Mysteries of the decay of the heaviest proton-emitting nucelus ^{185}Bi

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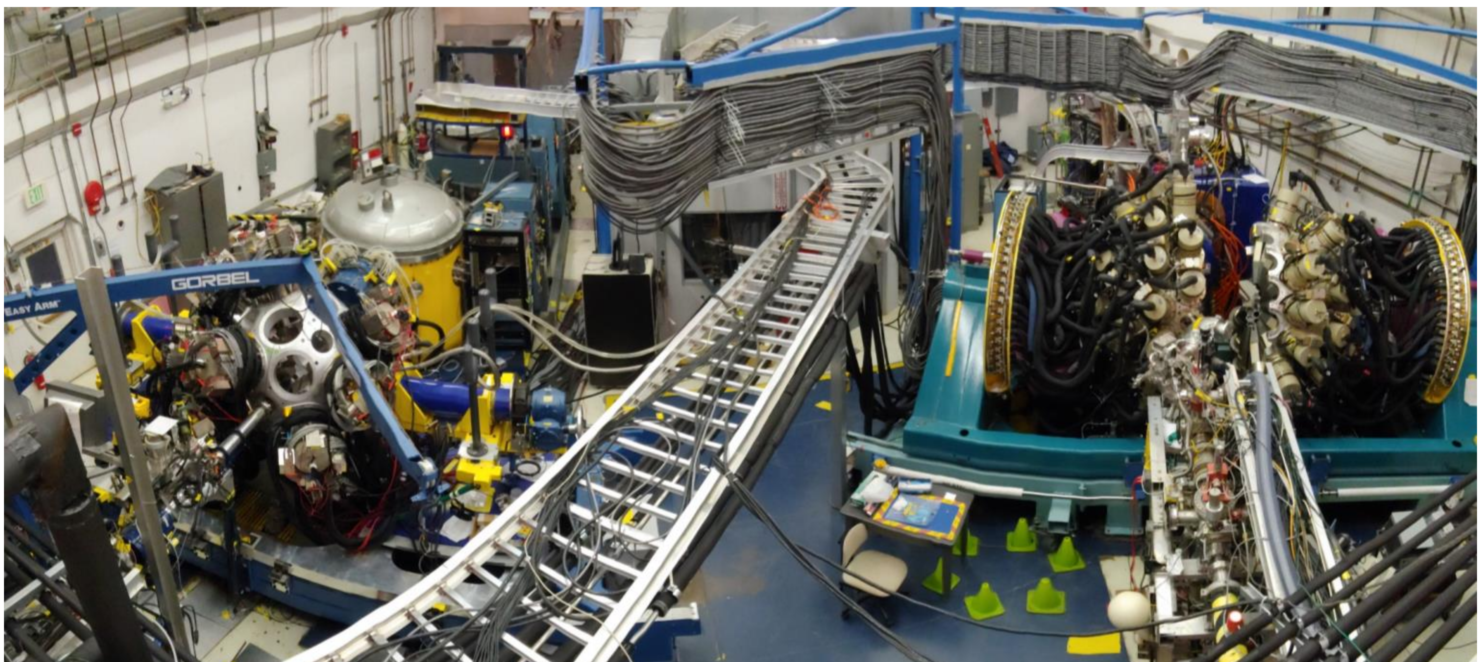


SSNET 2022, 30th May 2022

UNIVERSITY OF SURREY

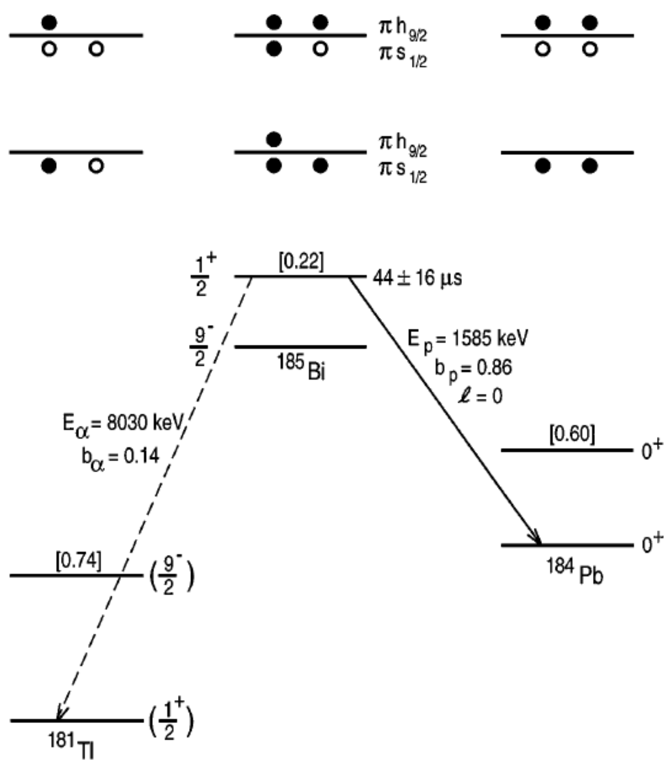
Heaviest Proton Emitter – ^{185}Bi (1)

Heaviest proton emitter is **^{185}Bi** (Z=83). This is the only one that decays to a daughter nucleus with a major shell closure – ^{184}Pb (Z=82)

- Discovered in 1996 by C. Davids at the FMA
  => **New region of proton radioactivity**

- E_p = 1.6 MeV and small α-decay branch also observed (7 protons and 1 alpha)

- Suggested that both proton and alpha emission were from an **intruder state**

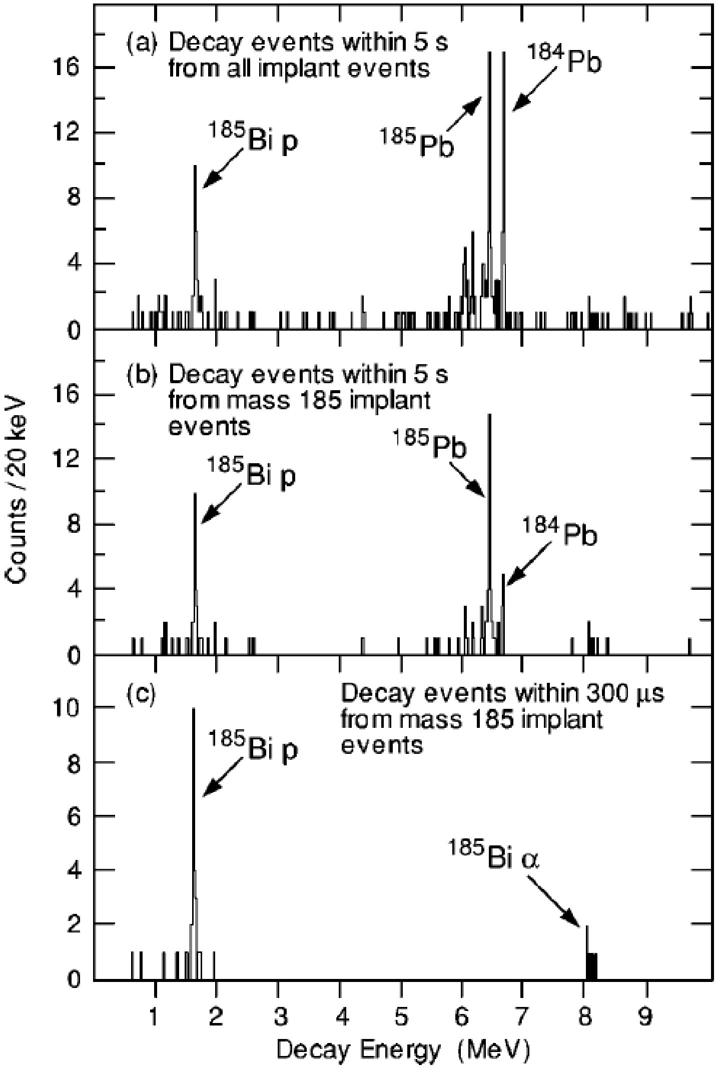


C.N. Davids *et al.*, PRL **76** 592 (1996)

Heaviest Proton Emitter – ^{185}Bi (2)

Improved statistics obtained in a further FMA study (Poli *et al.*)

- 23 protons and 5 alpha decays
- Dedicated proton calibration performed (^{147}Tm)
- **Configuration hinderance**/ shape change in decay invoked to explain decay half-life ($T_{1/2}$ = 49(7) μs)
- Suggestion that 1/2+ state could lie below the spherical $h_{9/2}$ orbital

