Low-lying states in ^{219}Ra and ^{215}Rn: sampling microsecond α-decaying nuclei

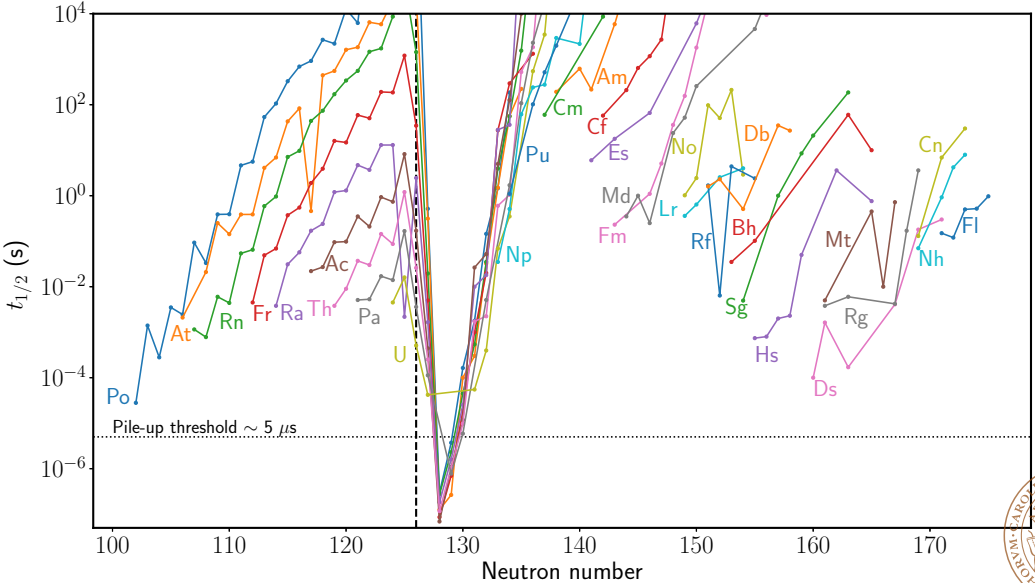
Anton Såmark-Roth

On behalf of the
TASCA E115 Collaboration

September 25, 2018

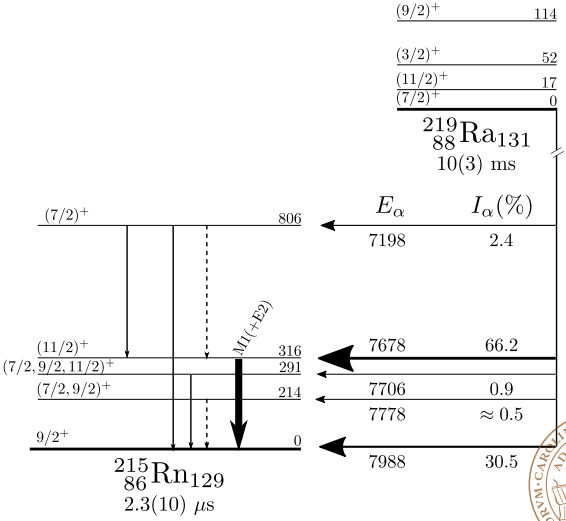
Knut och Alice Wallenbergs Stiftelse

LUND UNIVERSITY


10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
$t_{1/2}$ (s)
Pile-up threshold $\sim 5\ \mu$s
100
110
120
130
140
150
160
170
Neutron number
Po
At
Rn
Fr
Ra
Th
Ac
Pa
U
Np
Pu
Cm
Am
Cf
Es
Fm
Md
Lr
No
Db
Rf
Bh
Sg
Hs
Ds
Mt
Rg
Nh
Cn
Fl

Evaluated decay scheme of ^{219}Ra$\rightarrow^{215}$Rn

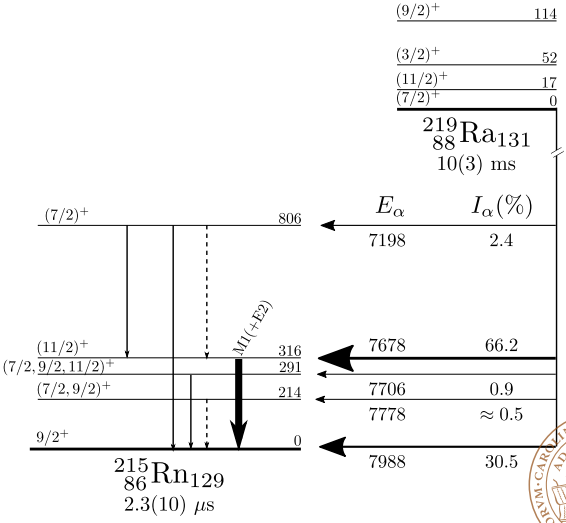
- Decay spectroscopy experiments performed: 1970 [1], 1987 [2] & 1994 [3].
- Angular correlation measurement 1989 excluded $I^\pi = 9/2$ for ^{219}Ra ground state [4].
- Low lying levels in ^{219}Ra from Riley *et al.* 2000 [5].



[1] K. Valli, *et al.*, Phys. Rev. C. **1**, 2115 (1970).
[2] A. M. Y. El-Lawindy *et al.*, J. Phys. G: Nucl. Phys., (1987).
[3] R. K. Sheline, *et al.*, Phys. Rev. C. **49**, 2 (1994).
[4] E. D. Hackett, *et al.*, Phys. Rev. C. **40**, 1234 (1989).
[5] L. A. Riley *et al.*, Phys. Rev. C. **62**, 021301(R) (2000).

Evaluated decay scheme of ^{219}Ra$\rightarrow^{215}$Rn

- Weisskopf estimate for 17 keV $E2$ transition: 0.2 µs.
- Additional hindrance due to difference in shape, single-particle composition and angular momentum between levels [6].
- Main focus: the existence of isomeric α-decaying 17 keV state in ^{219}Ra.



[6] Phil Walker and George Dracoulis, Nature 399, 35 (1999).

The 2012 E115-experiment

The reaction: ^{48}Ca+^{243}Am$\rightarrow^{291}$Mc*. Here nonfusion product background ...

