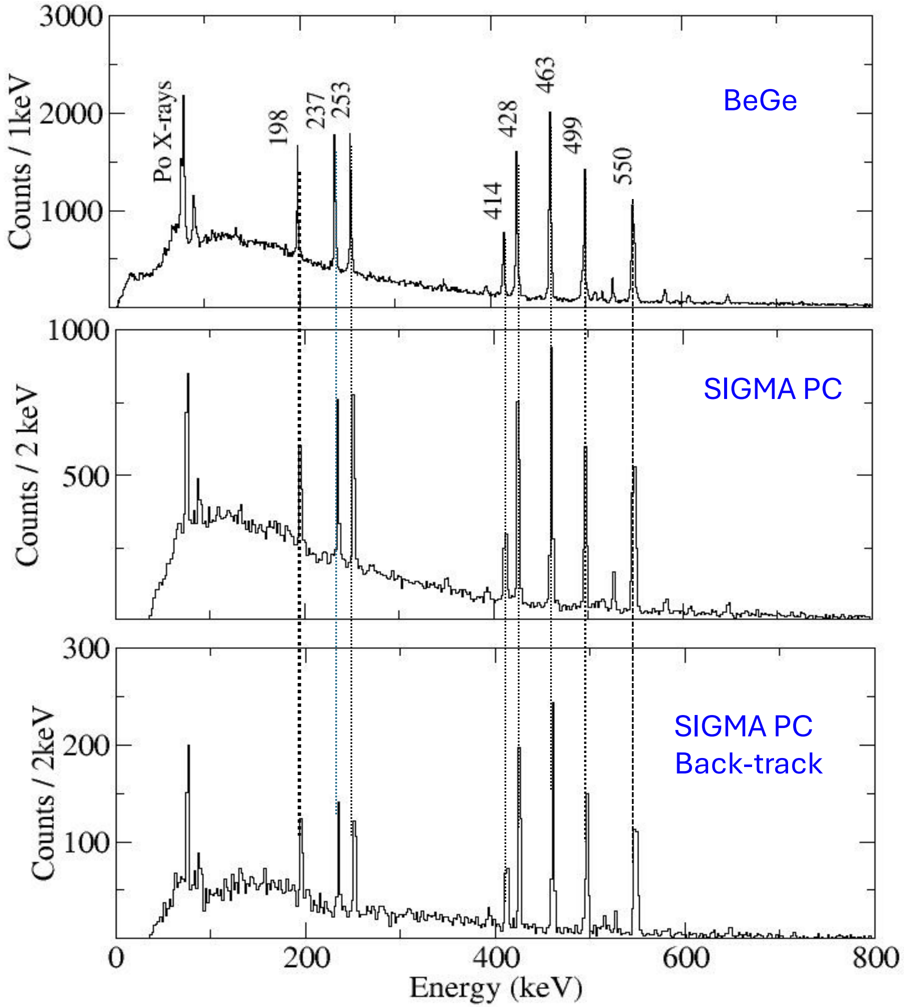


Recoil-correlated SIGMA spectrum



Comparison of SIGMA PC spectra before and after back-tracking with BeGe

Recoil- α tagged spectra for ^{196}Po



19 Segment traces, energies

Pulse-shape analysis (PSA)

γ-ray Interaction positions

Simple Back-projection (SBP)algorithm

DSSD position (x,y)

Spectrum	**Energy Resolution @1460 keV**	**P/B @ 550 keV**
BeGe (3)	0.24%	1.57(4)
SIGMA PC	0.27%	1.87(9)
SIGMA PC- Back-track	**0.27%**	**2.6(3)**

- P/B ratio significantly improves after vetoing out background from the initial analysis
- Further analysis is still in progress to achieve more optimized results