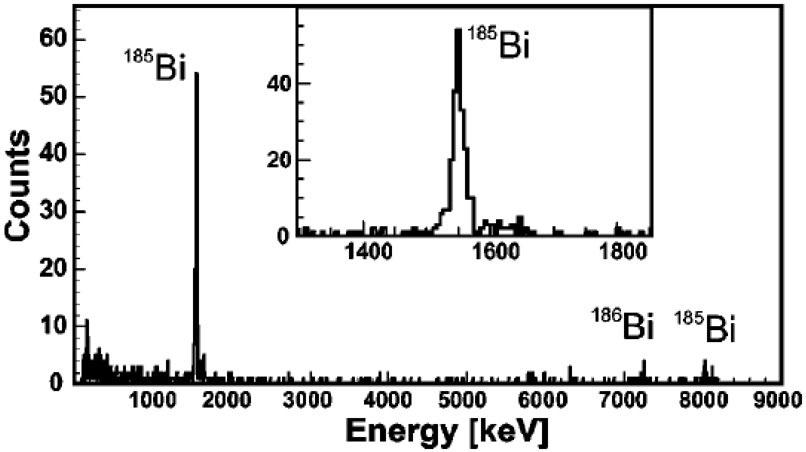


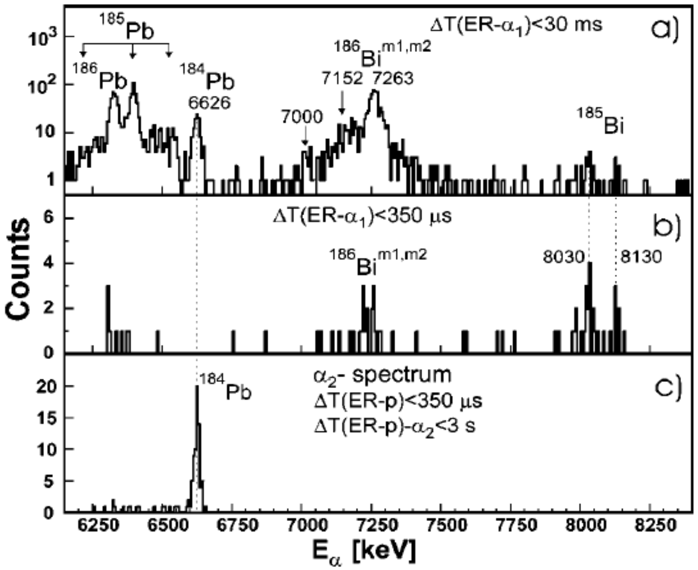
G.L. Poli *et al.,* PRC **63** 044304 (2001)

Heaviest Proton Emitter – ^{185}Bi (3)

Subsequently studies with the velocity filter SHIP at GSI

- Higher statistics data set (214 protons and 24 alpha decays)
- Used ^{93}Nb(^{95}Mo,3*n*) reaction instead of ^{95}Mo(^{92}Mo,*pn*) one used at FMA
- Interpretation supported by potential-energy surface calculations
- b_p **= 90(2) %,** b_α **= 10(2)%**





A.N. Andreyev *et al.,* PRC **69** 054308 (2004)

Unusual Case of ^{185}Bi

Decay, $l_p = 0$ ($1/2^+ \rightarrow 0^+$) to a daughter with a major shell closure should be a benchmark for the theory of proton emission, but

- Half-life of ~60 μs indicates strong hinderance and a spectroscopic factor of 0.025
  => mixing between ground state and a deformed 0^+ state at 570 keV in ^{184}Pb daughter?)

ΔL	$T_{1/2,p}^{\mathrm{WKB}}$ (μs)	S^{expt}
0	1.7	0.025(2)
1	3	0.045(4)
2	10	0.150(13)
3	70	1.05(8)
4	800	12(1)
5	15000	224(20)

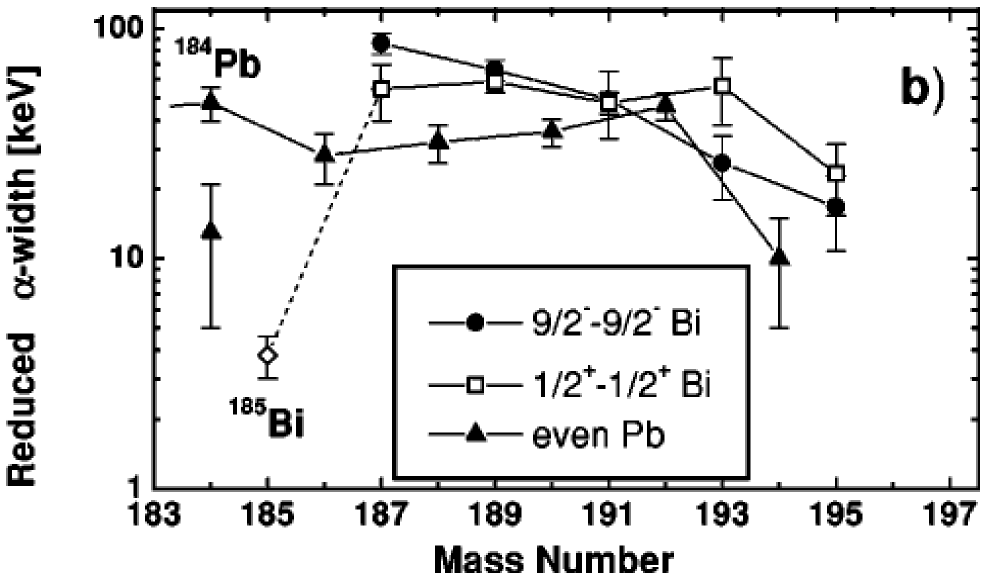
decay from $s_{1/2}$ (row ΔL = 0)

decay from $h_{9/2}$ (row ΔL = 4)

$$S^{exp} = \frac{T_{1/2}^{WKB}}{T_{1/2}^{exp}}$$

Unusual Case of ^{185}Bi

- Alpha decay also significantly hindered relative to neighbouring isotopes



Reduced alpha widths for L=0 alpha decays in odd-mass Bi isotopes and neighboring even-even Pb

- No $9/2^-$ level has been observed in ^{185}Bi, in contrast to $^{187-209}$Bi which all have $9/2^-$ ground states

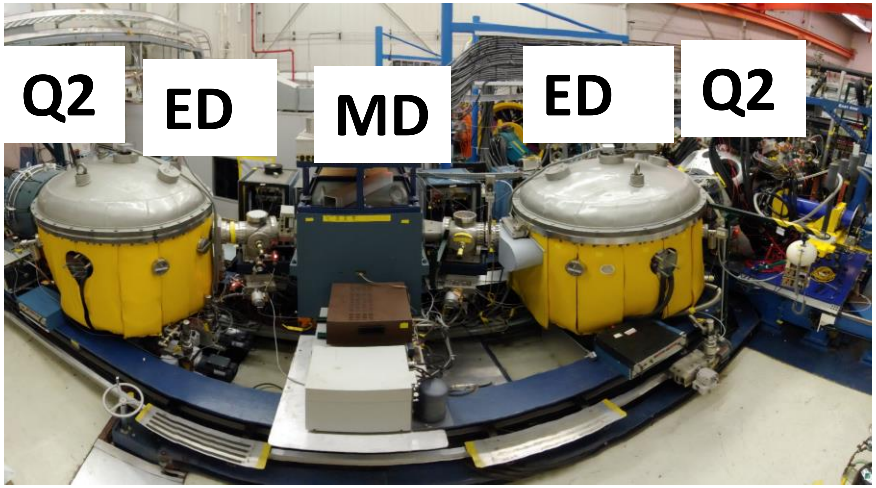
Experimental Introduction

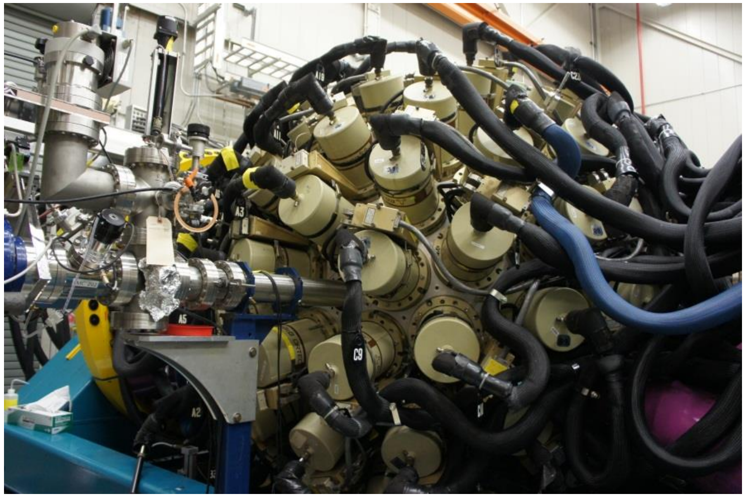
Proton-rich nuclei populated in fusion reactions and then examined in decay and recoil-decay tagging experiments

- A number of experimental challenges (small cross sections, large data rates, backgrounds etc). **Digital DAQ**.

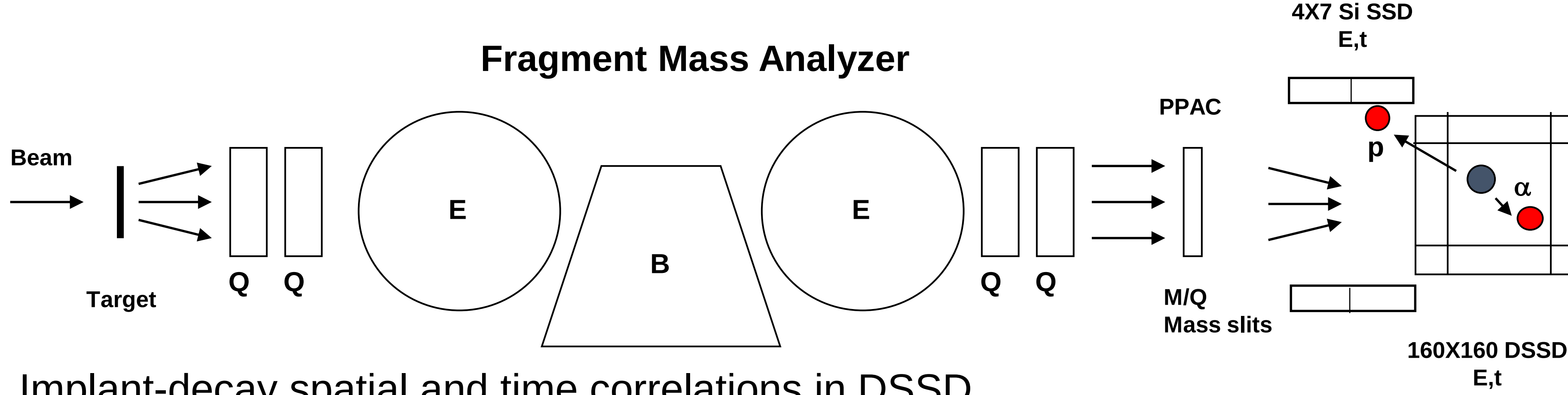
FMA experiment

- ^{93}Nb(^{95}Mo,3n)^{185}Bi reaction
- Beam intensity of ~20 pnA in an experiment lasting ~105 hours
- Gammasphere + FMA + DSSD + BOX + X array