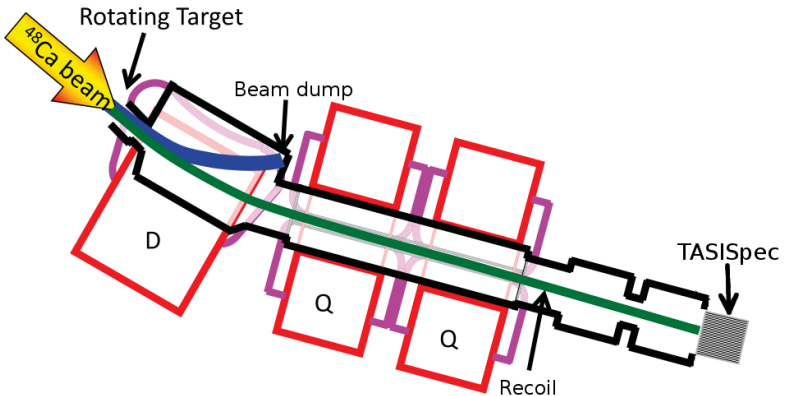


Figure: TASCA-separator. Source: Phys. Rev. C, **83**:054618.

Correlation analysis

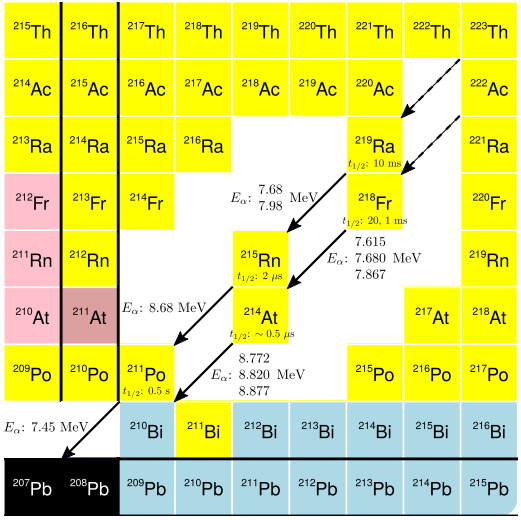
Pixel by pixel correlated events

Event

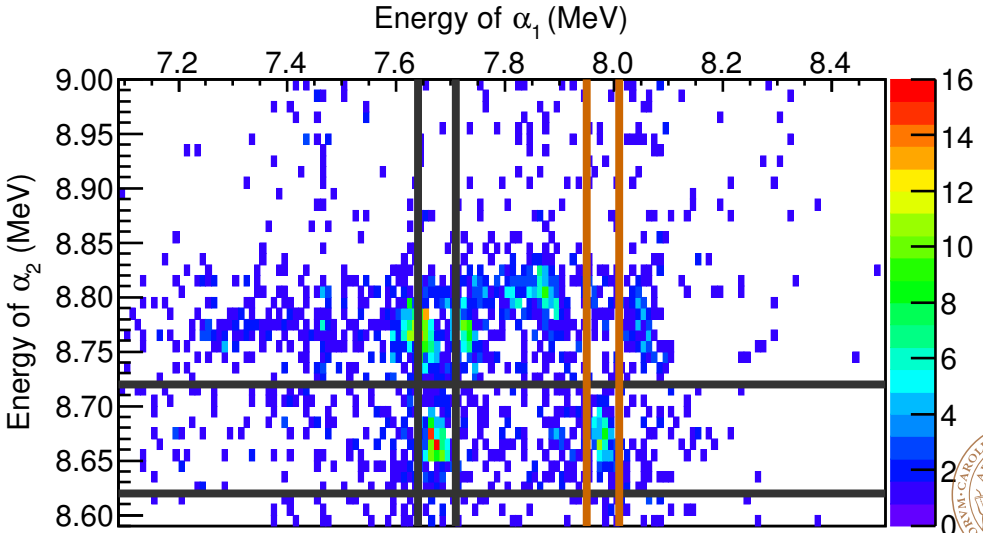
1. Pixel
2. Time
3. Beam ON/OFF
4. Silicon detector particle energies
5. Germanium detector photon energies

Aim: Select the data for just one decay path, i.e. ^{219}Ra$\rightarrow^{215}$Rn.

