BETA-DECAY SPECTROSCOPIC STUDIES OF THE NEUTRON-RICH ^{211,212,213}Tl and ^{219}Bi ISOTOPES

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MOTIVATION

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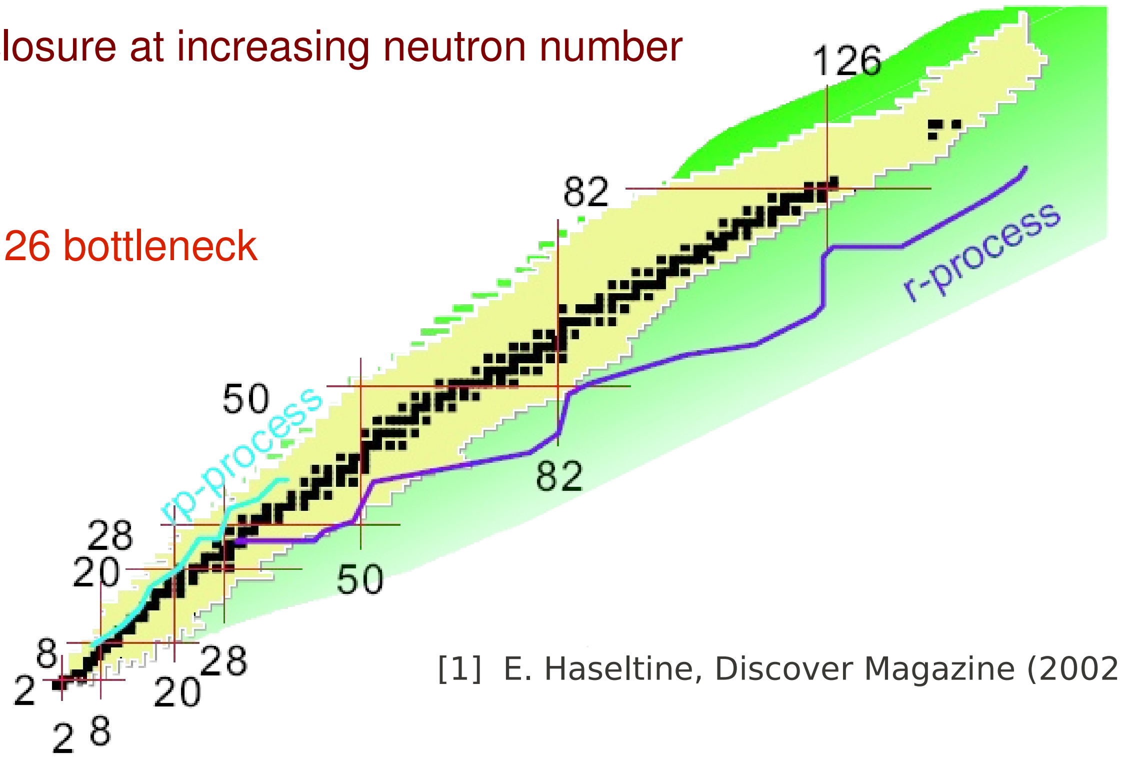
- The origin of heavy elements in the Universe is one of the foremost questions of this century [1]. Nearly half of the heavy elements are produced in the r-process

- A current major theme in nuclear physics is the evolution of shell structure

- The decay of nuclei in the vicinity of the neutron-rich Pb isotopes represents a key issue to investigate

  - ✓ The evolution of the 82-proton shell closure at increasing neutron number
  - ✓ The β-decay lifetimes, that determine
    - The matter flow through the N=126 bottleneck
    - The velocity of synthesis of the heavier r-process nuclei

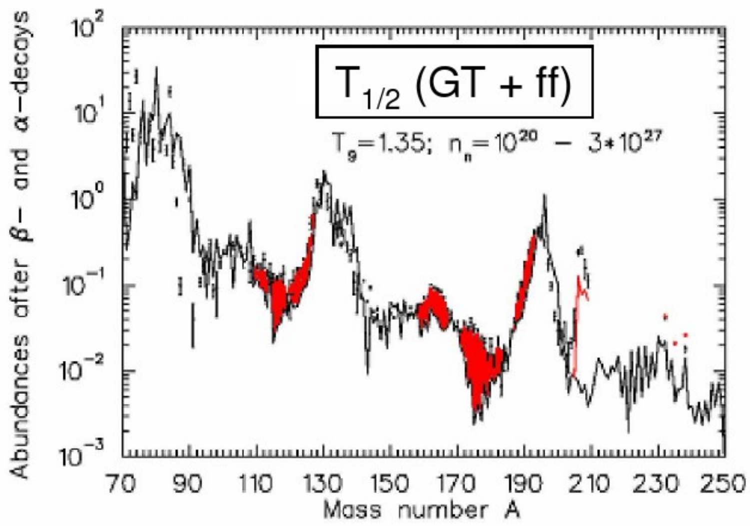
- Nuclei around the r-process waiting point A=195 are completely unexplored



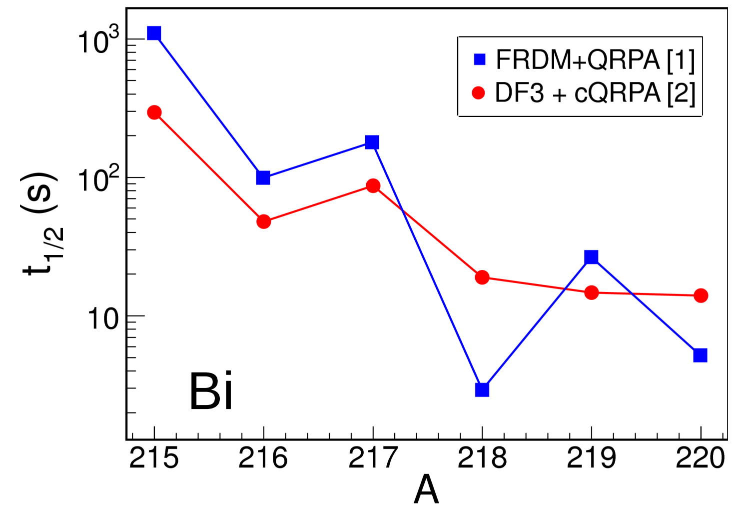
[1] E. Haseltine, Discover Magazine (2002)

MOTIVATION

- Half lives modify the abundance curve

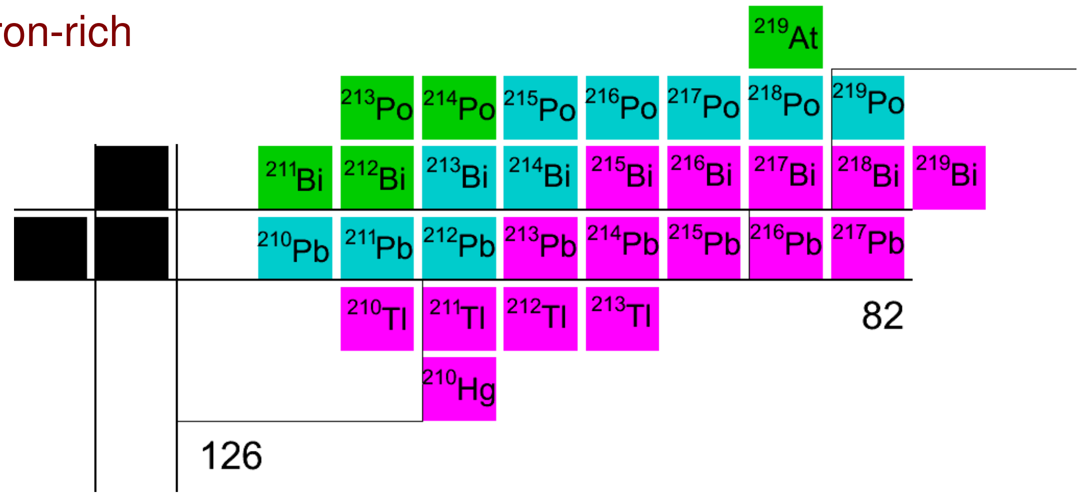


- Experimental lifetimes will constrain theoretical predictions around N~126



- Our goals:

  - Measure the structural properties of neutron-rich nuclei in the "east" side of ^{208}Pb using:
    - Isomeric spectroscopy
    - β-delayed gamma ray spectroscopy
  - Measure their β-decay half-lives



[1] P. Möller et al., PRC (2003)
[2] I.N. Borzov and S. Goriely, PEPAN (2003)

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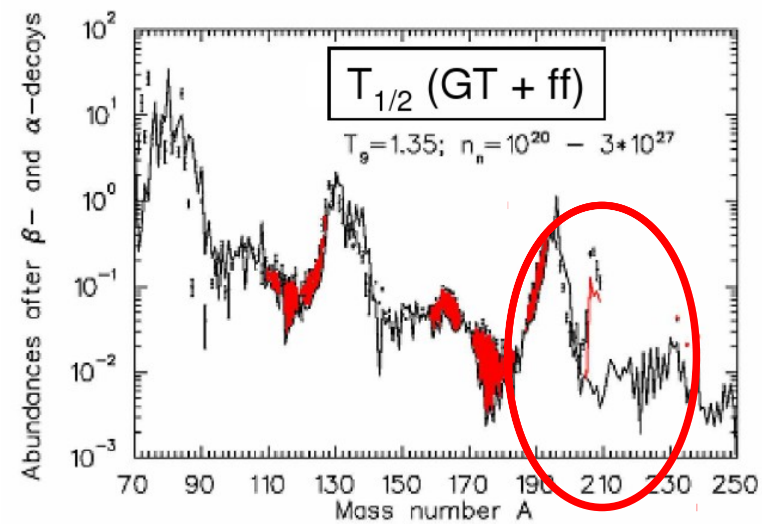