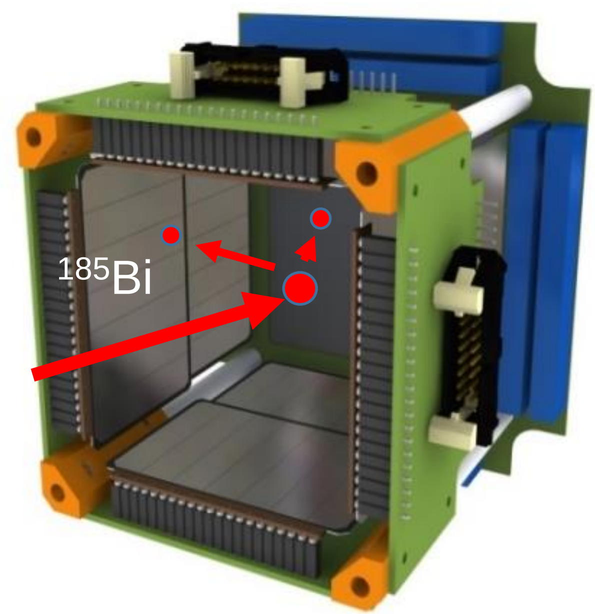


Recoil-Decay Correlation Measurements with FMA

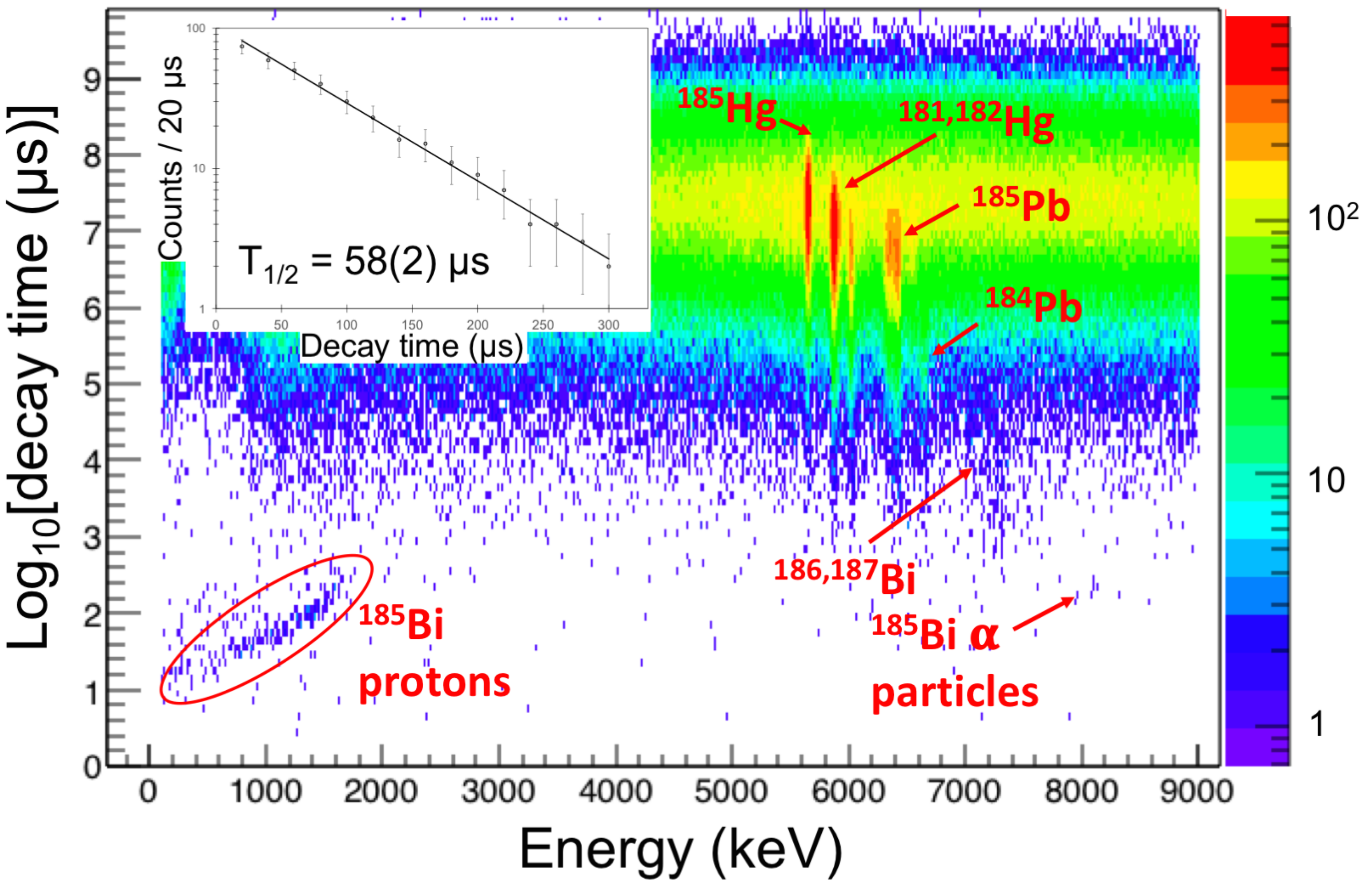


Implant-decay spatial and time correlations in DSSD
Digital DAQ to detect PU waveforms, 100 MHz clock
Si box to catch escaping particles, Ge detectors at focal plane