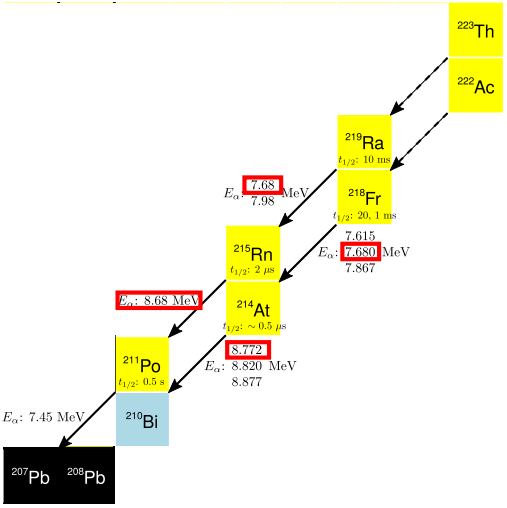
"imp-α_1-α_2" correlated events



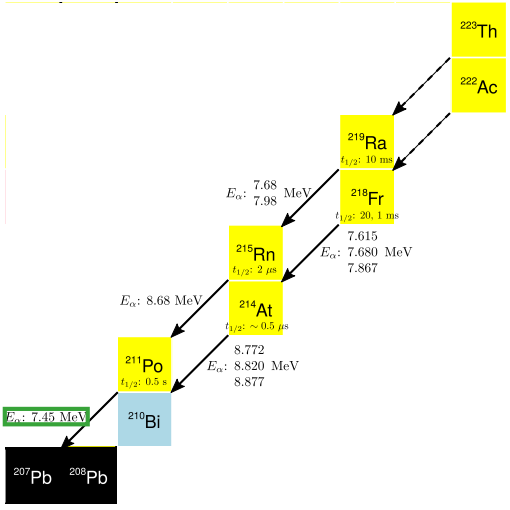
"imp-α_1-α_2" correlated events



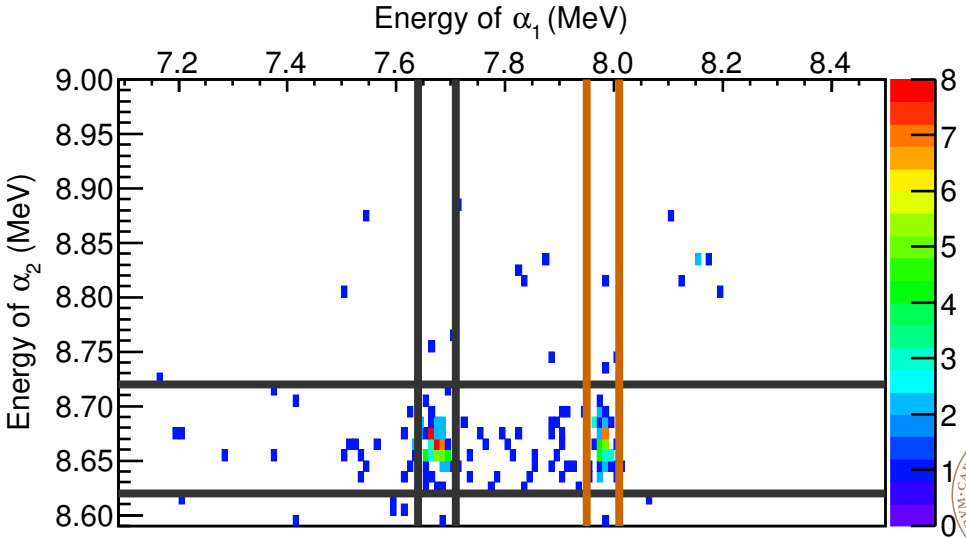
"imp-α_1-α_2" correlated events



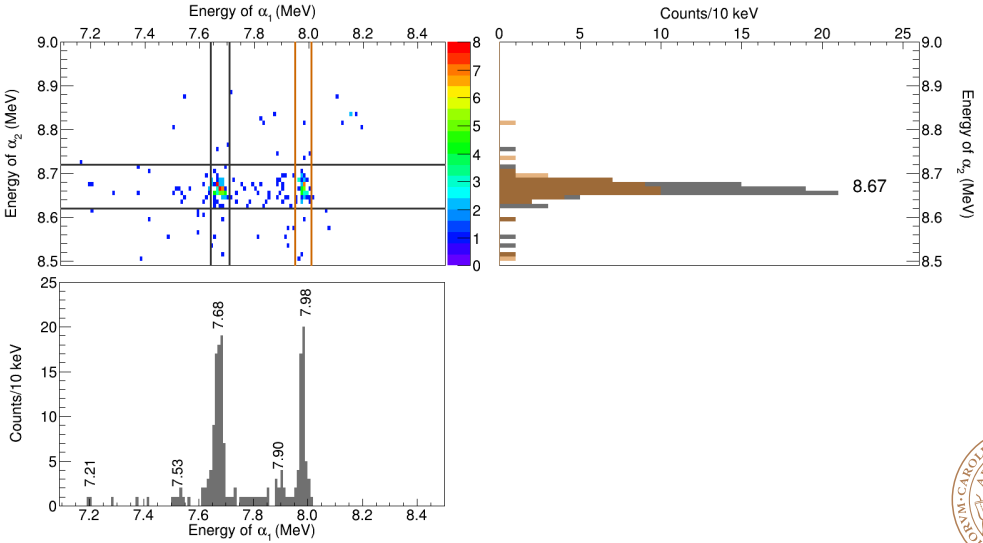
"α_1-α_2-α_3" correlated events



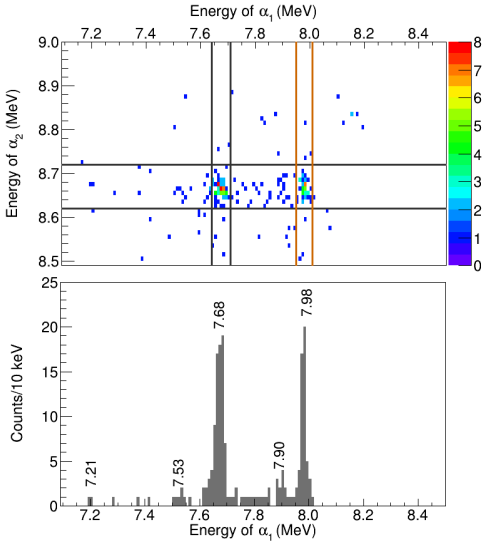
"α_1-α_2-α_3" correlated events

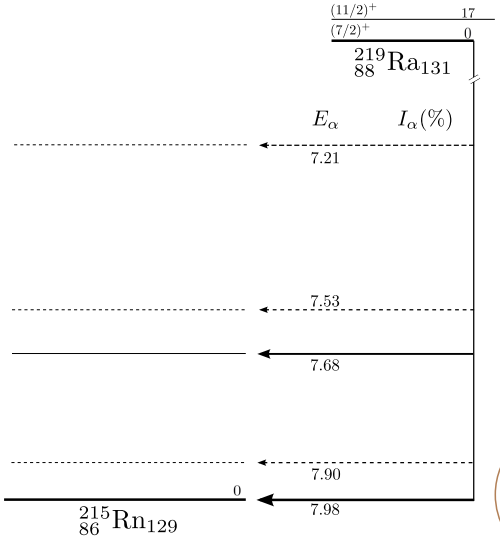


Decay scheme ^{219}Ra$\rightarrow^{215}$Rn

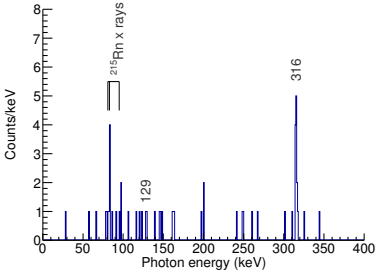


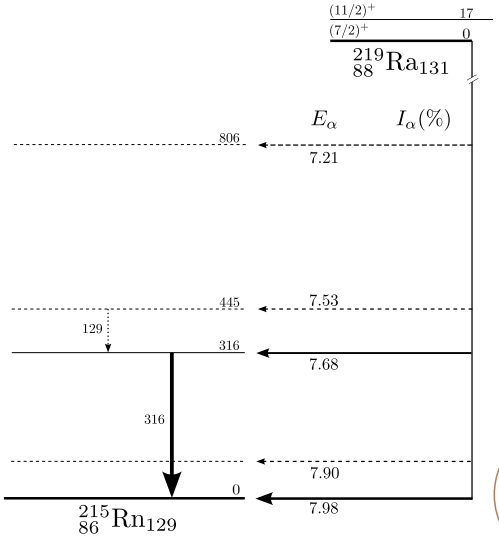
Decay scheme ^{219}Ra$\rightarrow^{215}$Rn