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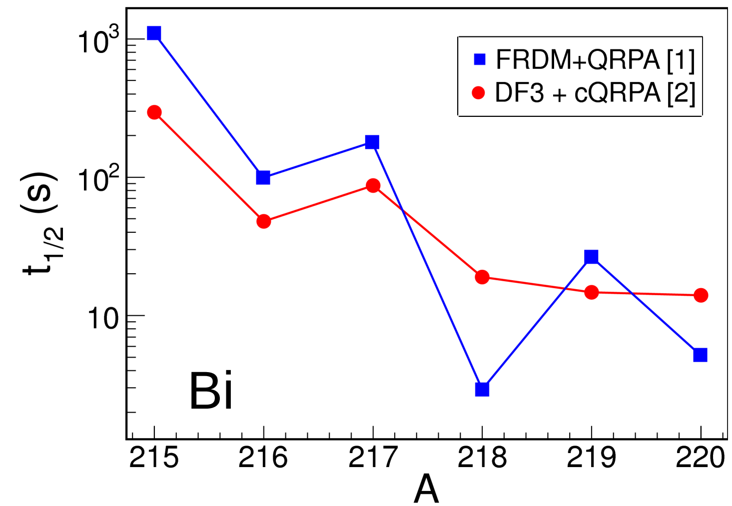

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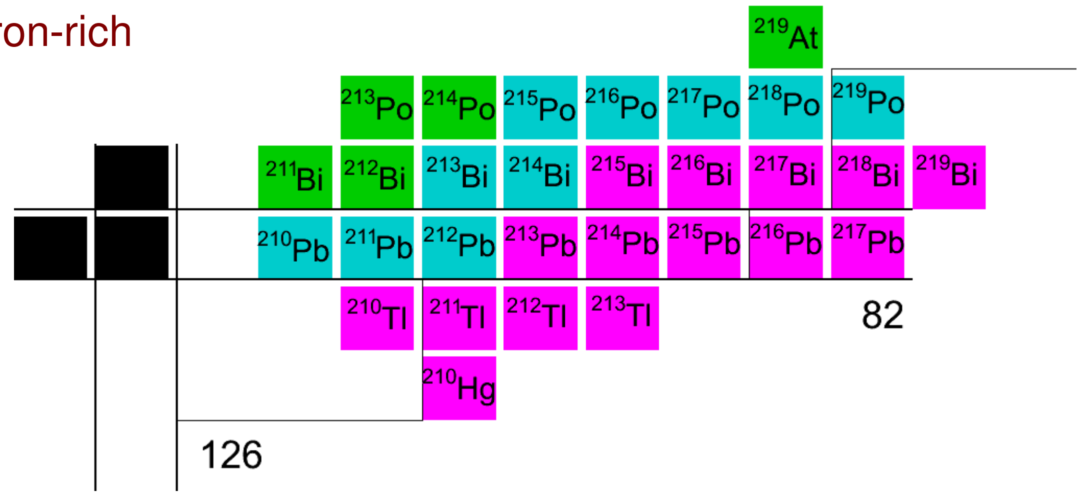

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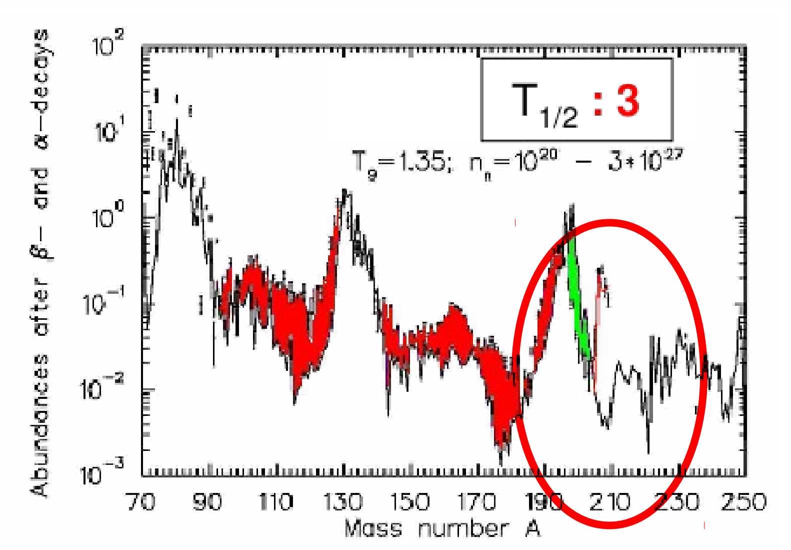

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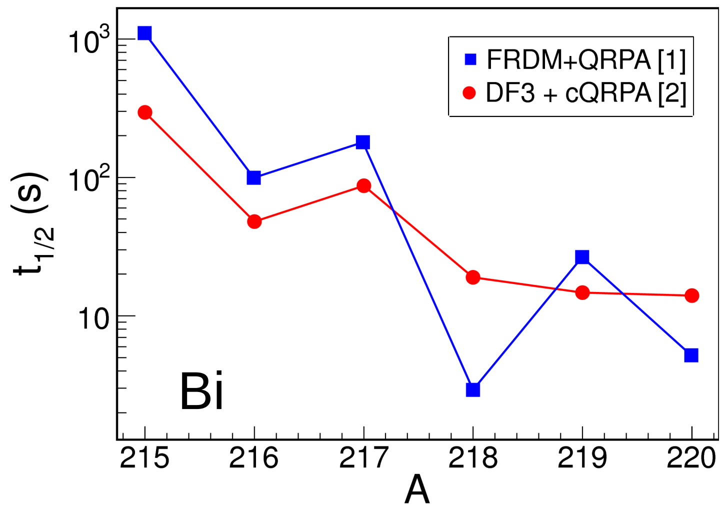

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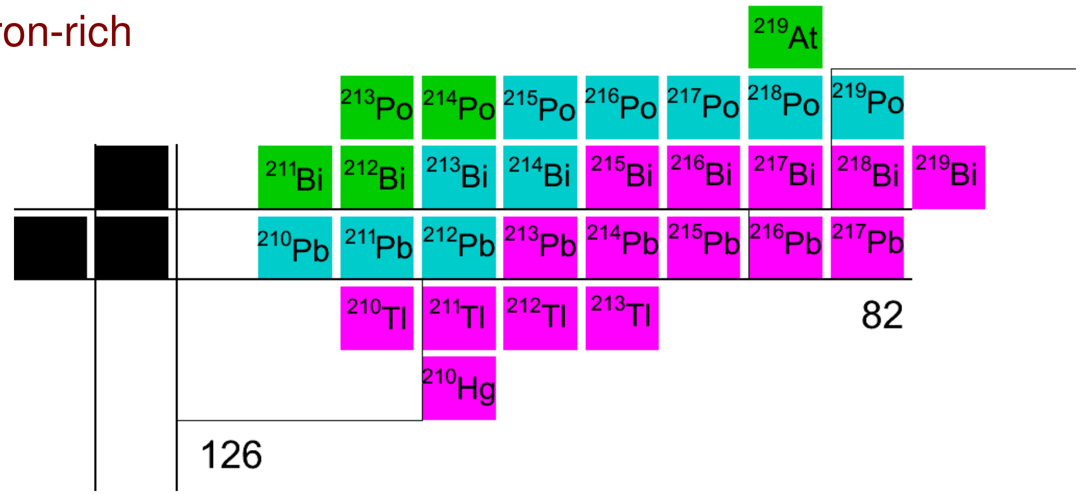

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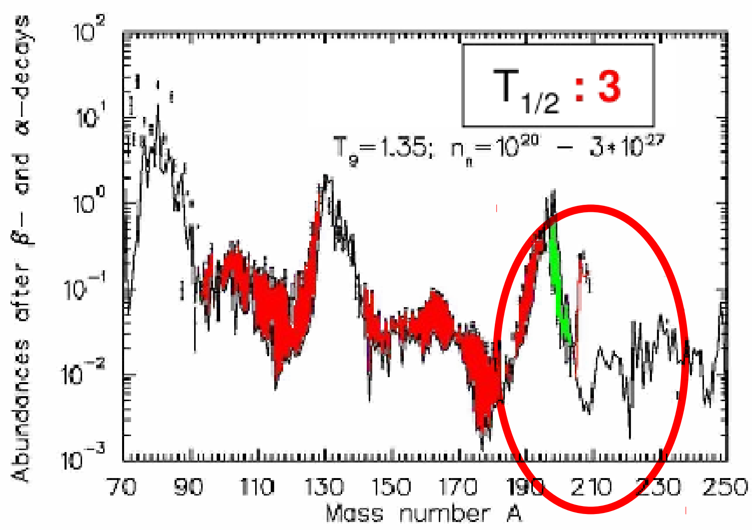