Argonne 'X-array' of 5 HPGe detectors installed at the focal plane

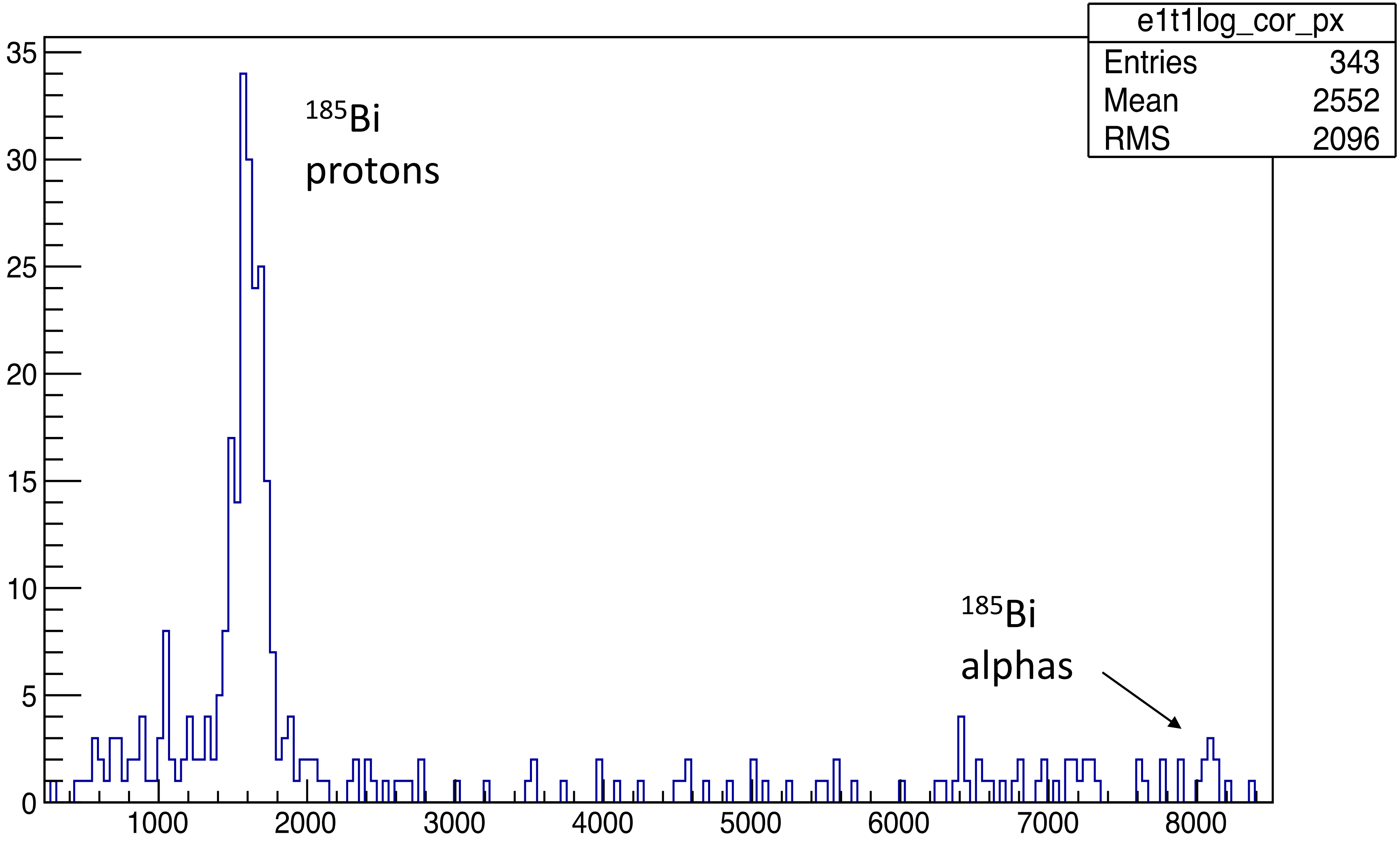


Recoil - charged particle decay correlations



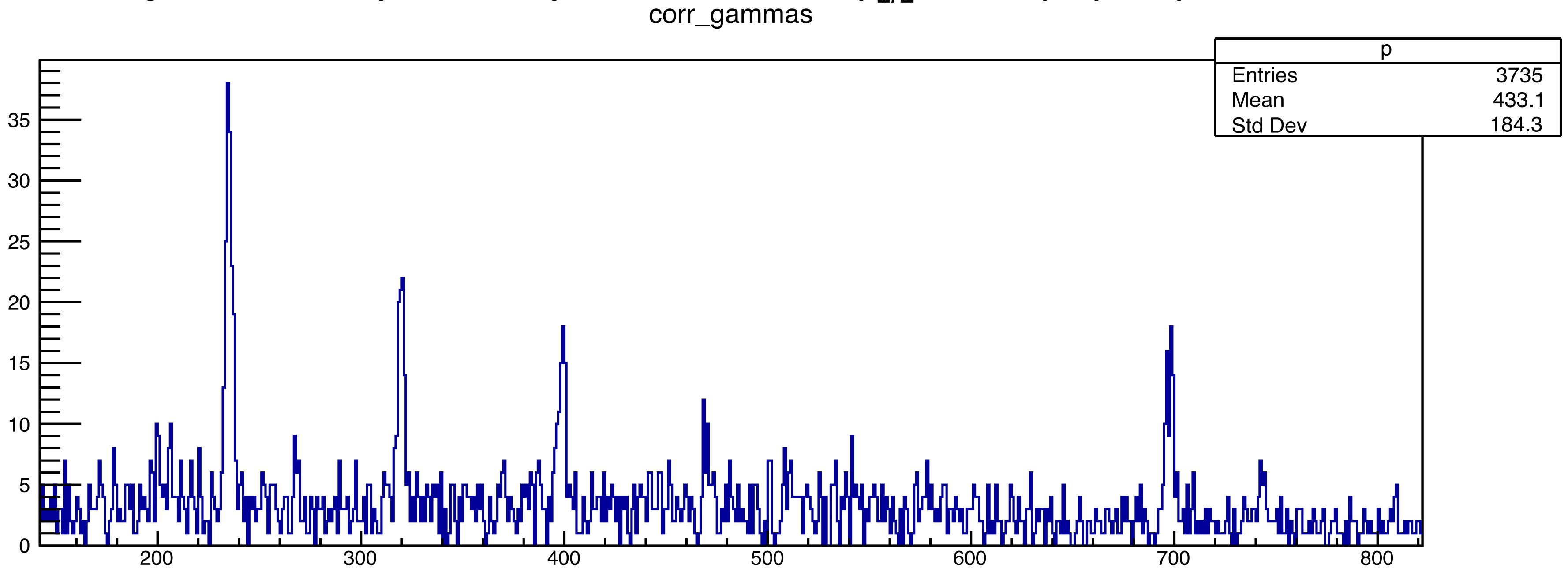
Recoil - charged particle decay correlations

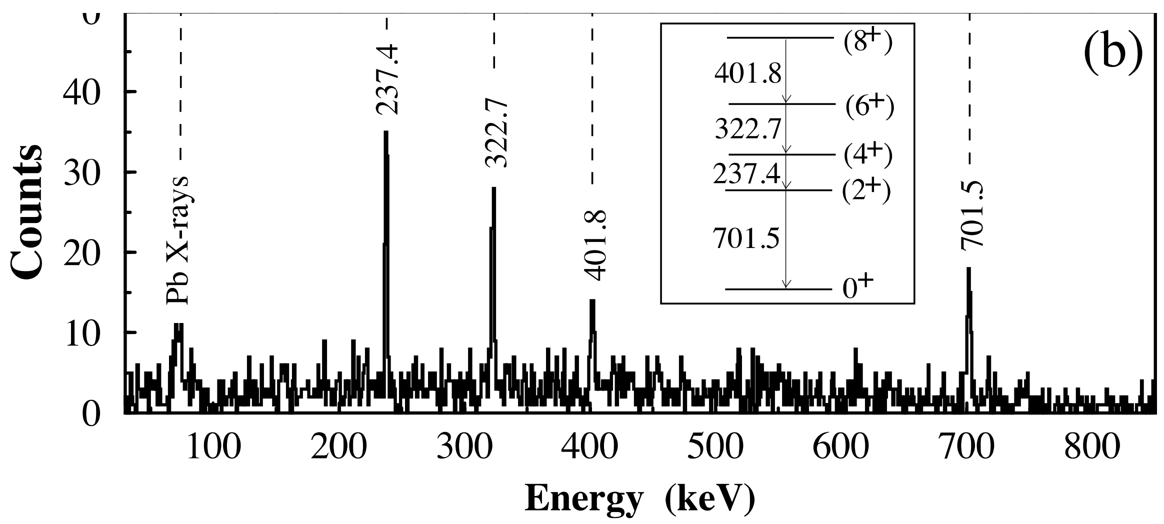
Decays < 300 μs with parabolic energy correction applied



Recoil decay tagging (RDT) analysis – ^{184}Pb

Gating on ^{184}Pb alpha decays in the DSSD ($t_{1/2}$ = 490(25) ms)

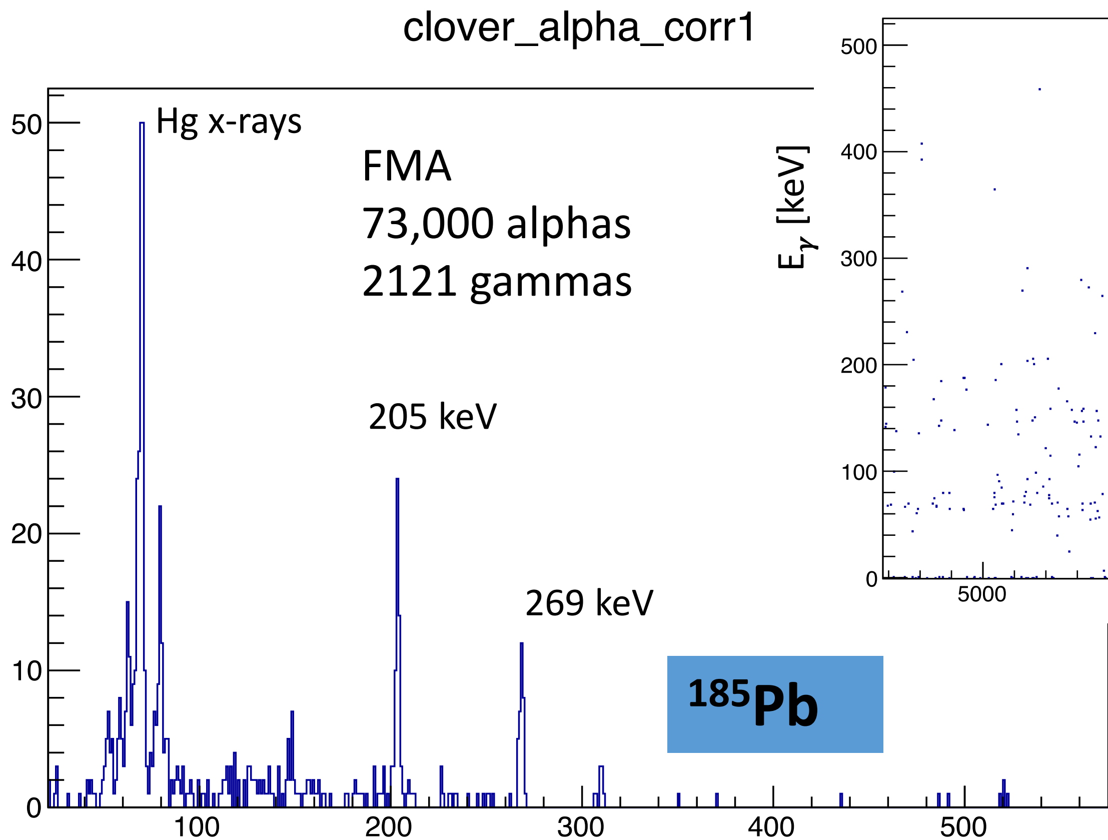


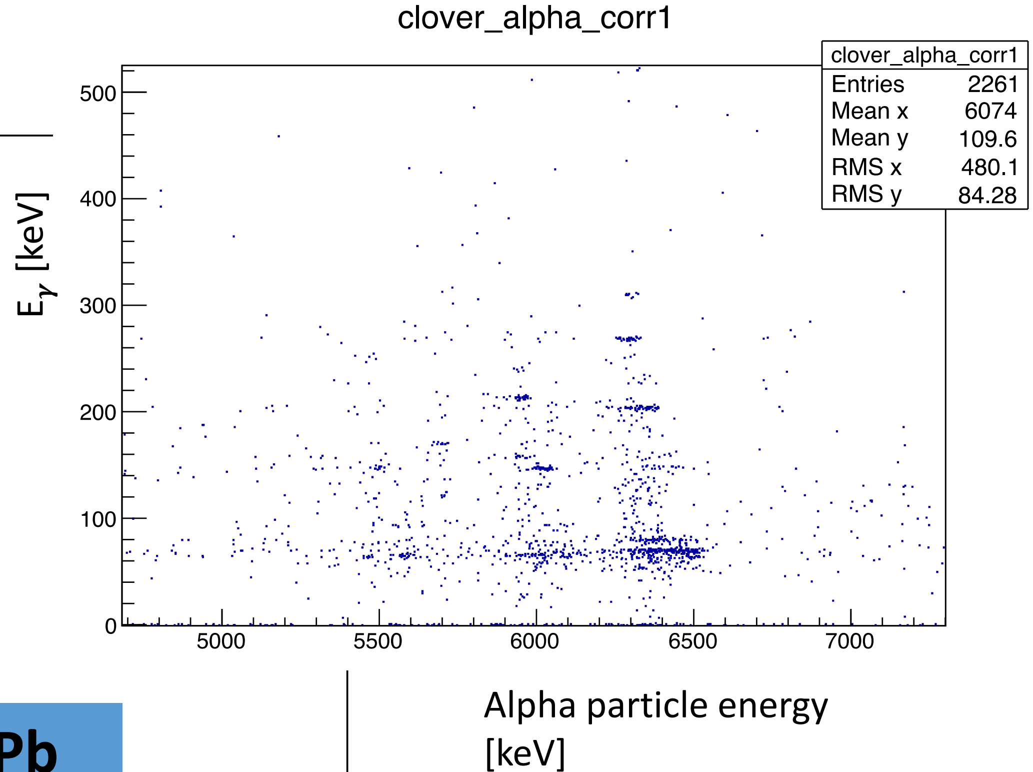


Confirms and **<u>slightly</u>** expands the level scheme proposed by Cocks et al., EPJA **3** 17 (1998)