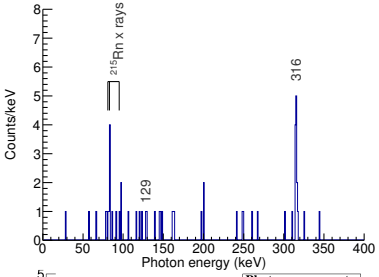


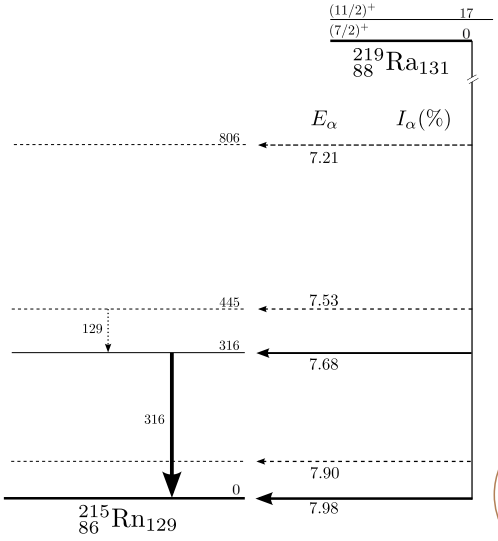
Decay scheme ^{219}Ra$\rightarrow^{215}$Rn



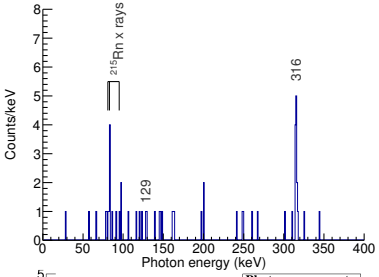


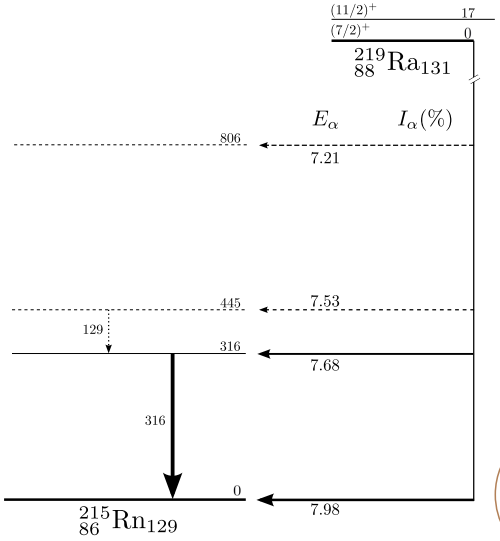
Decay scheme ^{219}Ra$\rightarrow^{215}$Rn



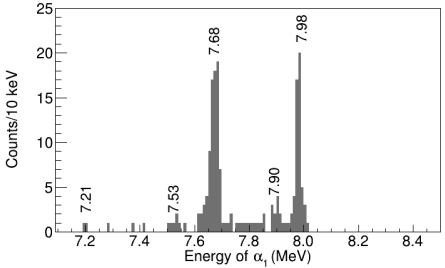


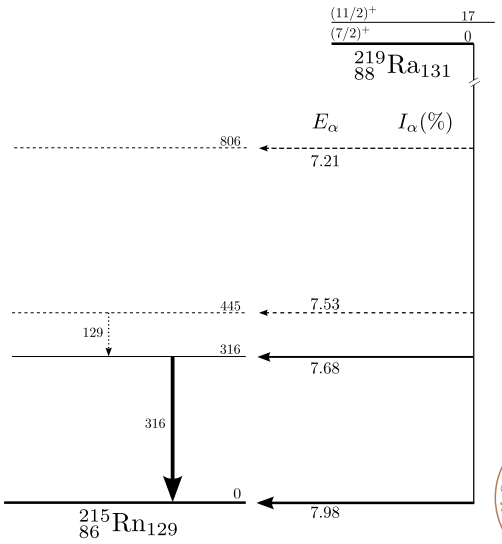
Decay scheme ^{219}Ra$\rightarrow^{215}$Rn



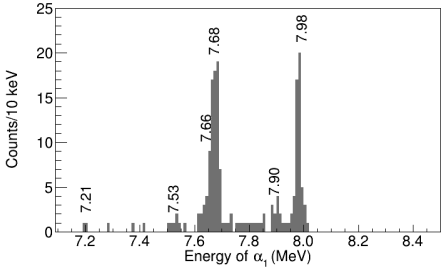


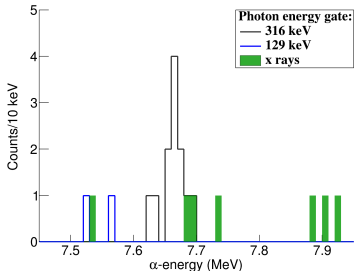
Decay scheme ^{219}Ra$\rightarrow^{215}$Rn

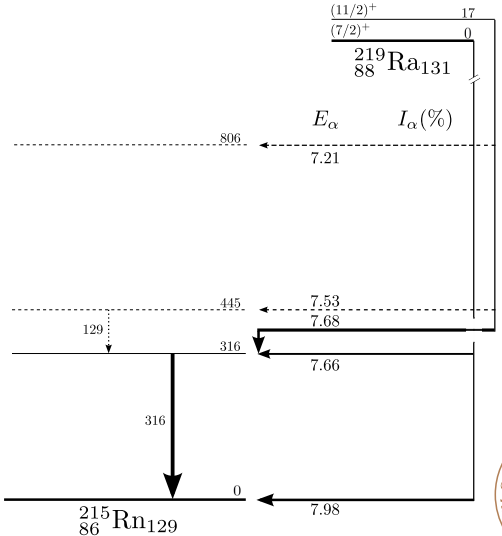




Decay scheme ^{219}Ra$\rightarrow^{215}$Rn







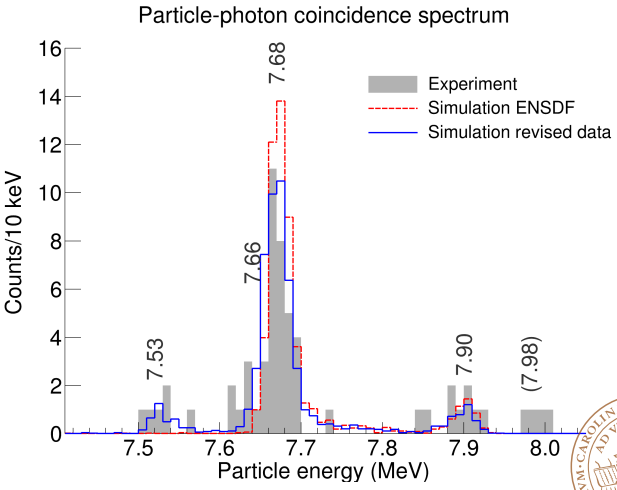
Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn

- TASISpec experiment in a virtual Geant4 environment [6].
- 10 000 ^{219}Ra were implanted 80 ± 5 MeV.
- Particle and photon spectra were normalised with a common factor.
- Decay scheme complexity built up step-by-step.
- σL of transitions w.r.t. yields in particle and photon spectra were optimised.

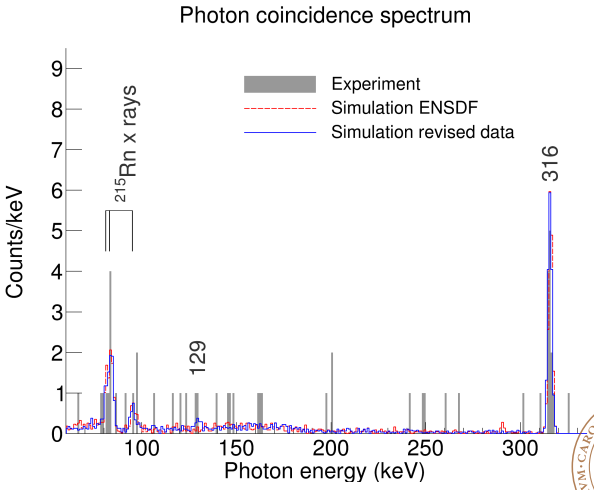
[7] L.G. Sarmiento, L.-L. Andersson, and D. Rudolph, Nucl. Instrum. Meth. **A 667**, 26–31 (2012).

Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn

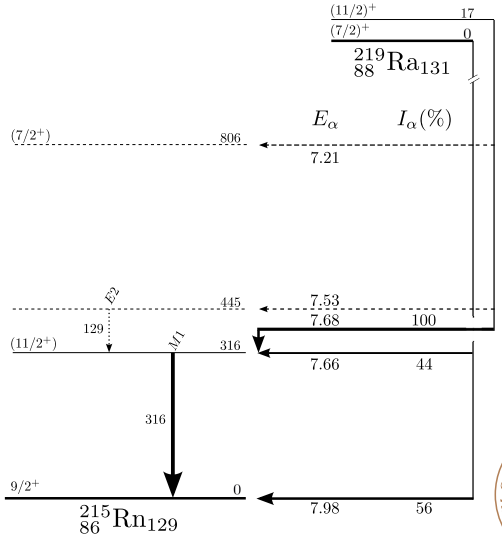
- Two branches with $E_\alpha = 7.66$ & 7.68 MeV were included.
- Branching ratios were varied for best match.



Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn

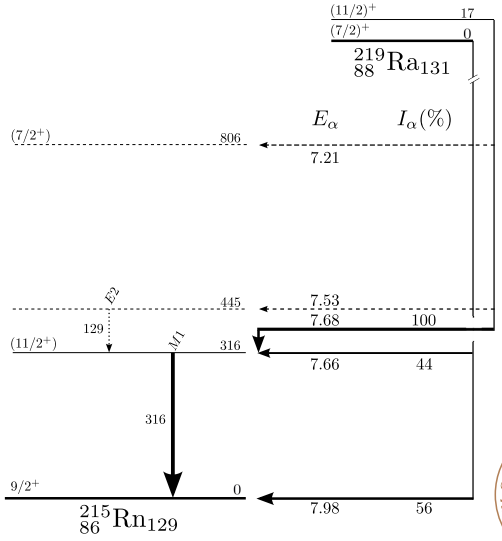


Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn



Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn

What is the origin of the 7.98 MeV branch?



Summary of ^{219}Ra$\rightarrow^{215}$Rn

α decay of ^{219}Ra

^{219}Ra			^{215}Rn
E_α (MeV)	$t_{1/2}$ (ms)	Q_α (MeV)	E_f (keV)
7.68(2)[a]	10(3)	8.14(2)[a]	316
7.66(2)[a]	10(3)	8.13(2)[a]	316
7.98(1)	8(3)	8.13(1)	0
7.53(2)		8.10(2)	445
7.21(2)		8.15(2)	806

[a] Guided by the simulation.

Summary of ^{219}Ra$\rightarrow^{215}$Rn

α decay of ^{219}Ra

	^{219}Ra		^{215}Rn
E_α (MeV)	$t_{1/2}$ (ms)	Q_α (MeV)	E_f (keV)
7.68(2)[a]	10(3)	8.14(2)[a]	316
7.66(2)[a]	10(3)	8.13(2)[a]	316
7.98(1)	8(3)	8.13(1)	0
7.53(2)		8.10(2)	445
7.21(2)		8.15(2)	806

[a] Guided by the simulation.

Summary of ^{219}Ra$\rightarrow^{215}$Rn

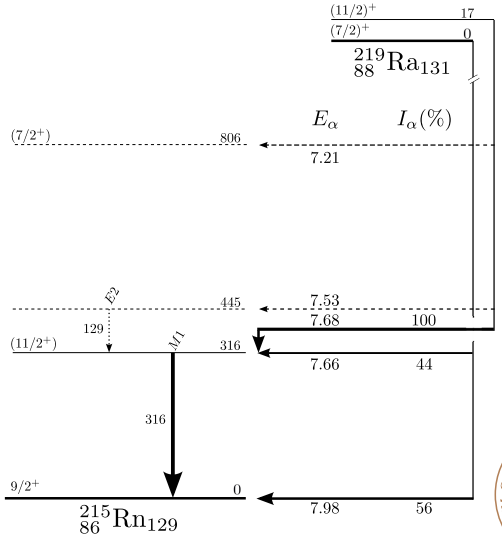
α decay of ^{219}Ra

	^{219}Ra		^{215}Rn
E_α (MeV)	$t_{1/2}$ (ms)	Q_α (MeV)	E_f (keV)
7.68(2)[a]	10(3)	8.14(2)[a]	316
7.66(2)[a]	10(3)	8.13(2)[a]	316
7.98(1)	8(3)	8.13(1)	0
7.53(2)		8.10(2)	445
7.21(2)		8.15(2)	806

[a] Guided by the simulation.