Summary & Future plans

Summary

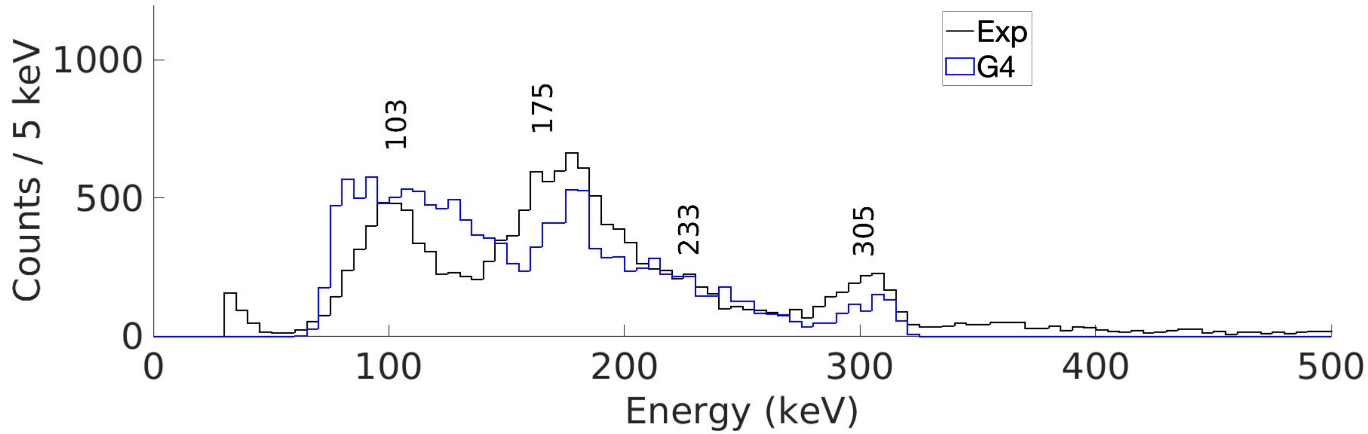
- The internal decay path of the high spin states odd–odd At isotopes investigated
  - For ^{198}At
    The new decay path connecting 10^- to 3^+ has been established
  - For ^{196}At
    - The indication of internal decay path is observed
    - The performance of the novel detector SIGMA was tested as a spectroscopic & tracking detector

Future plans

- Finalization of low-lying level structure of ^{196}At
- To optimize PSA and back-tracking algorithm to get more refined output from SIGMA