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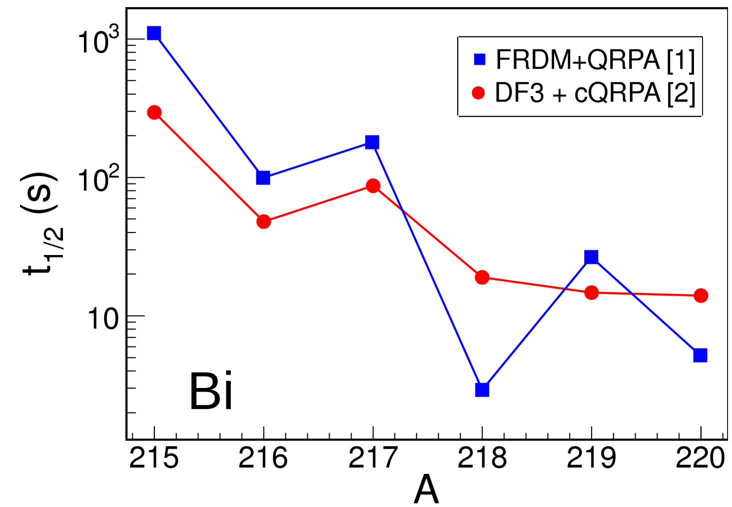
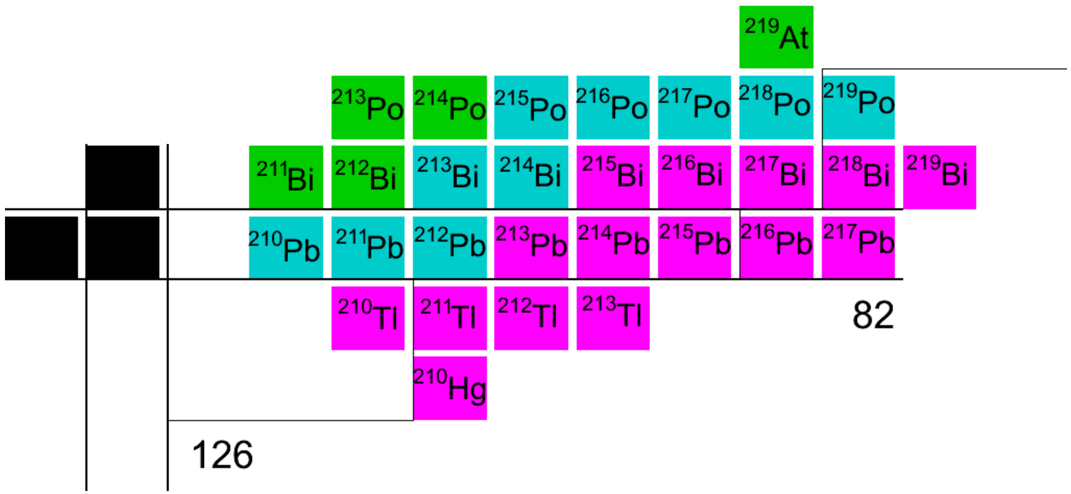


- Previous investigations in this region:

✓ ^{211}Pb [1,2] ✓ ^{213}Tl [3] ✓ ^{218}Bi [4]

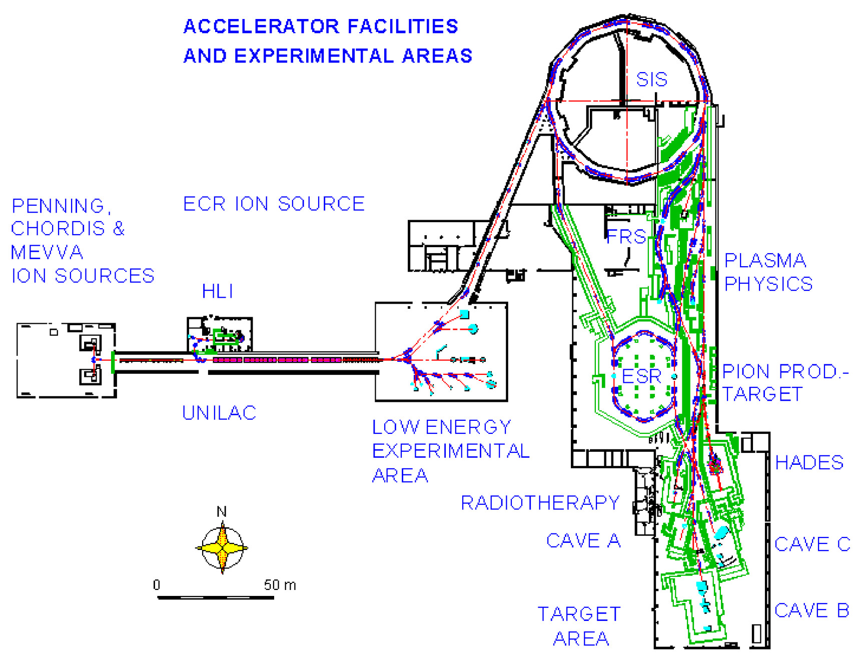


[1] G.J. Lane et al., PLB (2005)
[2] C. Ellegaard et al., NPA (1976)
[3] L. Chen et al., PLB (2010)
[4] H. de Witte et al., PRC (2004)

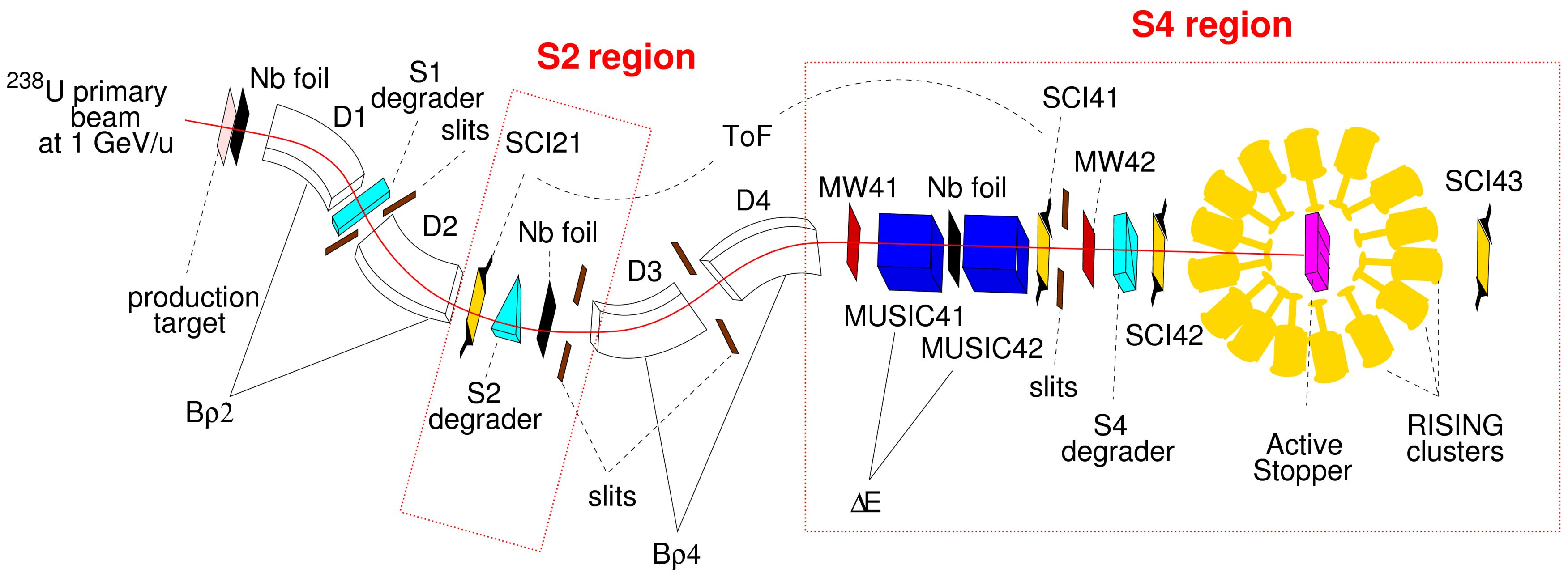
THE EXPERIMENT

EXPERIMENTAL TECHNIQUE

- Inverse kinematics [(^{238}U+^{9}Be) at 1 GeV/A]
  - ✓ In-flight projectile fragmentation
  - ✓ Good charge-state rejection
- β-decay studies
  - ✓ Projectile residues stopped in a β-delayed spectroscopy set up
  - ✓ Heavy ion-β-γ correlations



EXPERIMENTAL SET UP



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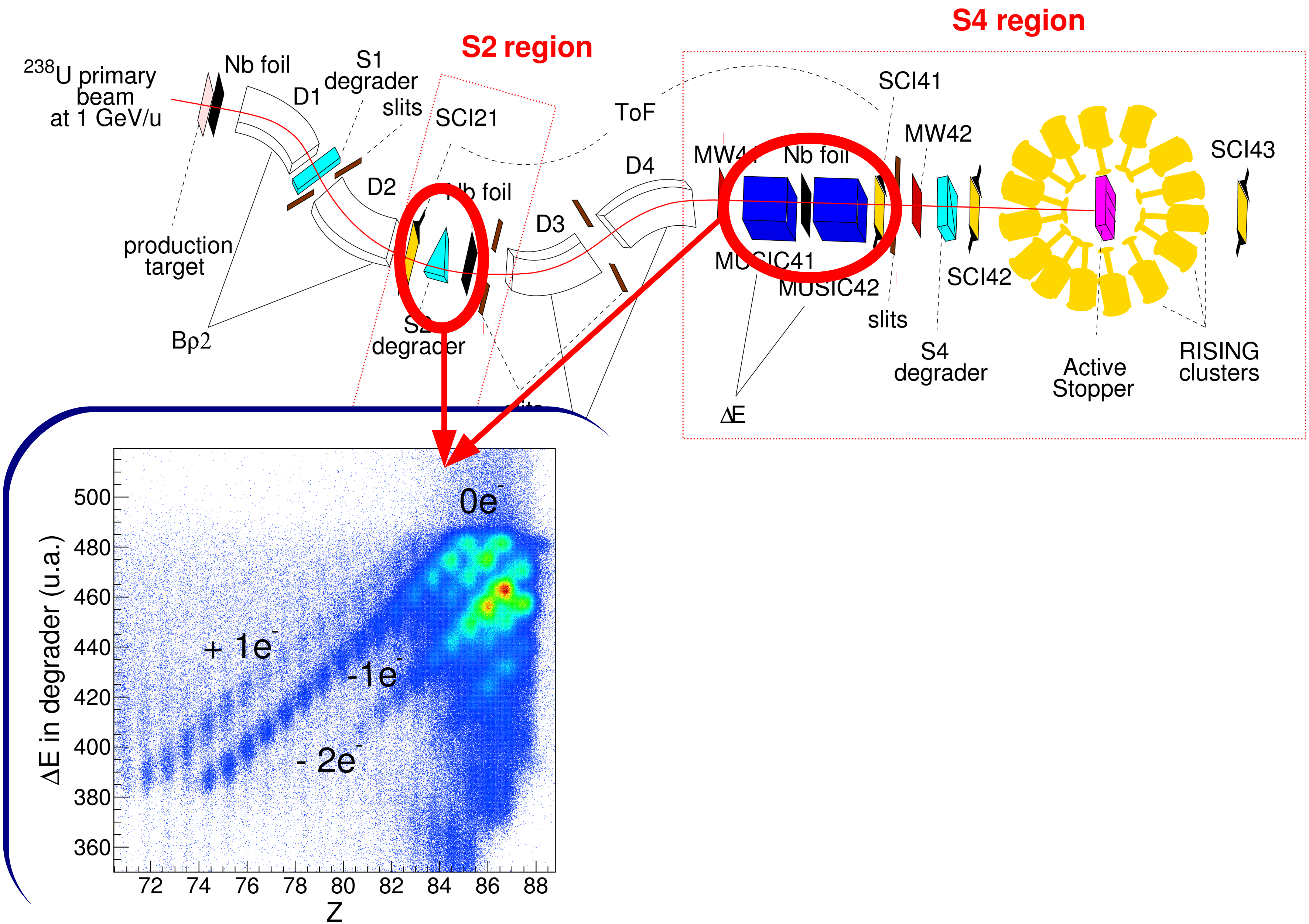