Decay Correlated Gamma Rays at the Focal Plane

Argonne ‘X-array’ of 5 HPGe detectors installed at the focal plane. Setup benchmarked with well-known α-γ coincidences





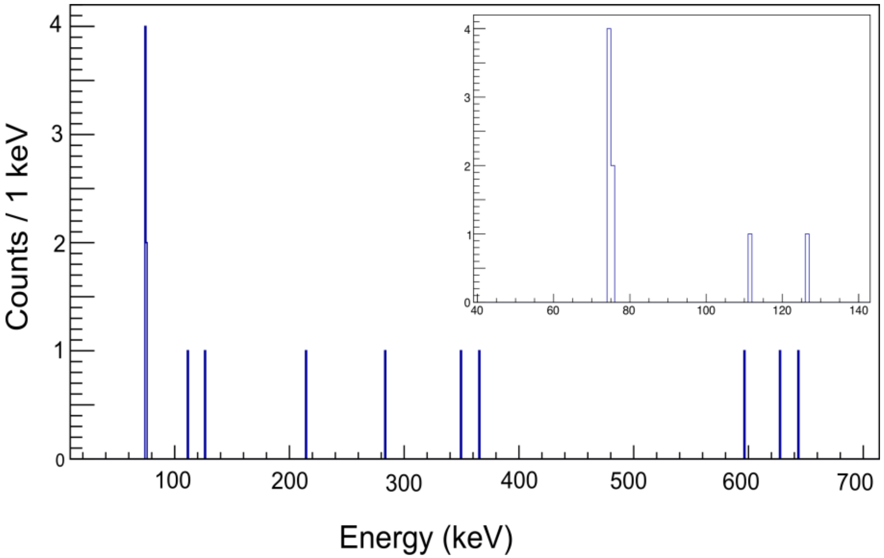
Results in good agreement with results from ISOLDE - A.N. Andreyev et al., EPJA **14** 63 (2002)

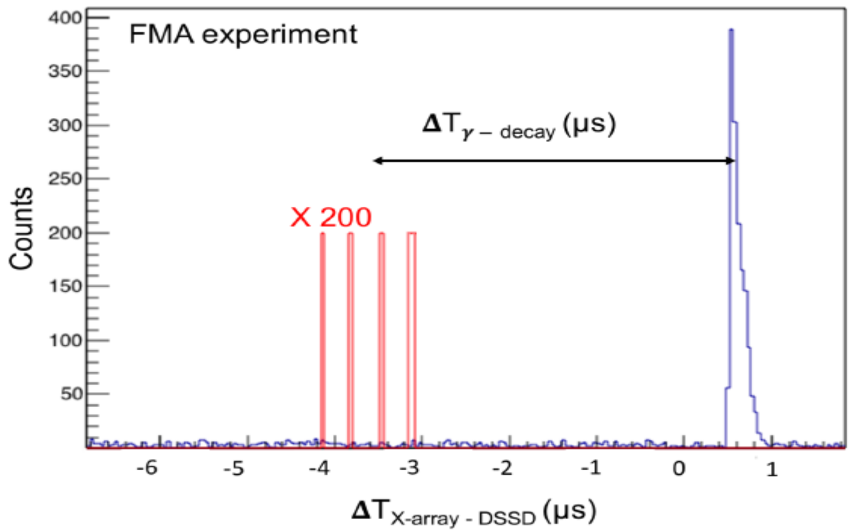
Decay Correlated Gamma Rays at the Focal Plane

Argonne 'X-array' of 5 HPGe detectors installed at the focal plane

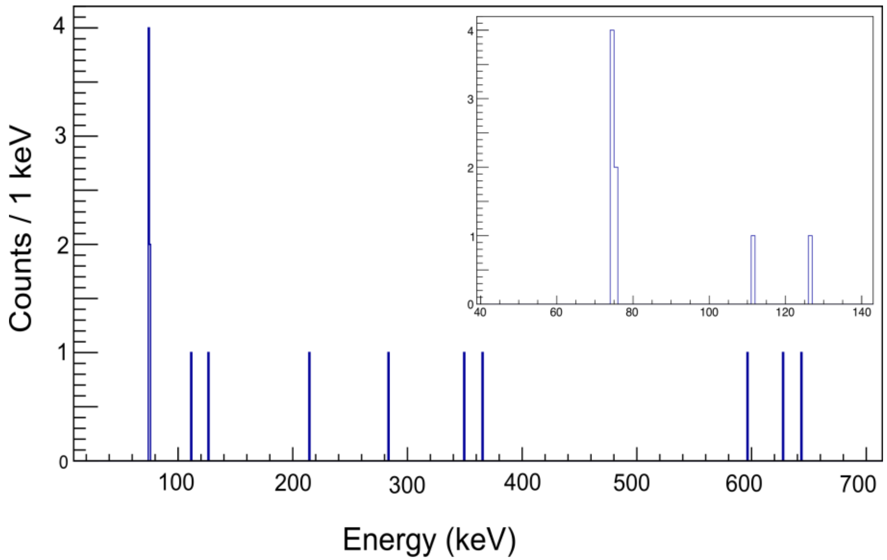
- Setup benchmarked with well-known α-γ coincidences
- **Six** 74-keV delayed gamma rays (including one gg coincidence) with $T_{1/2}$=$2.8^{+2.3}_{-1.0}$ μs (from 216 protons and 19 α decays). Determined in maximum likelihood analysis.

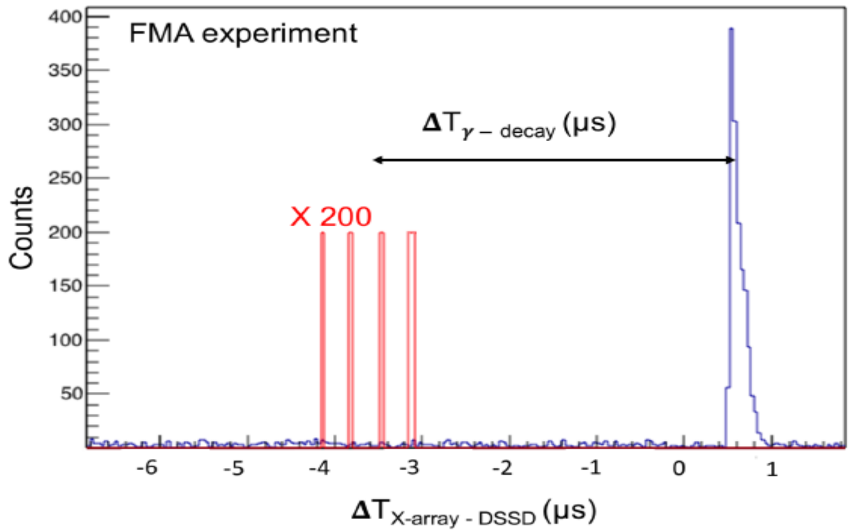
=> Suggests isomer with $T_{1/2}$ = 57(23) μs





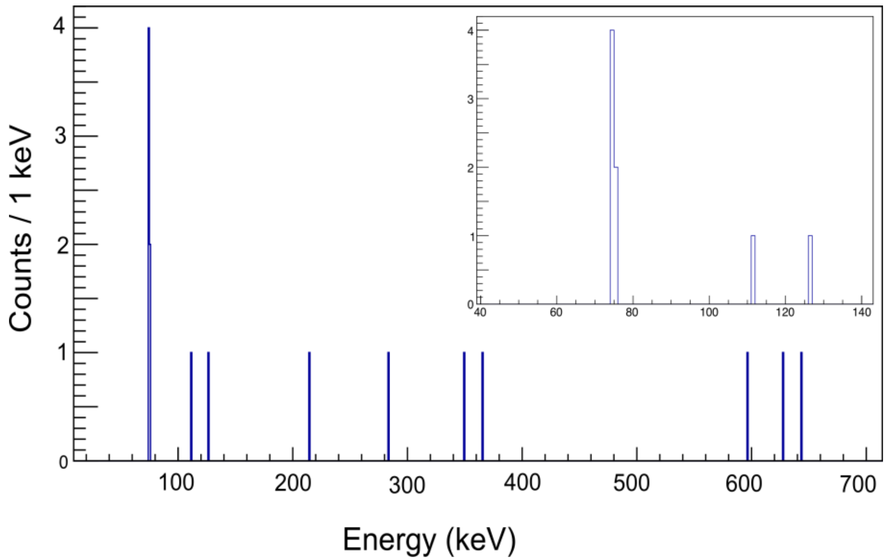
Decay Correlated Gamma Rays at the Focal Plane