Summary of ^{219}Ra$\rightarrow^{215}$Rn

What is the origin of the 7.98 MeV branch?



Theoretical calculations of ^{219}Ra

- Density Functional Theory calculations indicate prolate and octupole deformations.
- Low-lying levels cannot be explained without careful treatment of angular momentum coupling between the odd particle and the core.
- Many-particle+rotor calculations are able to reproduce the experimental rotational bands in ^{219}Ra.

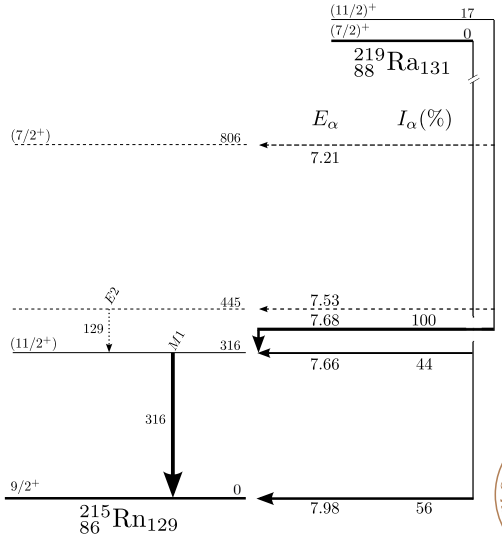
[8] M. V. Stoitsov *et al.*, Comp. Phys. Commun. 184, 1592 (2013).
[9] B. G. Carlsson and I. Ragnarsson, Phys. Rev. C 74, 044310 (2006).

Figure: Single-particle energy levels for neutrons obtained with the code HFBTHO using the Skyrme functional UNE1 without pairing. To the left of the vertical line $\beta_3 = 0$ and to the right $\beta_2 = 0.1$.

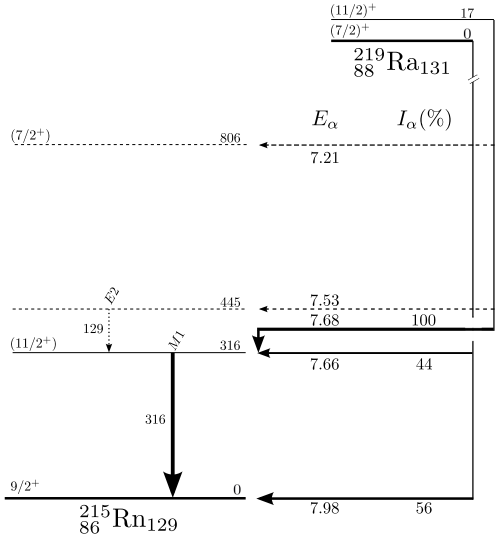
Theoretical calculations of ^{219}Ra

Main conclusion:

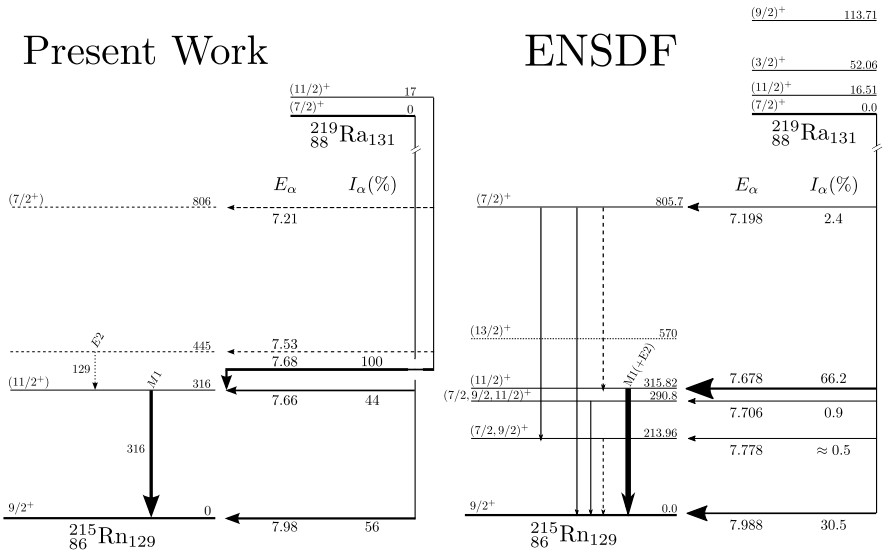
- The $7/2^+$ ground state seems to have components from both the $g_{9/2}$ and $i_{11/2}$ orbitals while the isomeric $11/2^+$ state is dominated by the odd-neutron in the $i_{11/2}$ orbital.
- This justifies the strong $11/2^+ \rightarrow 11/2^+$ decay branch and the split decay branches of the $7/2^+$ ground state into $9/2^+$ and $11/2^+$ in ^{215}Rn.



Summary of ^{219}Ra$\rightarrow^{215}$Rn



Summary of ^{219}Ra$\rightarrow^{215}$Rn



Further decay chains - starting with ^{220,221}Ra and ^{219}Fr

Nucleus	*Correlation*	*Present Work* E_α (MeV)	ENSDF E_α (MeV)
^{215}Rn	α_1-α_2^a-(α_3)	8.67(1)	8.674(8)
^{220}Ra	(imp^b)-α_1^a-α_2-α_3	7.46(1)	7.453(7)
^{216}Rn	α_1-α_2^a-α_3	8.05(2)	8.050(10)
^{212}Po	α_1-α_2-α_3^a	8.78(2)	8.78486(12)
^{219}Fr	(imp^b)-α_1^a-α_2-α_3	7.32(1)	7.3123(18)
^{215}At	α_1-α_2^a-α_3	8.02(1)	8.026(4)
^{221}Ra	(imp^b)-α_1^a-α_2-α_3	6.76(1)	6.754(5)
^{217}Rn	α_1-α_2^a-α_3	7.74(1)	7.741(2)
^{213}Po	α_1-α_2-α_3^a	8.37(1)	8.376(3)

[a] Step corresponding to the isotope that is focused.