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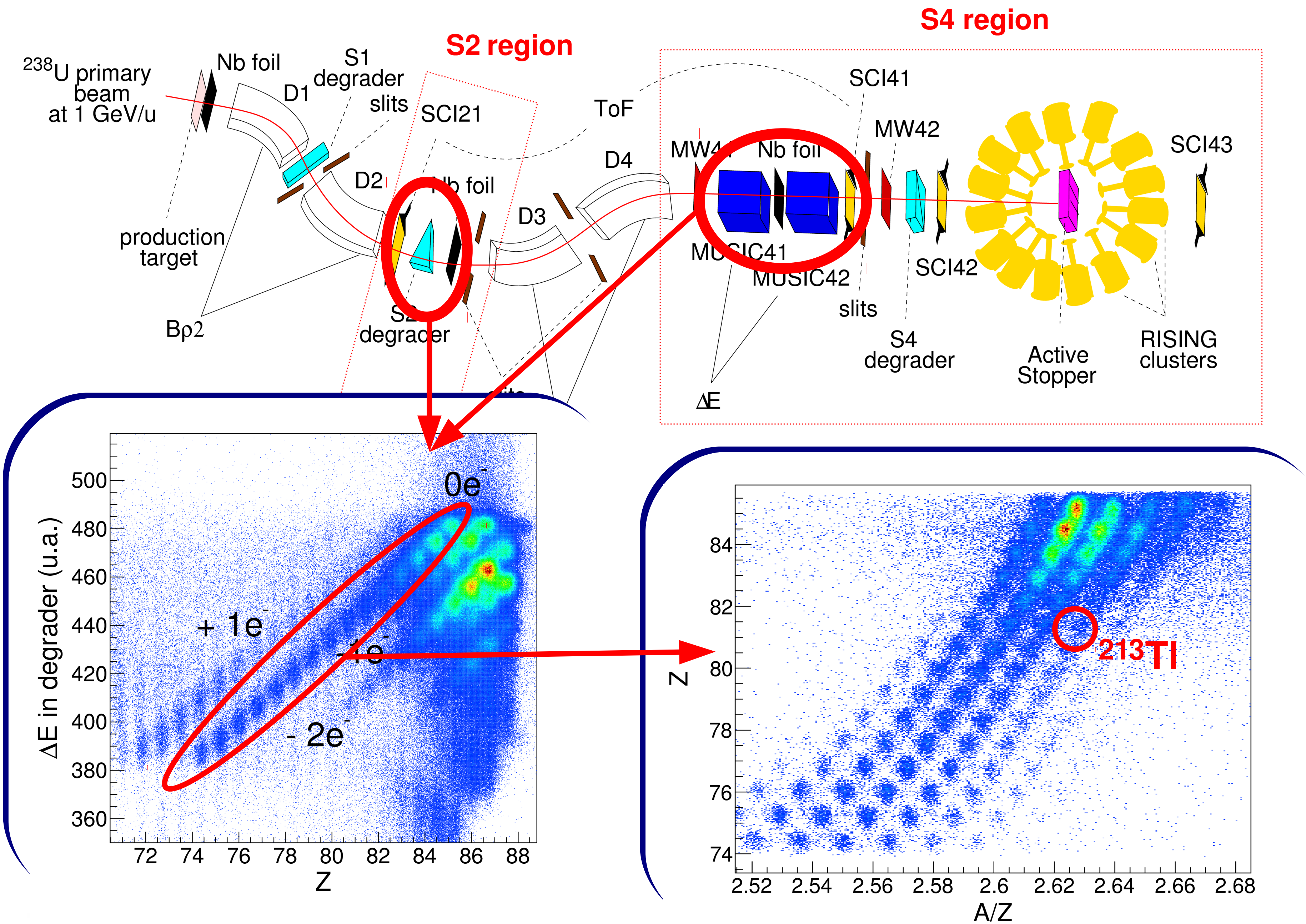
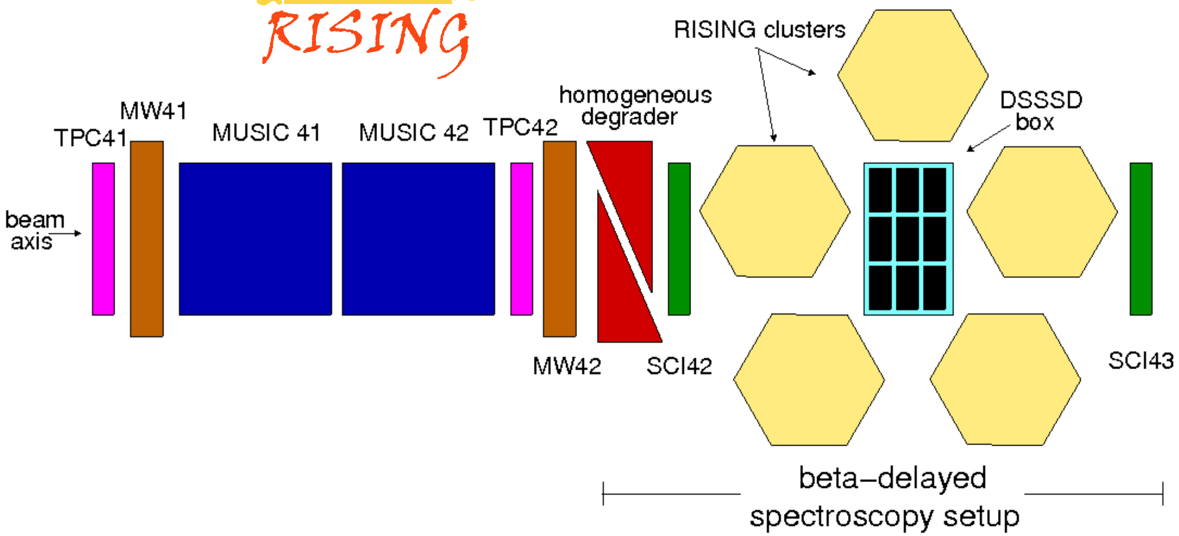


β–DELAYED SPECTROSCOPY SET UP

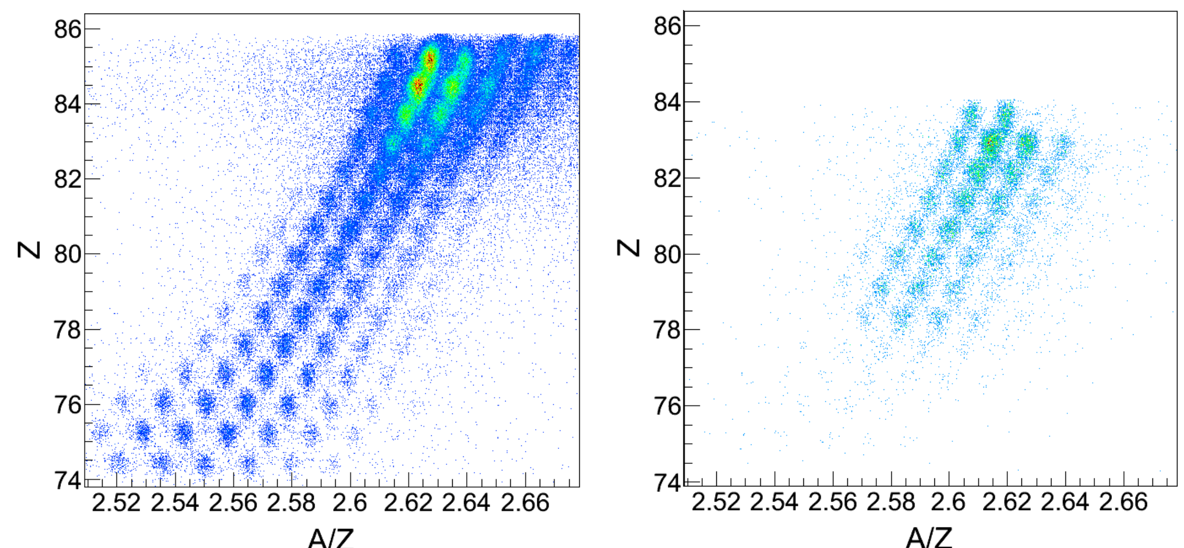
RISING



β-delayed spectroscopy set up

- ✓ Variable thicknes Al degrader
- ✓ Veto scintillators (SCI42 + SCI43)
- ✓ Active Stopper
- ✓ RISING γ-ray spectrometer

- ➢ Fragments slowed down in the homogeneous Al degrader
- ➢ Halted in the Active Stopper