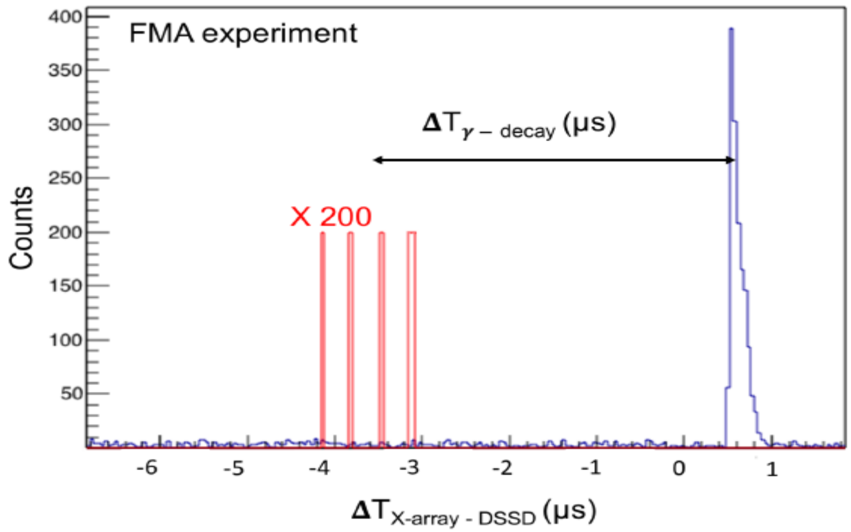




- One event in prompt coincidence (within 20 ns). Important consequences for level structure.
- 74-keV transition is **most probably** a γ ray, K_α X-ray energy is 77.1 keV (and K_β X-rays are much less intense
- Delayed a γ rays interpreted as being due to deexcitation of an isomer with $T_{1/2}$ = 57(23) μs

Decay Correlated Gamma Rays at the Focal Plane





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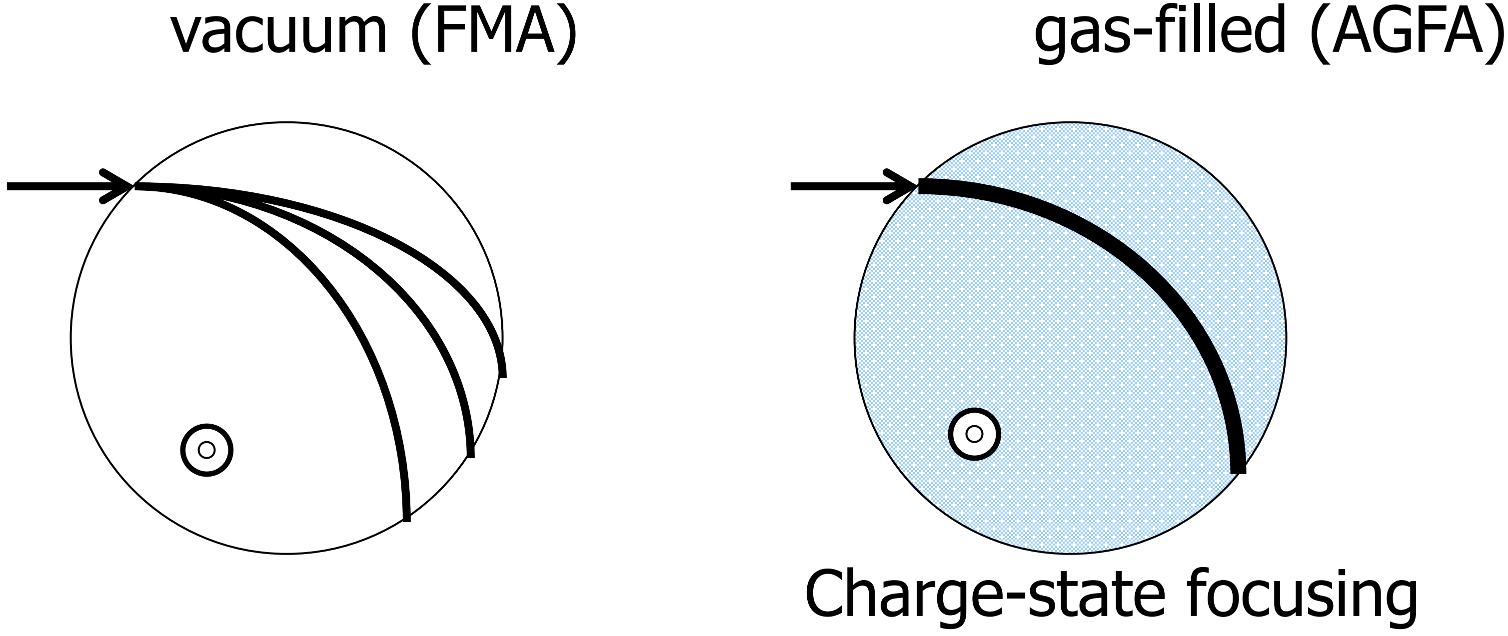
Motivated follow-up experiment to confirm this scenario

Follow-up Experiment with AGFA

AGFA experiment

- ^{93}Nb(^{95}Mo,3*n*)^{185}Bi reaction (same as in FMA experiment)
- Beam intensity of ~10 pnA in an experiment lasting ~92 hours
- Same focal plane setup as in AGFA experiment



Symmetric reactions present a significant challenge for gas-filled separators

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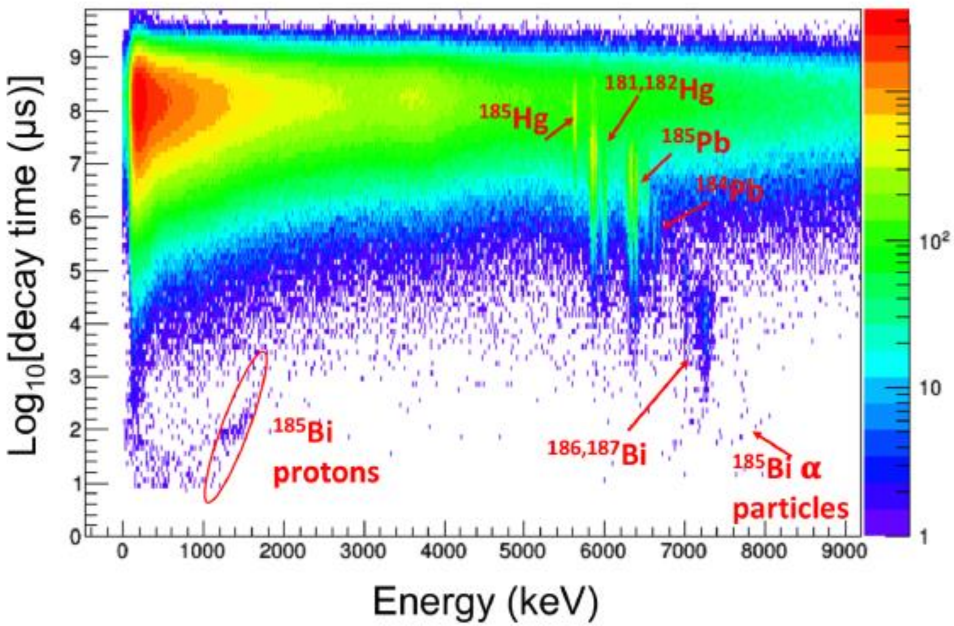
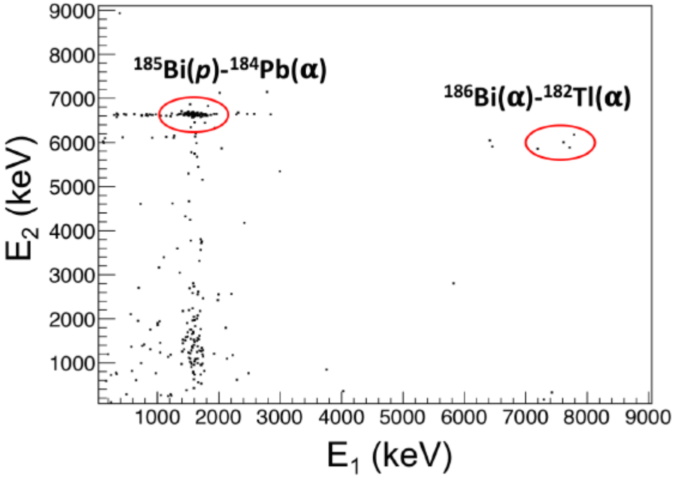
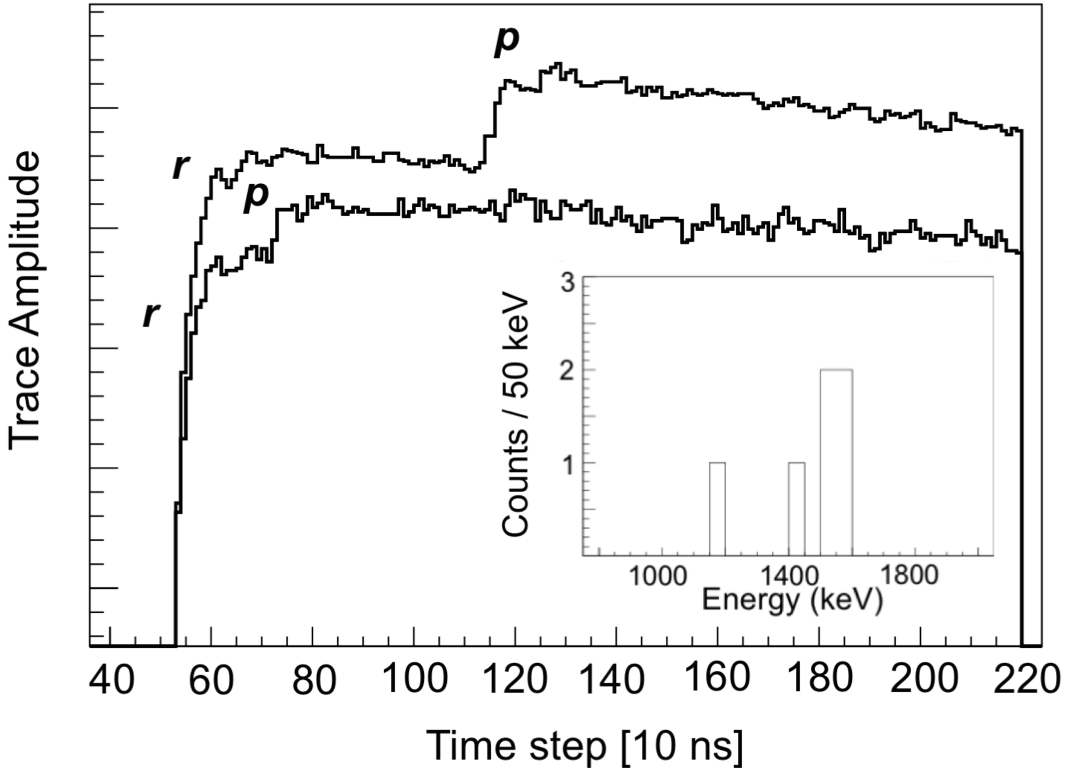