Further decay chains - starting with ^{220,221}Ra and ^{219}Fr

Nucleus	*Correlation*	*Present Work* $t_{1/2}$	ENSDF
^{215}Rn	α_1-α_2^a-(α_3)	2.5(3) µs	2.30(10) µs
^{220}Ra	(imp^b)-α_1^a-α_2-α_3	19(3) ms	18(2) ms
^{216}Rn	α_1-α_2^a-α_3	29(4) µs	45(5) µs
^{212}Po	α_1-α_2-α_3^a	0.35(6) µs	0.299(2) µs
^{219}Fr	(imp^b)-α_1^a-α_2-α_3	28(3) ms	20(2) ms
^{215}At	α_1-α_2^a-α_3	37(3) µs	0.10(2) ms
^{221}Ra	(imp^b)-α_1^a-α_2-α_3	16(2) s	28(2) s
^{217}Rn	α_1-α_2^a-α_3	0.67(6) ms	0.54(5) ms
^{213}Po	α_1-α_2-α_3^a	3.5(3) µs	3.72(2) µs

^{a}Step corresponding to the isotope that is focused.

^{b}Step in the correlation search that was merely used to estimate the half-life.

Further decay chains - starting with ^{220,221}Ra and ^{219}Fr

Nucleus	*Correlation*	*Present Work* $t_{1/2}$	ENSDF
^{215}Rn	α_1-α_2^a-(α_3)	2.5(3) µs	2.30(10) µs
^{220}Ra	(imp^b)-α_1^a-α_2-α_3	19(3) ms	18(2) ms
^{216}Rn	α_1-α_2^a-α_3	29(4) µs	45(5) µs
^{212}Po	α_1-α_2-α_3^a	0.35(6) µs	0.299(2) µs
^{219}Fr	(imp^b)-α_1^a-α_2-α_3	28(3) ms	20(2) ms
^{215}At	α_1-α_2^a-α_3	37(3) µs	0.10(2) ms
^{221}Ra	(imp^b)-α_1^a-α_2-α_3	16(2) s	28(2) s
^{217}Rn	α_1-α_2^a-α_3	0.67(6) ms	0.54(5) ms
^{213}Po	α_1-α_2-α_3^a	3.5(3) µs	3.72(2) µs

[a] Step corresponding to the isotope that is focused.

[b] Step in the correlation search that was merely used to estimate the half-life.

Further decay chains - starting with ^{220,221}Ra and ^{219}Fr

Measured half-lives differ significantly in the cases of:

- ^{216}Rn [1].
- ^{219}Fr & ^{215}At [10,11].
- ^{221}Ra [12].
- ^{217}Rn [13].

[1] K. Valli, *et al.*, Phys. Rev. C. **1**, 6 (1970).
[10] G. Bastin *et al.*, J. Phys.(Paris) Suppl.No.1, Colloq.C1-181 (1968).
[11] G. Graeffe and P. Kauranen, J. Inorg. Nucl. Chem., **28** 933–936 (1966).
[12] P. A. Tove, Arkiv Fysik, **13** (1958).
[13] C. P. Ruiz, United States (1961).

Conclusion

- An α-decay branch from the excited state at 17 keV in ^{219}Ra, unknown in previous decay spectroscopy experiments, is proposed.
- The results are consistent with Geant4 simulations.
- Theoretical calculations justify the nuclear structure interpretation.
- To gain more confidence in the proposed decay scheme, further experimental studies are encouraged.
- A revision of the evaluated half-lives ^{216,217}Rn, ^{219}Fr, ^{215}At and ^{221}Ra α-decays – from measurements made before 1970 – is suggested.

Knut och Alice Wallenbergs Stiftelse

LUND UNIVERSITY

DFT deformation calculations - ^{219}Ra

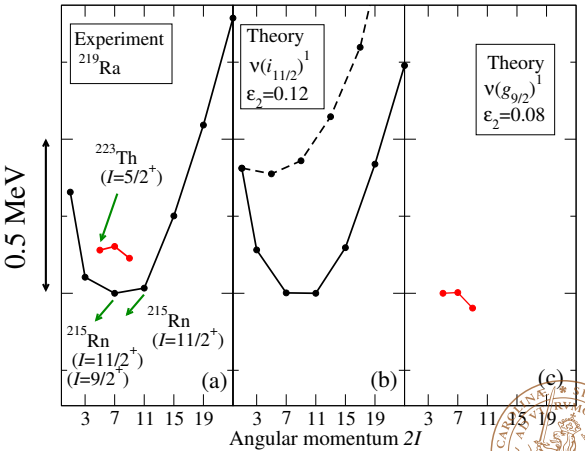
Table: Deformation and excitation energy, ΔE, for some quasi-particle states in ^{219}Ra obtained with the code HFBTHO using the Skyrme functional UNE1.

Shell	K^π	β_2	β_3	ΔE (MeV)
$2g_{9/2}$	$3/2^+$	0.12	-0.04	0.0
$2g_{9/2}$	$5/2^+$	0.12	-0.06	0.2
$1i_{11/2}$	$1/2^+$	0.10	0.00	0.4
$2g_{9/2}$	$1/2^+$	0.15	-0.06	1.1
$2g_{9/2}$	$7/2^+$	0.10	-0.04	1.1
$2g_{9/2}$	$9/2^+$	0.08	-0.04	1.4
$1i_{11/2}$	$11/2^+$	-0.05	0.00	1.6

Figure: Single-particle energy levels for neutrons obtained with the code HFBTHO using the Skyrme functional UNE1 without pairing. To the left of the vertical line $\beta_3 = 0$ and to the right $\beta_2 = 0.1$.