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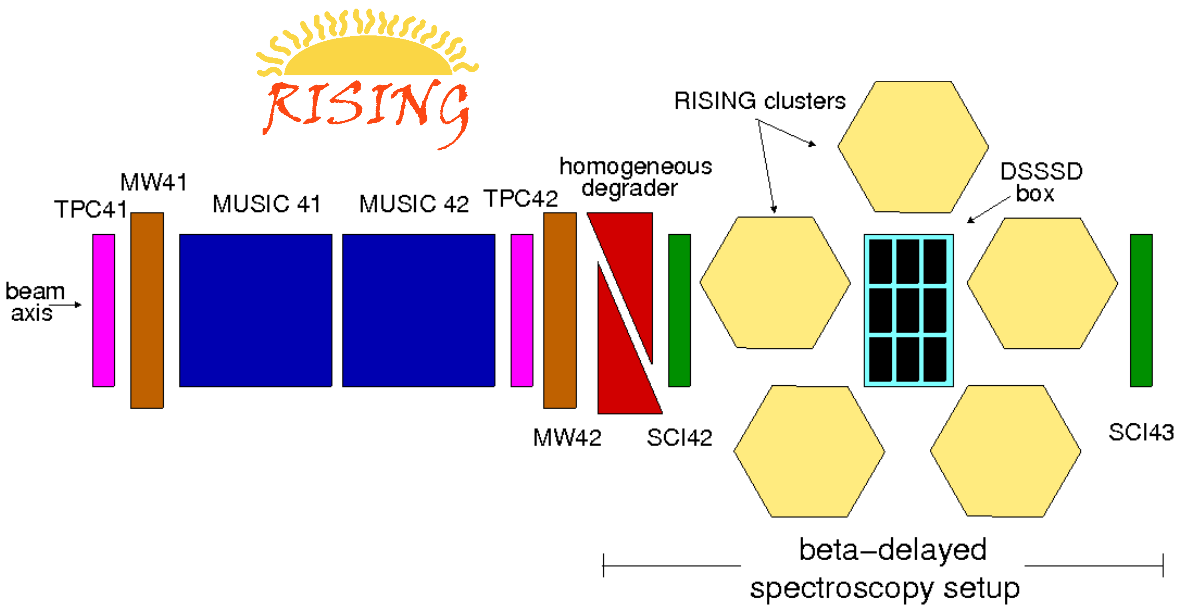

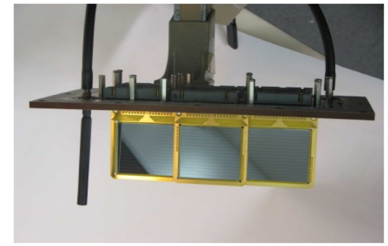

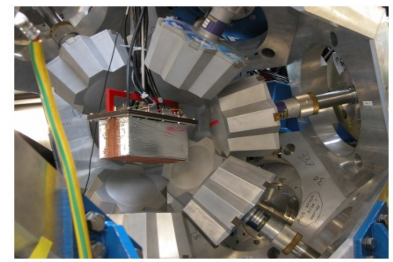

- Active Stopper: Ion-β time-position correlations
- RISING γ-array: β-γ prompt-time correlations

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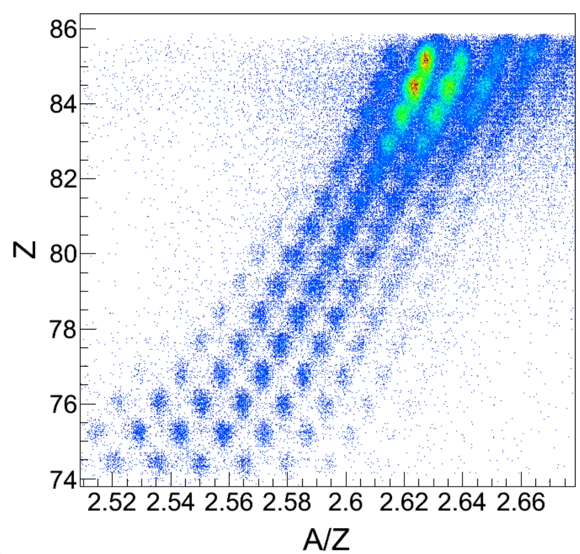

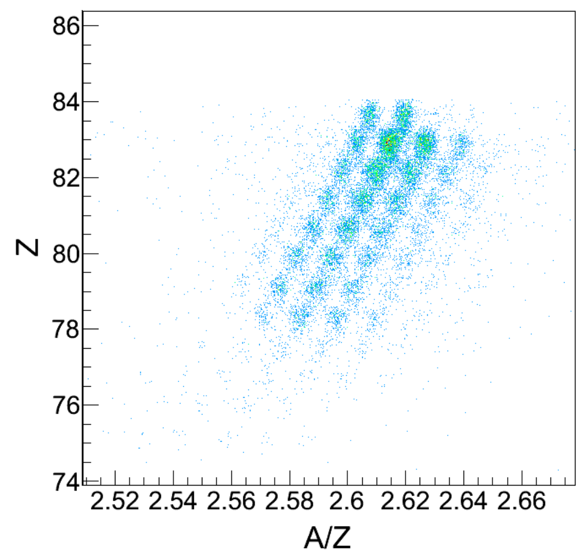

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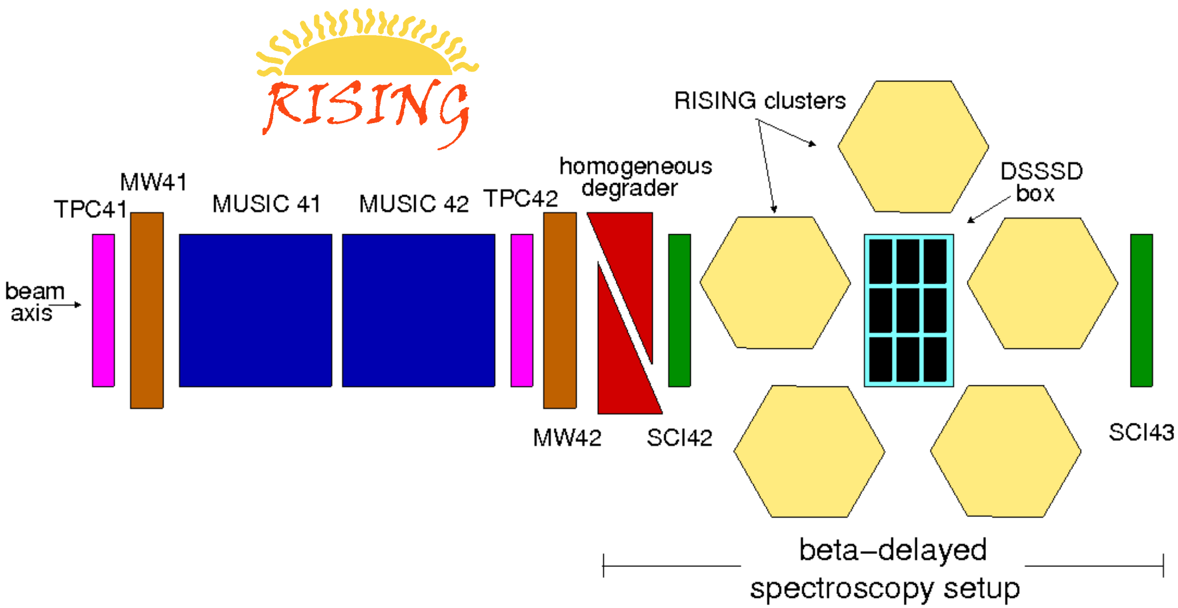

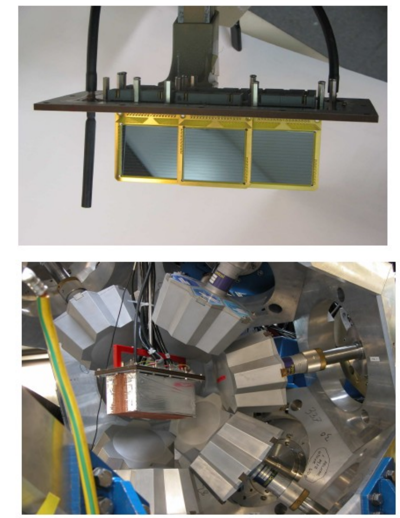

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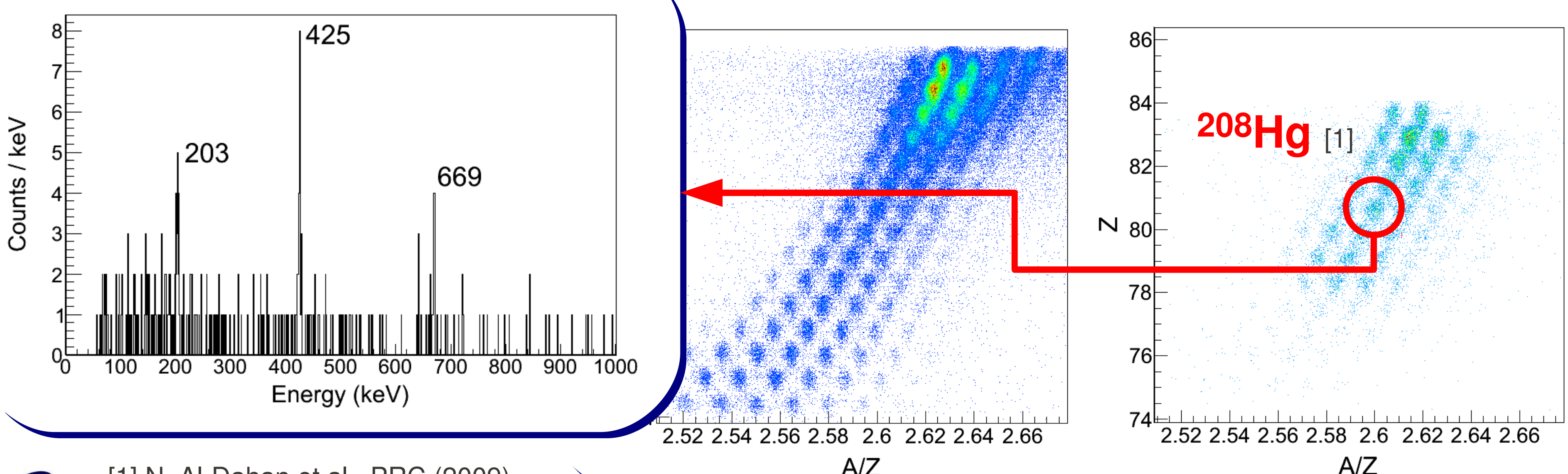