- 139 protons and 11 alpha particles from ^{185}Bi obtained in ~92 hours (with half the beam current)
- **50% increase in transport efficiency**
- Use of X-array prohibited by random rate but **waveforms recorded for offline analysis**

Follow-up Experiment with AGFA – Pile-up Analysis

- Search for events where **isomer is bypassed**
- Analyse events where recoil is followed by α decay from ^{184}Pb in same DSSD pixel
- Six candidates identified (upper limit of 1 expected if $T_{1/2}$ = 60 μs)
- Energy in agreement
- Half-life consistent with FMA one ($T_{1/2}=2.8^{+2.3}_{-1.0}\ \mu s$)
- Estimated populations of ~80% for isomer and ~20% for ground state





Interpretation for ^{185}Bi (Ground State)

Possible to suggest a new level scheme for ^{185}Bi

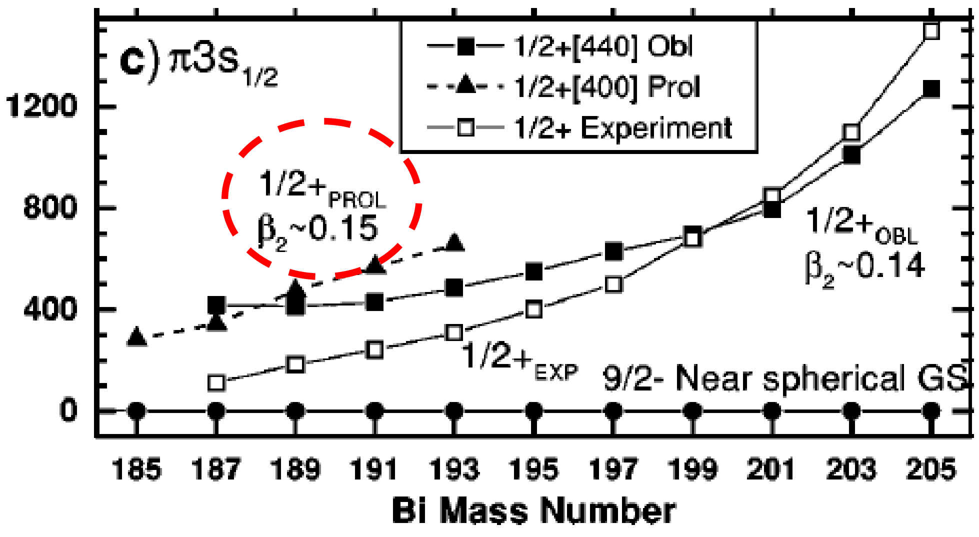
- Previous studies deduced a proton emission spectroscopic factor of 0.025 based on the ~60 μs half-life

  $\Rightarrow$ **Significant change** in configurations between parent and daughter

- New ~3 μs half-life corresponds to spectroscopic factor of 0.6 and unhindered decay.

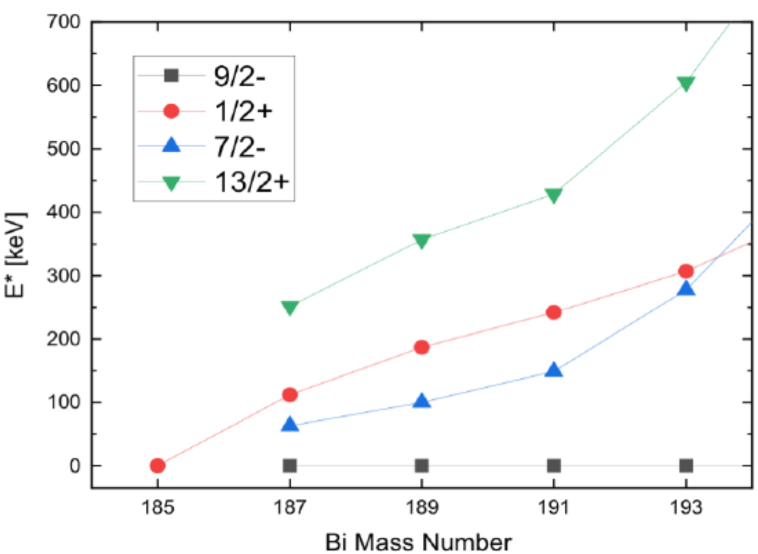
- Alpha decay now also unhindered $\delta_\alpha^2 = 64^{+61}_{-21}$ keV, in agreement with the rest of the Bi chain

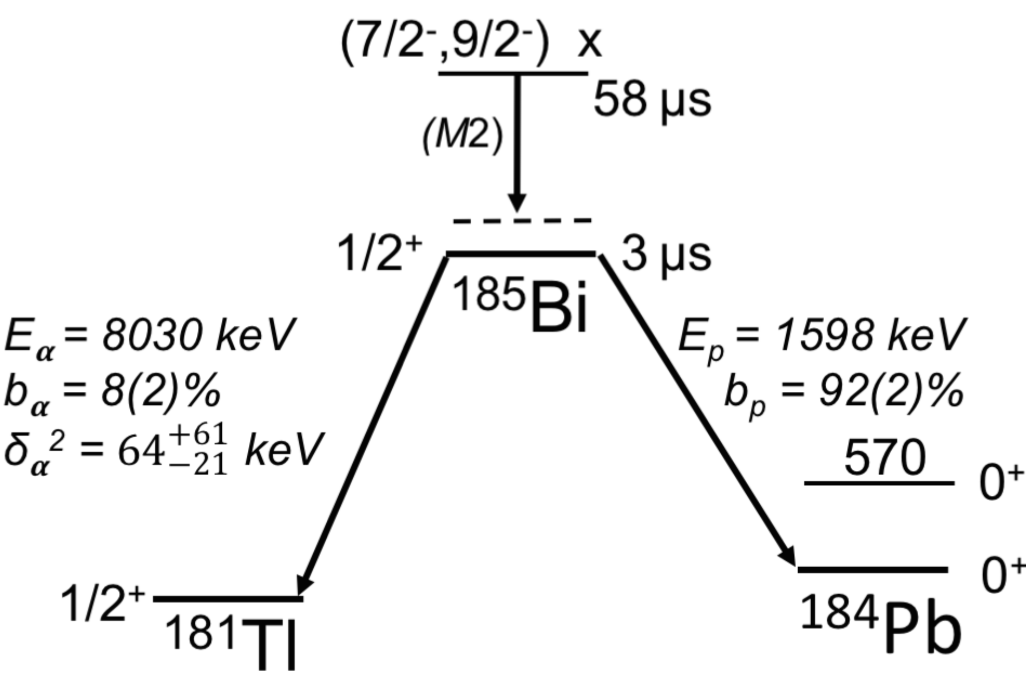
Calculated energies extracted from PES calculations



Interpretation for ^{185}Bi (Isomer)

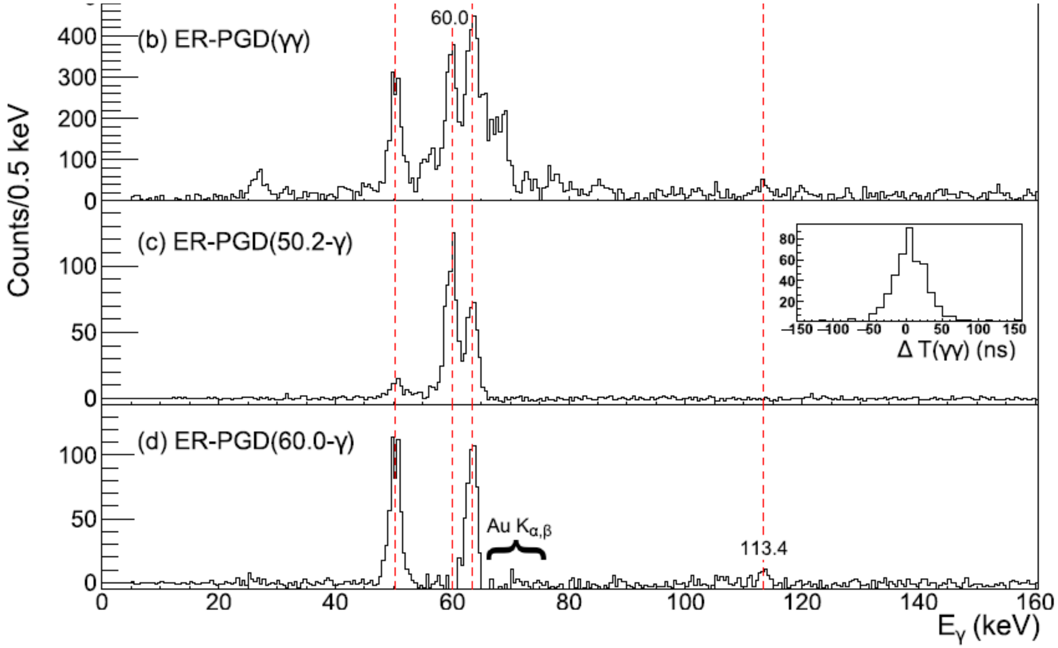
- Transition energy below K-shell binding energy (91 keV), L-shell energies (11 keV)
- *M*2 transition best fits observed $T_{1/2}$ (*E*3 too slow, *E*2 => unusual hinderance)
- Observation of gg coincidence suggests an intermediate state (supported by bands observed in less neutron-deficient Bi isotopes)