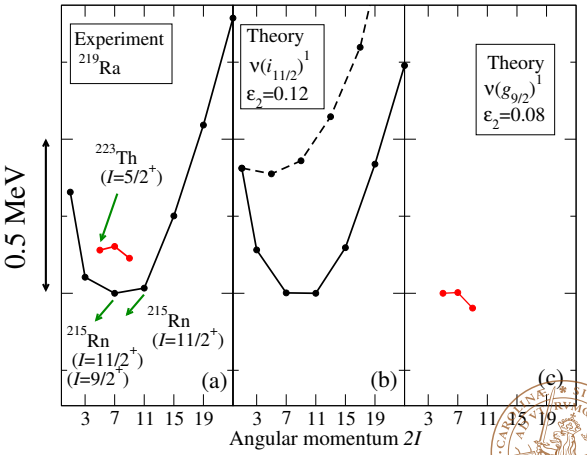
Dynamics of angular-momemtum coupling - ^{219}Ra

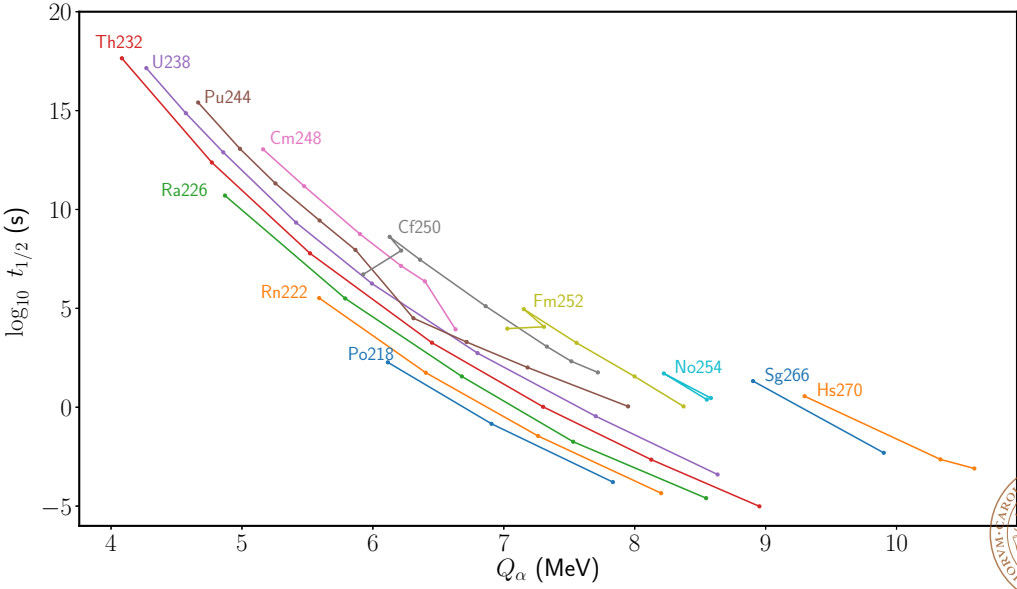
- Many-particle+rotor model with prolate and small octupole deformation.
- Experimental rotational bands are compared to theoretical calculations where the odd neutron has been placed in $i_{11/2}$ and $g_{9/2}$.



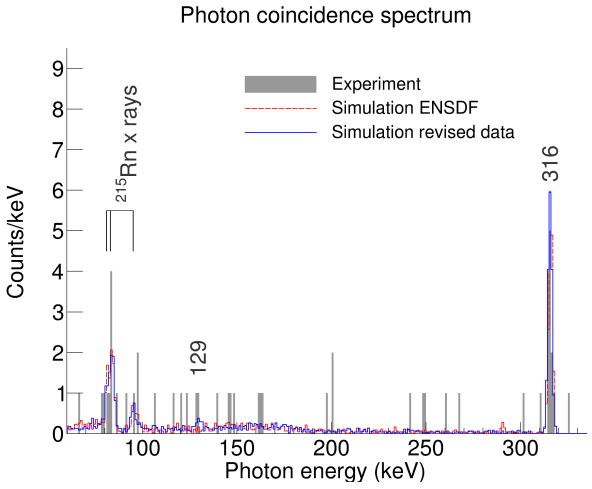
Dynamics of angular-momemtum coupling - ^{219}Ra

- A possible interpretation is that the $11/2^+$ isomeric state is built from the yrast state inpanel (b). This explains the one strong decay branch from the isomeric state into the $11/2^+$ state in ^{215}Rn.
- Further, the $7/2^+$ ground state may be a result of mixing between the bands in panels (b) and (c). As this state then has components of both $i_{11/2}$ and $g_{9/2}$ orbitals it explains the two strong decay branches of the $7/2^+$ ground state.

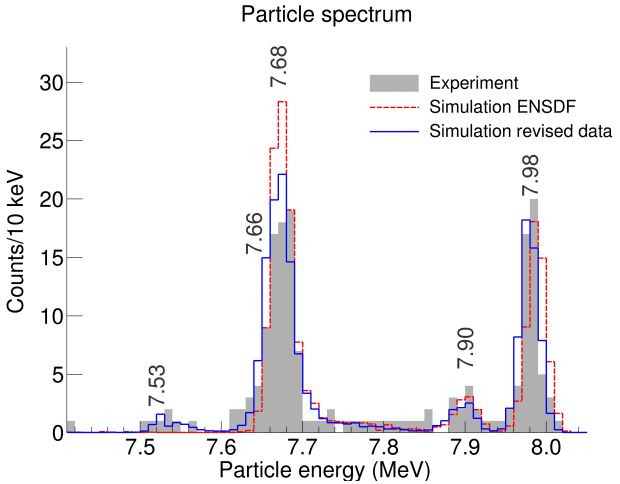



Th232
U238
Pu244
Cm248
Ra226
Cf250
Rn222
Fm252
Po218
No254
Sg266
Hs270
$\log_{10}\ t_{1/2}$ (s)
Q_α (MeV)
20
15
10
5
0
−5
4
5
6
7
8
9
10

Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn



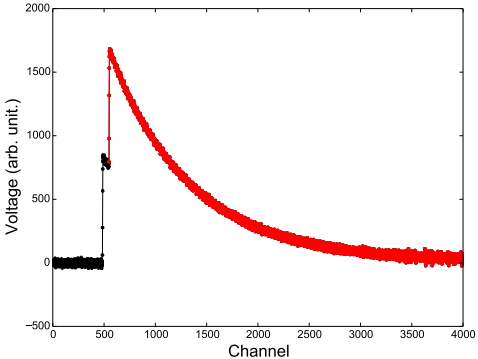
Geant4 Simulations of ^{219}Ra$\rightarrow^{215}$Rn



Fast Sampling ADCs

Pile-ups

Digital



Analogue