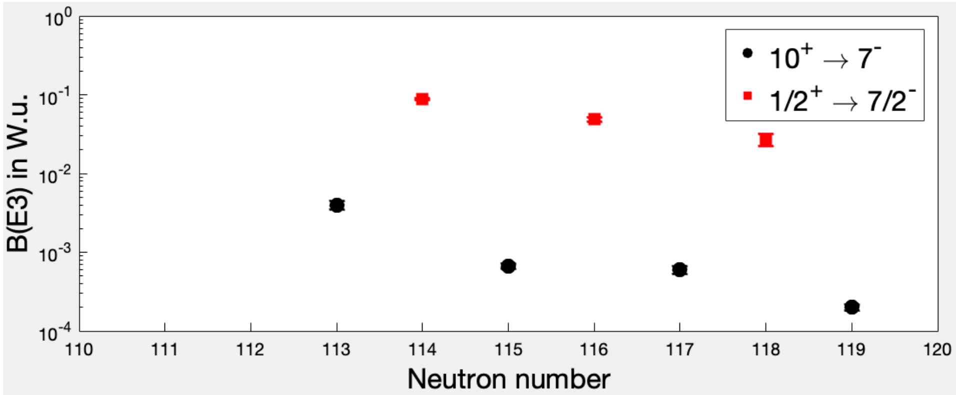
Thanks to Collaborators

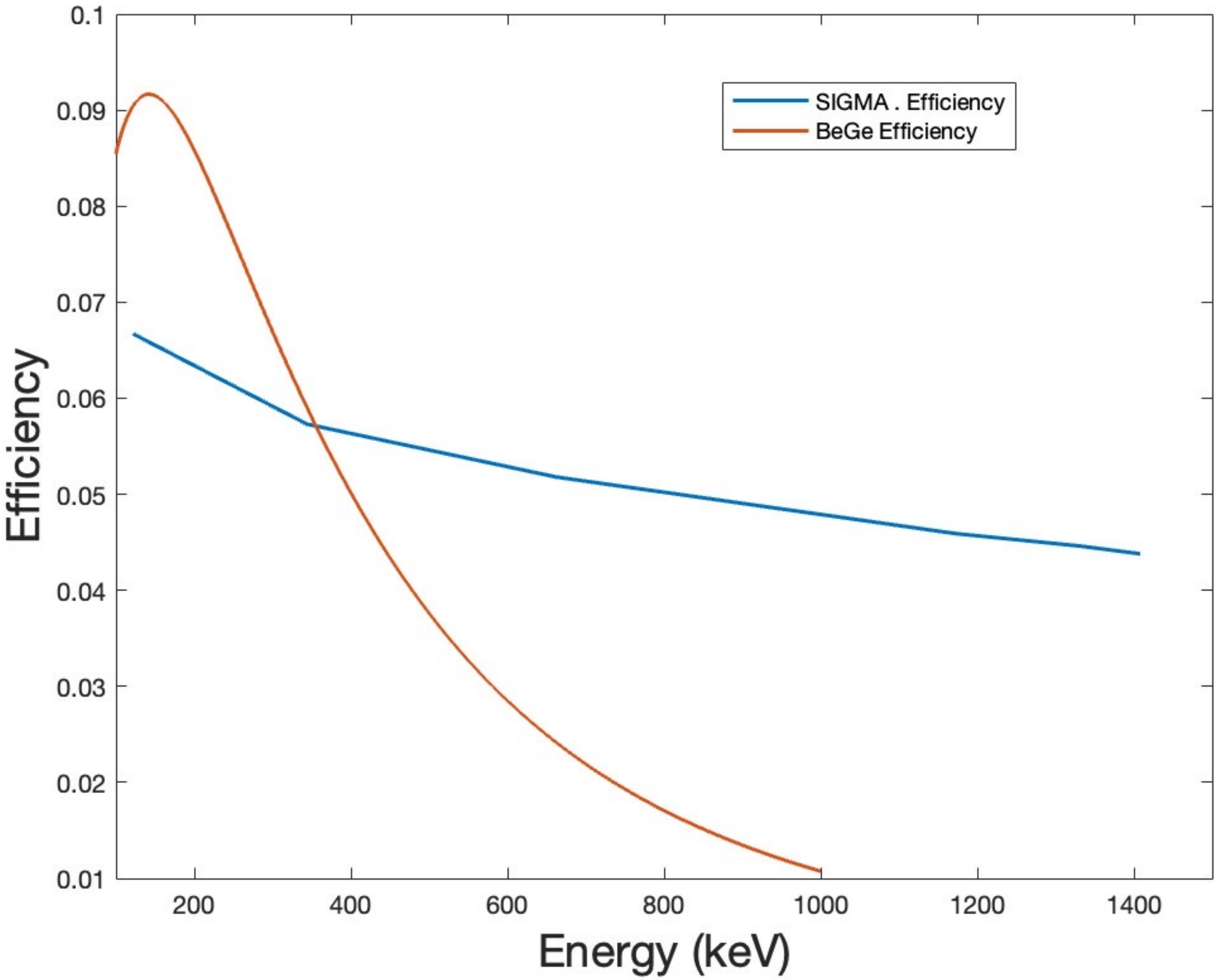
Backup slides

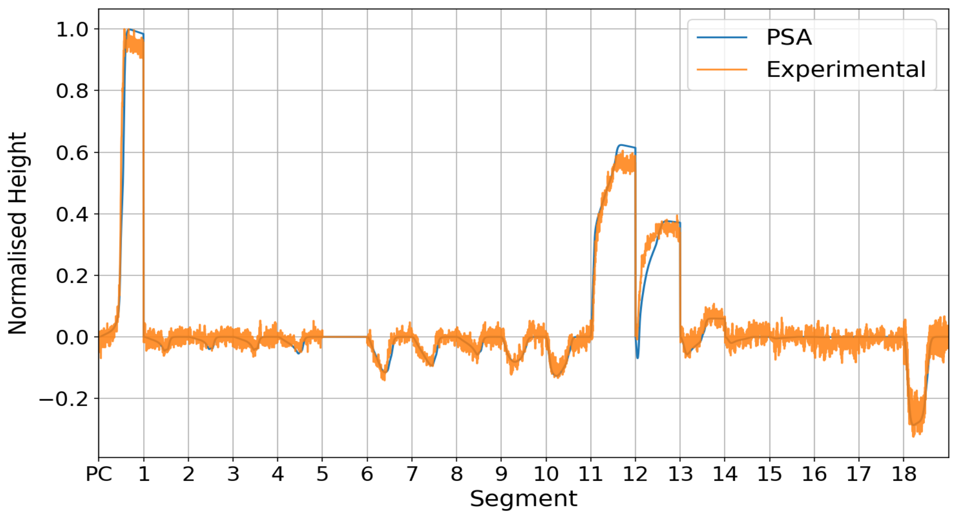


- For 103 (E3) → 72 (E2) → 130 (E2) keV cascade
- Considering all K,L subshell relaxations according to their multipolarities
- Matches quite well with the experimental one