[1] N. Al-Dahan et al., PRC (2009)

ISOMERIC SPECTROSCOPY

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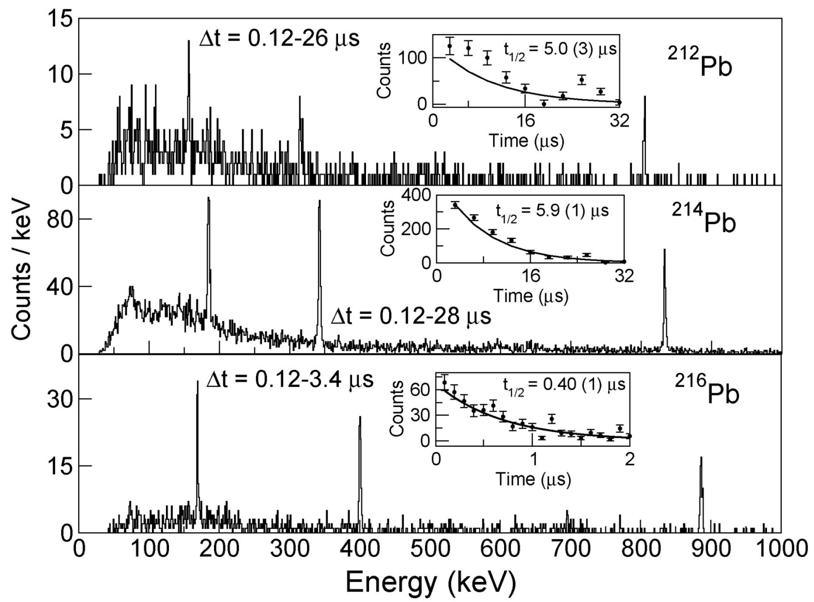
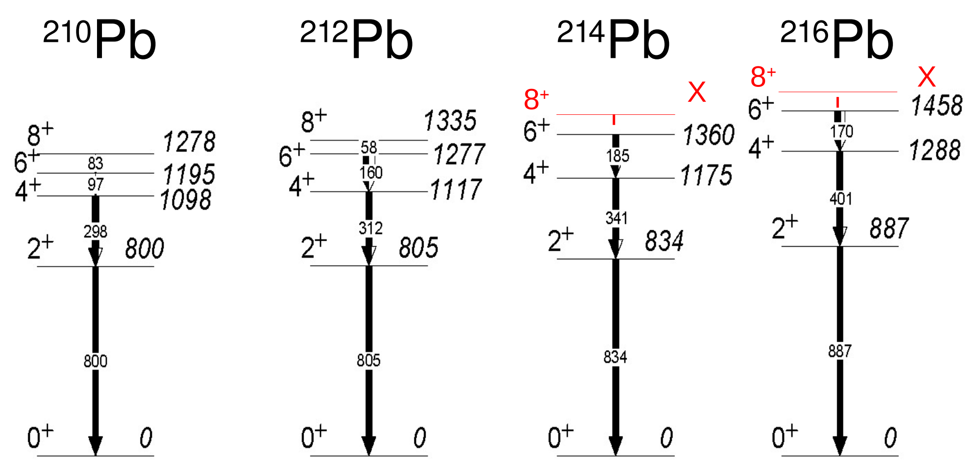
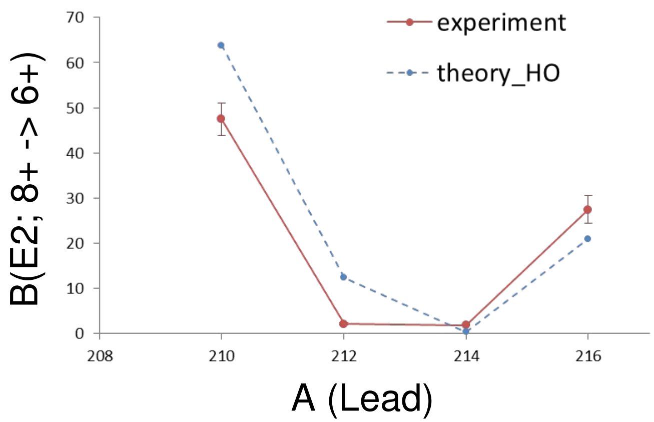


A. Gottardo et al., to be published

The expected seniority scheme in the even-even Pb isotopes is confirmed by the observation of the 8^+ isomer





Experimental B(E2) differ significantly from theory

- Further investigation on the coupling to quadrupole excitations
- Inclusion of three-body forces and the associated two-body transition operators

β-DECAY DELAYED SPECTROSCOPY

β–DECAY DELAYED SPECTROSCOPY

Characterization of low-lying excited states

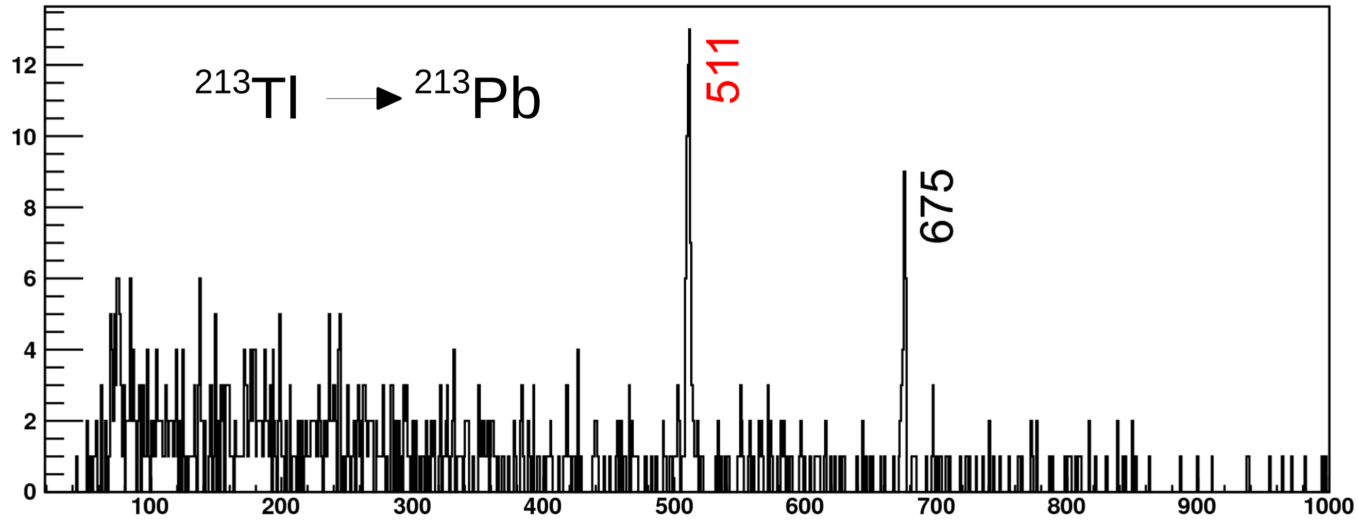
- Ion-β time-position correlations

✓ Between fragments and β-decays detected in the same pixel

✓ Between a fragment and the first β-decay detected during the beam pause in a maximum time $T=3T_{1/2}$