^{185}Bi Outstanding Questions

- Configuration of the ground state based on PES calculations
  - Revisit in-beam **RDT studies** (very challenging!)
- More detailed decay spectroscopy
  - Will require Ge detectors at the focal plane that are **very sensitive at low energies**



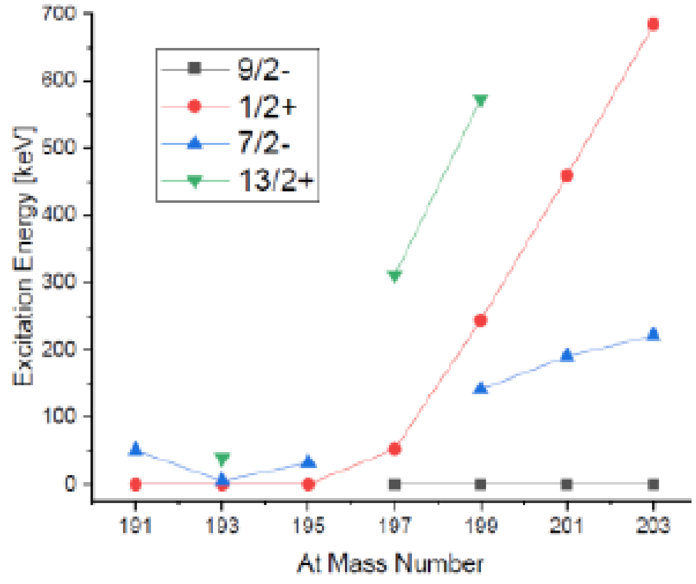
Example planar Ge spectra from RITU gas-filled separator at JYFL
^{178}Au

S. A. Gillespie *et al.*, Phys. Rev. C **103**, 044307 (2021)

A new region of proton radioactivity

- The new isotopes ^{189,190}At could be produced in **symmetric reactions with AGFA** (significant increase in cross section compared to asymmetric reactions). Decay-decay correlations with known daughter activities
- Predicted to be **highly-deformed proton emitters** (half-lives of the order μs if decay from $s_{1/2}$ and ~50 μs from 9/2- state)
- Alpha decay of ^{189}At would give additional information on ^{185}Bi
- Opens the door for studies of heavier systems (^{194,195}Fr & ^{200,201}Ac)

Energy systematics of At isotopes



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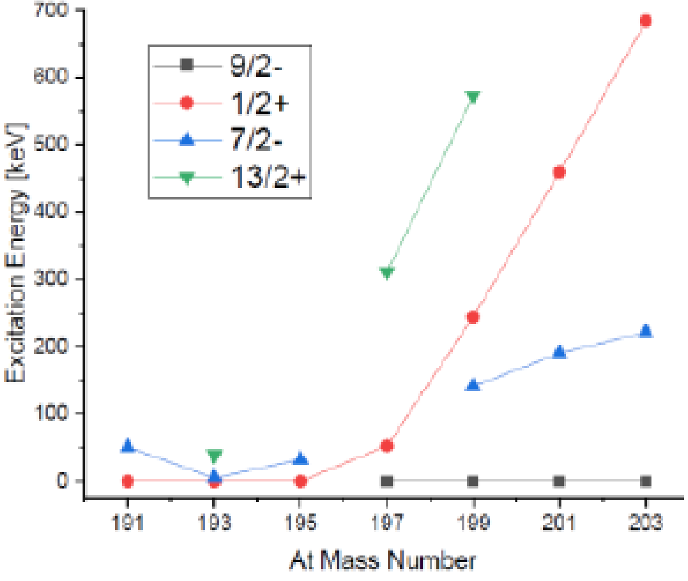
Proposal recently accepted by the ATLAS (ANL) PAC
P.Is: Seweryniak and Andreyev

Energy systematics of At isotopes



PHYSICAL REVIEW LETTERS **127,** 202501 (2021)

Editors' Suggestion

Solving the Puzzles of the Decay of the Heaviest Known Proton-Emitting Nucleus ^{185}Bi

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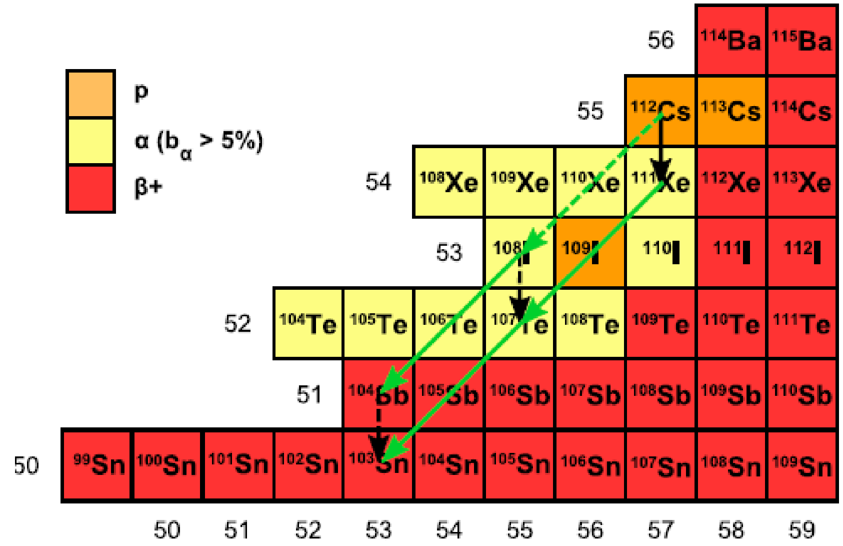
THANK YOU VERY MUCH!!

Ground-state Proton Radioactivity (1)

Experimentally observed in all of the most neutron-deficient odd-*A* isotopes between Z = 53 and 83. Promethium (Z=61) only exception.

- Key, and often only, source of information at and beyond the proton dripline.
- Quantum tunnelling phenomenon but easier to treat theoretically than α decay (no preformation factor)
- Important for understanding the flow of the astrophysical *rp*-process, see recent example of ^{108}I



K. Auranen *et al.*, Phys. Lett. B **792**, 187 (2019)

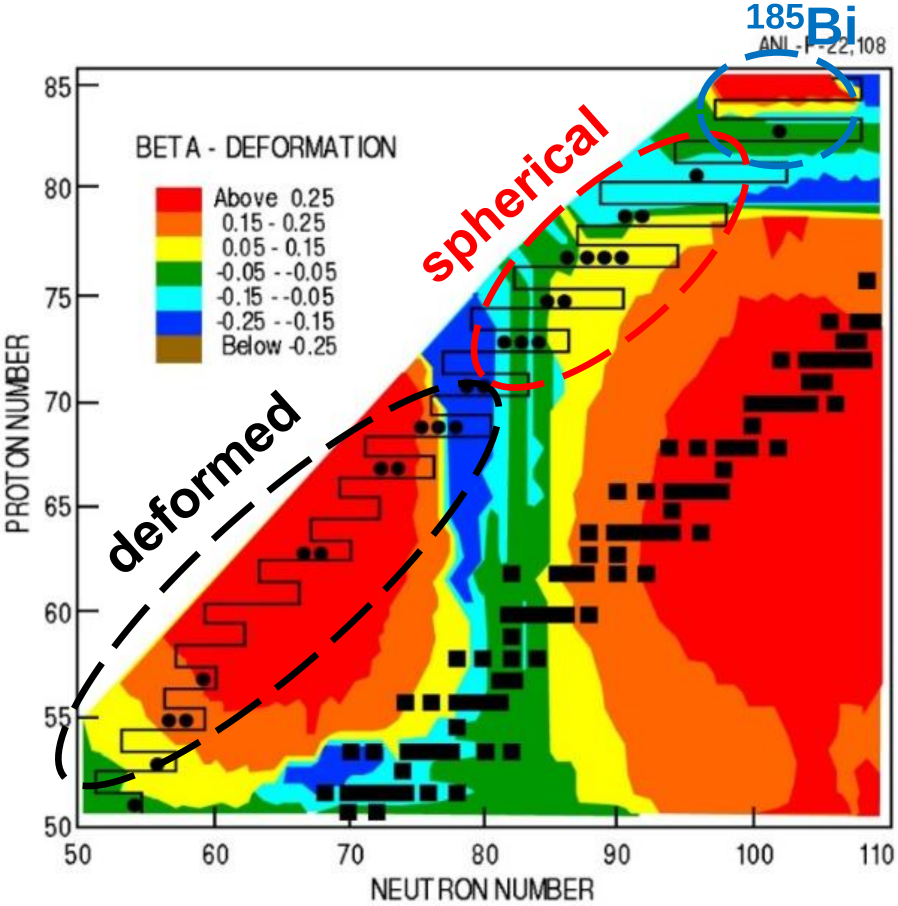
Ground-state Proton Radioactivity (2)

- Various theoretical descriptions reproduce well the half-lives and spectroscopic factors of *spherical* proton emitters (Z = 69-81)

- For *deformed* proton emitters (Z = 53-67) the situation is more complex

- **Coriolis interaction** plays a key role

- Various l_p values can contribute to decay rate



Argonne National Laboratory (ANL)