- This actually in turn validates the internal decay path of the 10- state as 103 → 72 → 130

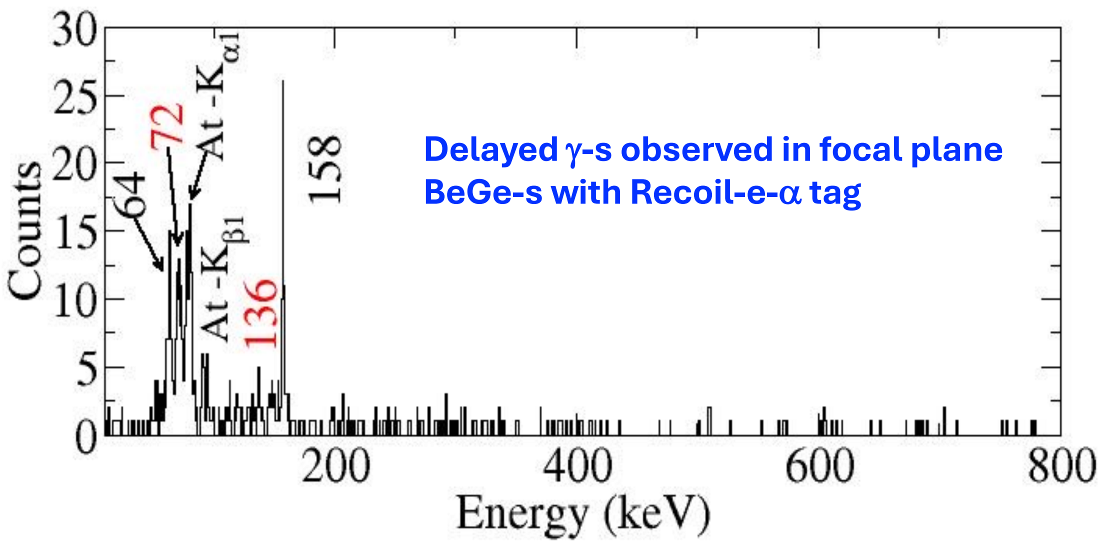
B(E3) branching of 198At




SIGMA . Efficiency
BeGe Efficiency
Efficiency
Energy (keV)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
200
400
600
800
1000
1200
1400