Characterization of background

- Uncorrelated decays are determined from backward-time ion-β correlations



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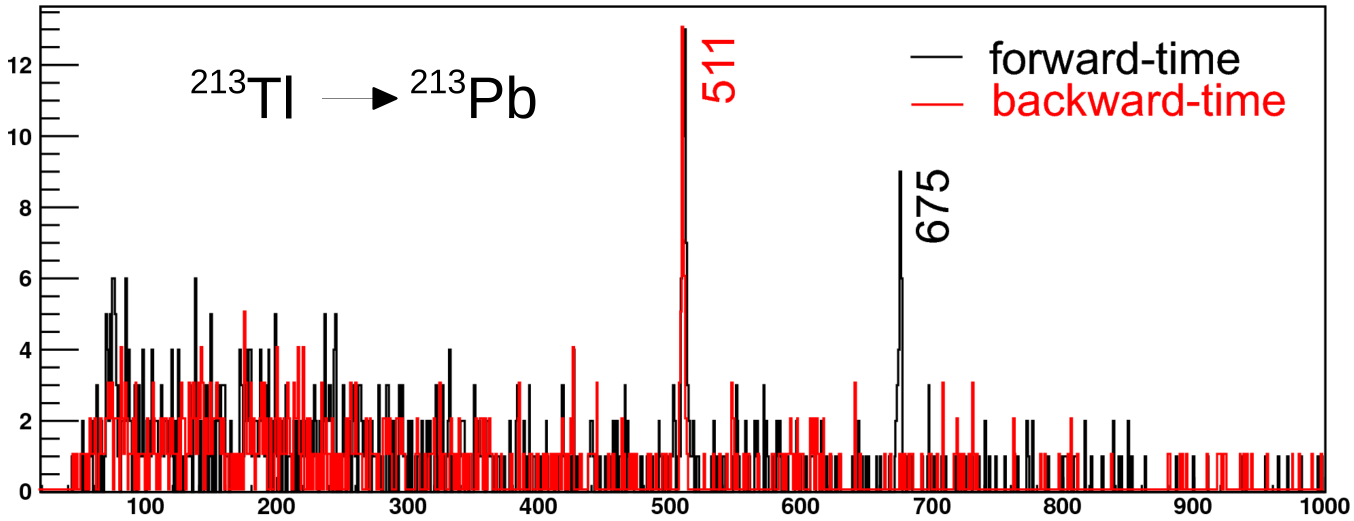
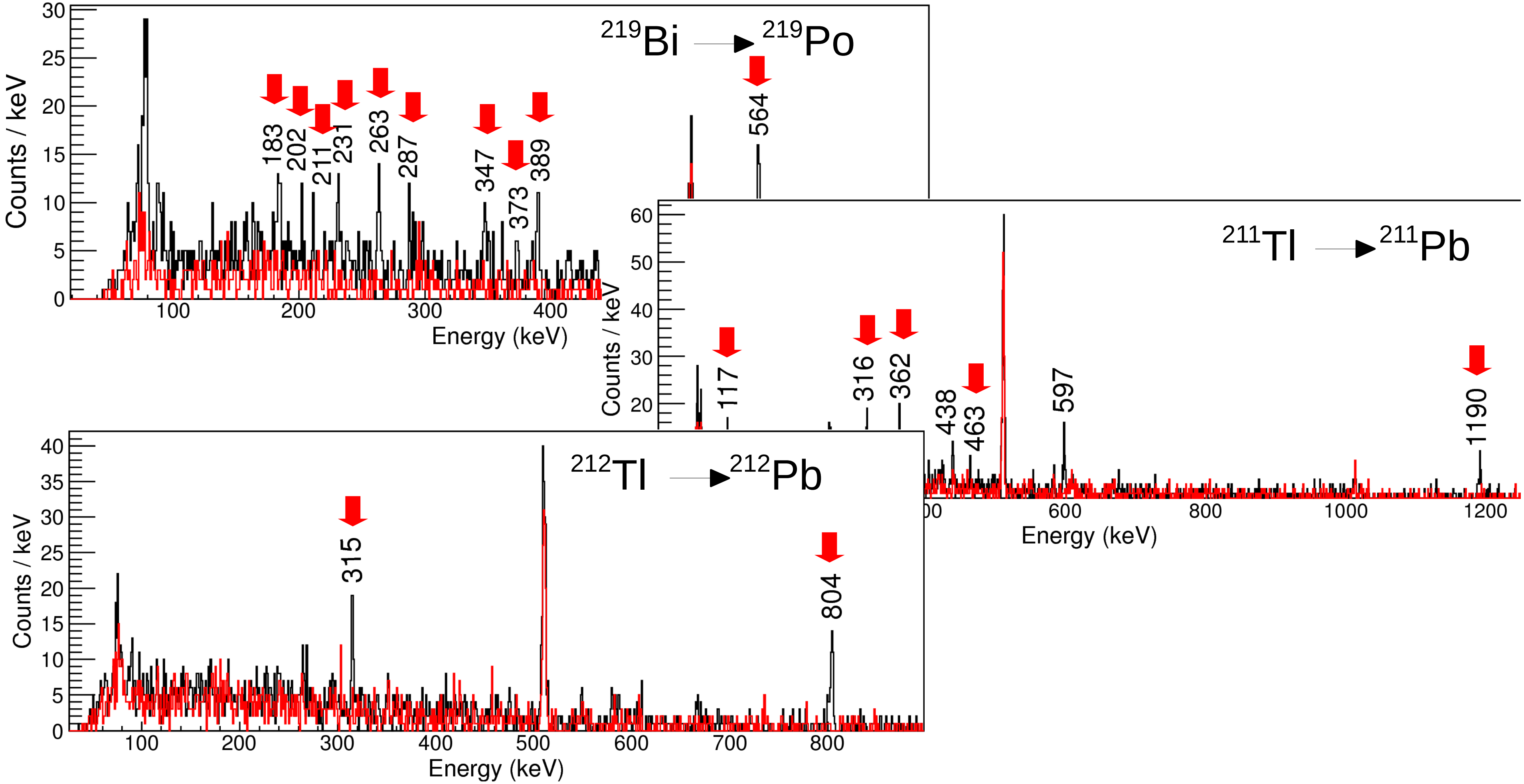


Also new spectroscopic information on ^{219}Po, $^{211-212}Pb$!



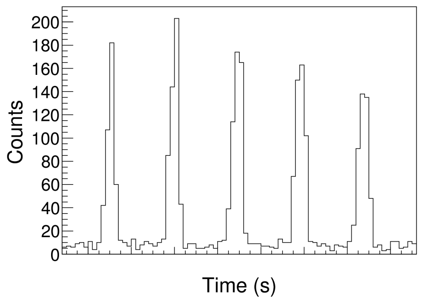
MEASUREMENT OF β–DECAY HALF LIVES

Background sources

- δ-electrons
- β-decay electrons from other nuclides
- “false” β-decays / implantations

Lifetime measurement

- Standard exponential fits
- Novel numerical procedure [1]



[1] T. Kurtukian-Nieto et al.., NIMA 67, 055802 (2008)

Background evaluation

➢ The reverse time sequence of ion-β correlations reproduces qualitatively the shape
Of the remaining background in the β-decay curves

Numerical Fit

➢ Based on Monte Carlo simulations of the implantation-decay process including experimental implantation rates and having as free parameters the β decay half life and the β detection efficiency

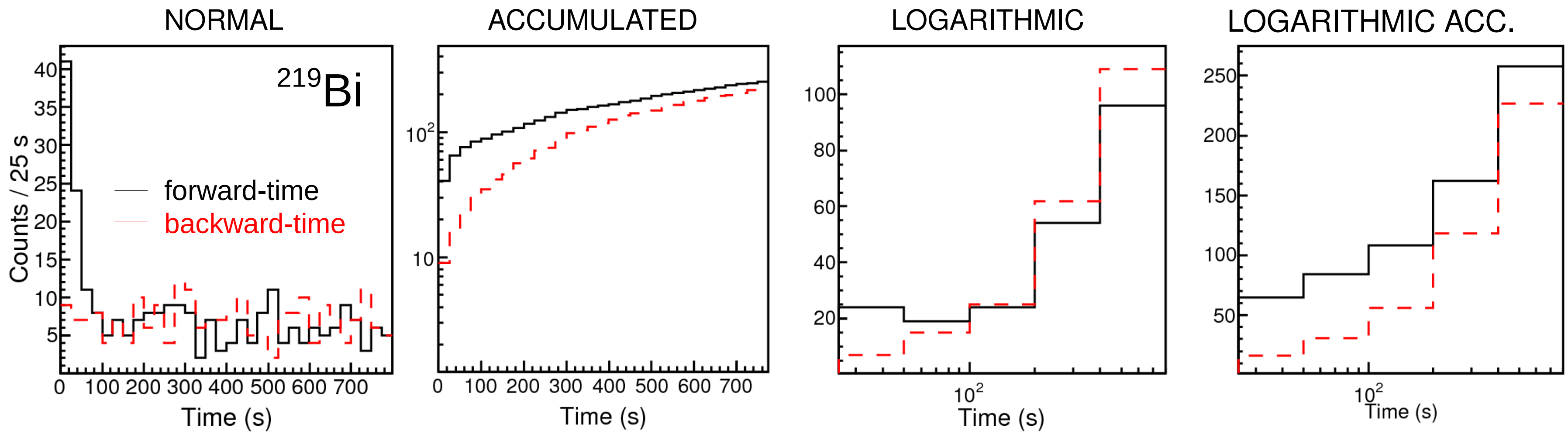
➢ χ^2 fits to two independent time correlations:

- Experimental ion-β time-correlated spectra
- Calculated time distribution obtained from Monte-Carlo simulations

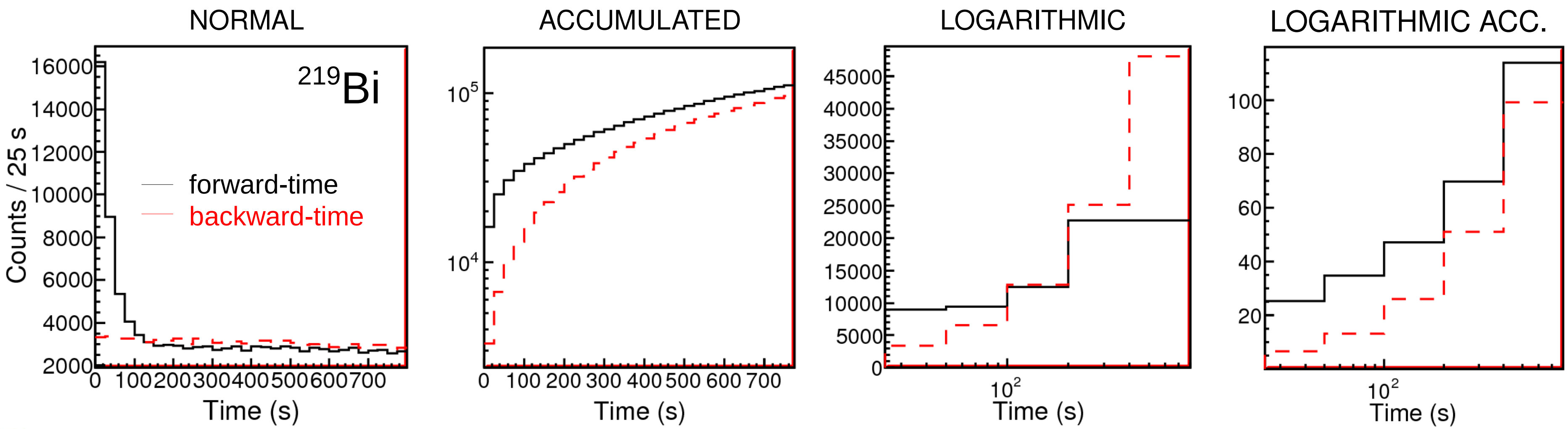
➢ Fitting function: ratio of forward/backward time-distribution functions