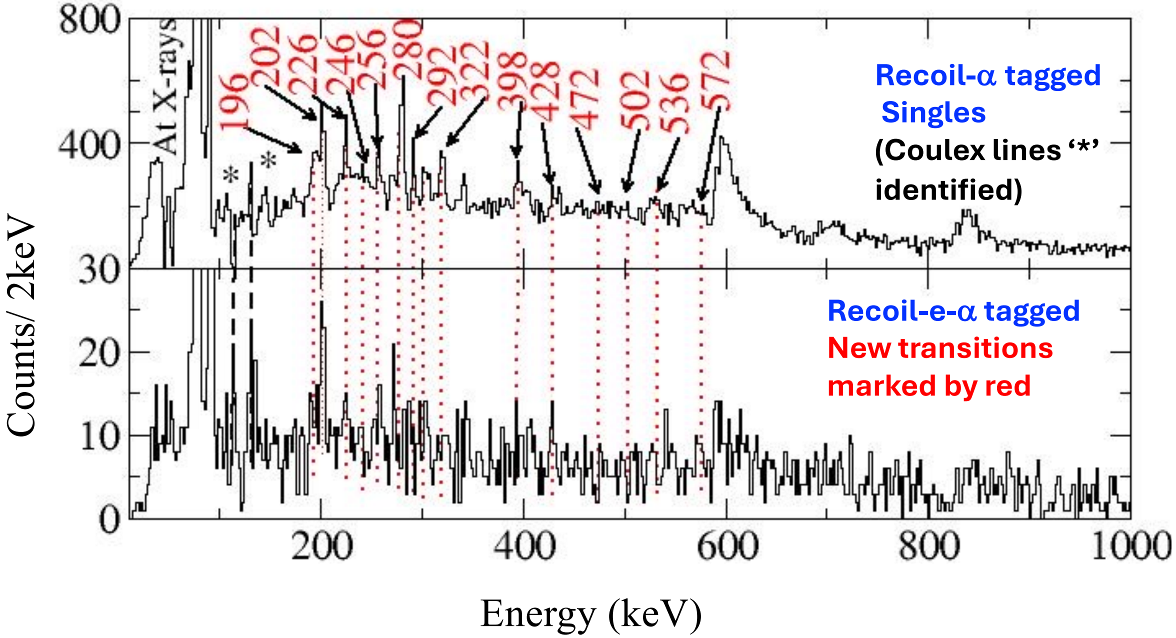


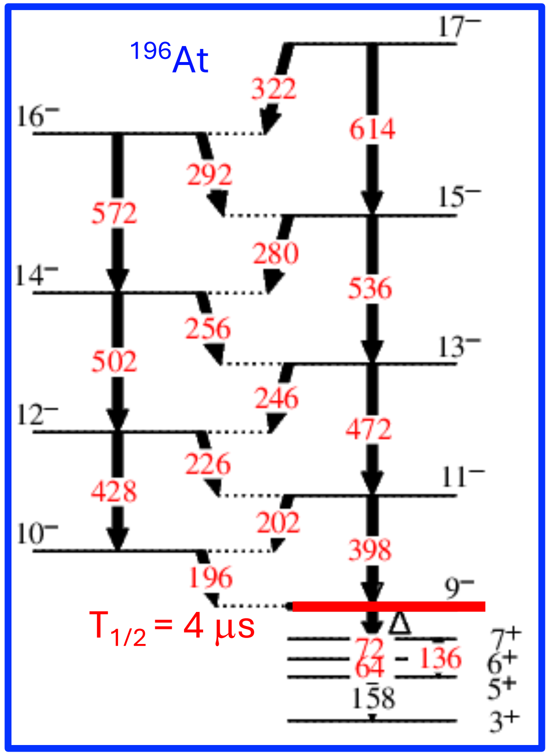
Comparison of the experimental signals to the validated simulated database


Delayed γ-s observed in focal plane
BeGe-s with Recoil-e-α tag
Counts
Energy (keV)
64
72
At -Kα1
At -Kβ1
136
158
0
5
10
15
20
25
30
200
400
600
800

Results: High spin states above the isomer & preliminary level scheme

Prompt γ-rays observed in JUROGAM3 array





Level scheme proposed from the present experiment(preliminary)

Most of the prompt and delayed γ–s observed in R-α tagged are also observed in R-e-α tagged spectra

→ High spin structure is connected to the ground state via delayed γ -decays