TIME CORRELATED SPECTRA

Experimental Distributions

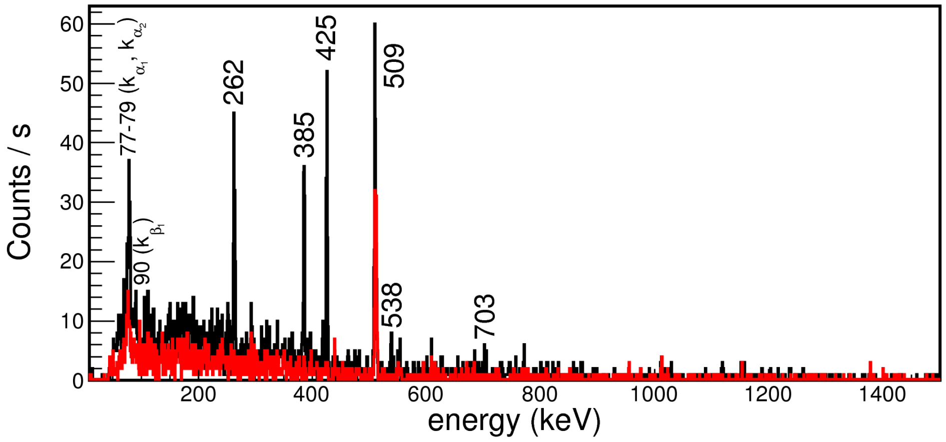


Simulated Distributions



^{218}Bi: Benchmark Of The Analysis

- This work:



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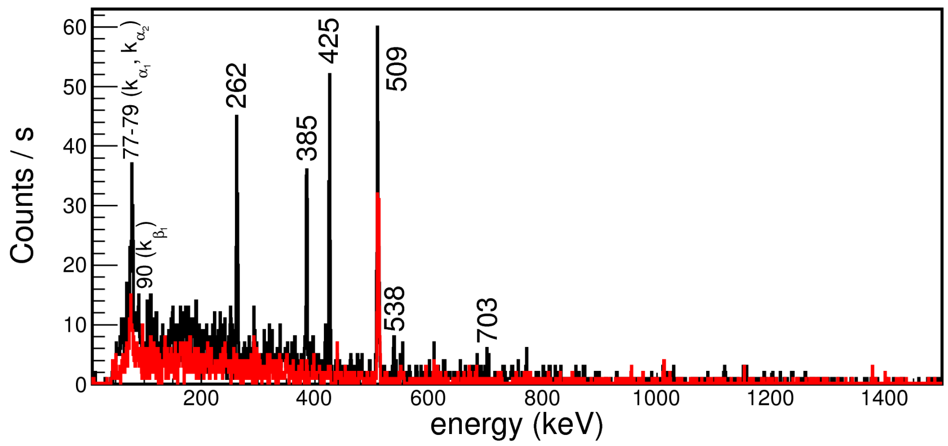

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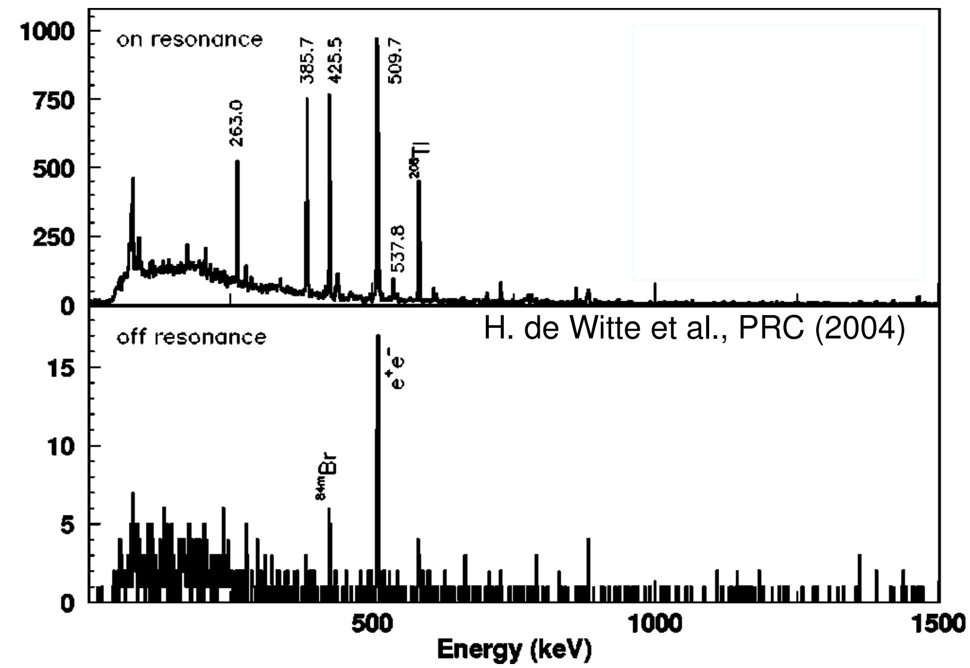

H. de Witte et al., PRC (2004)

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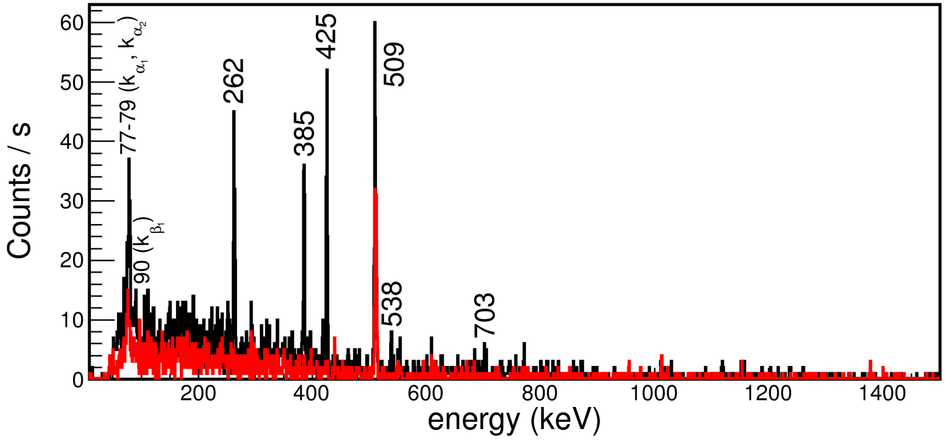

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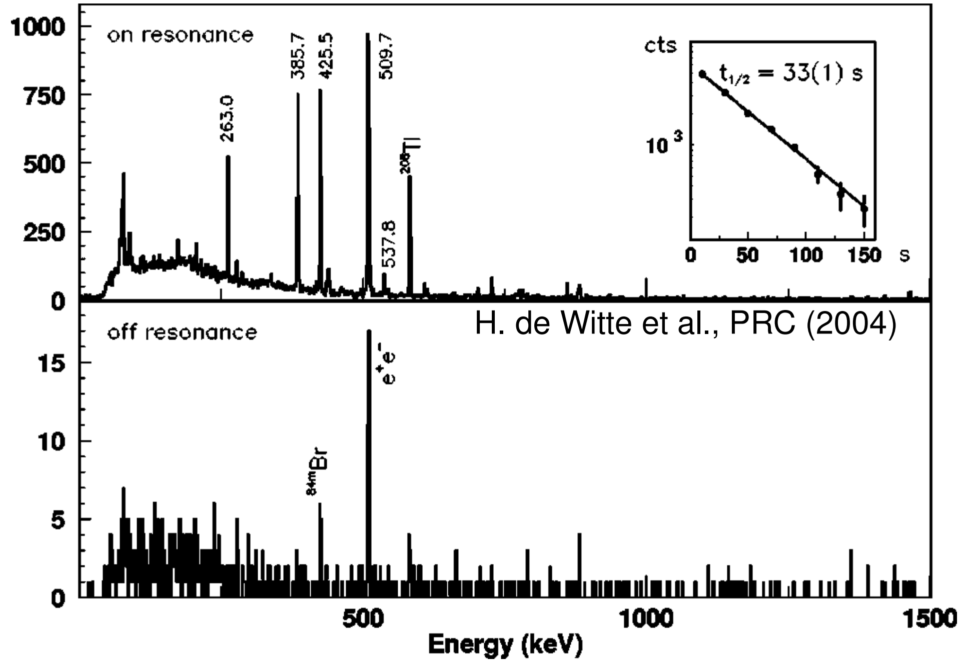

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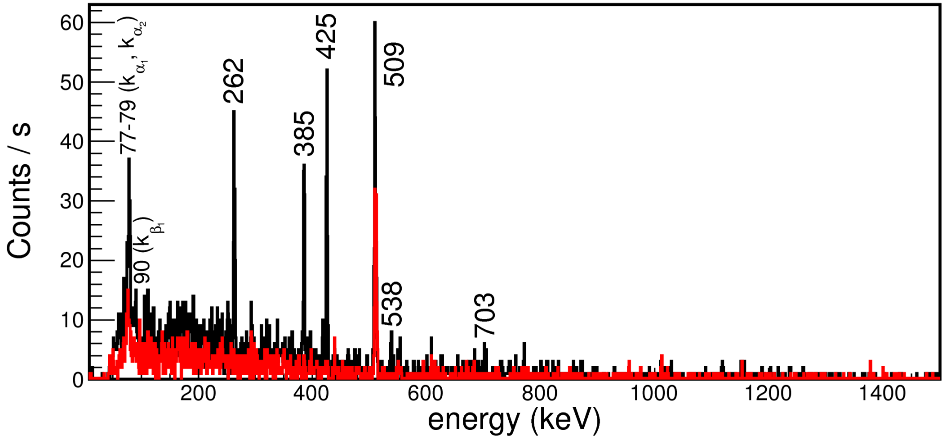

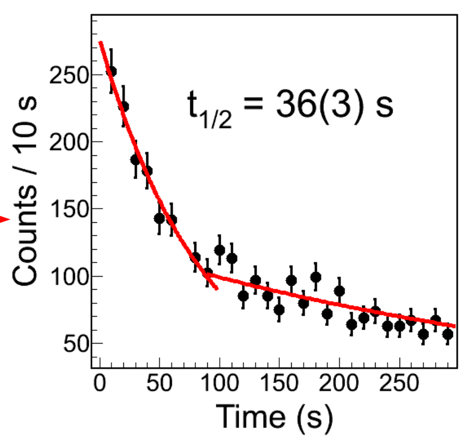

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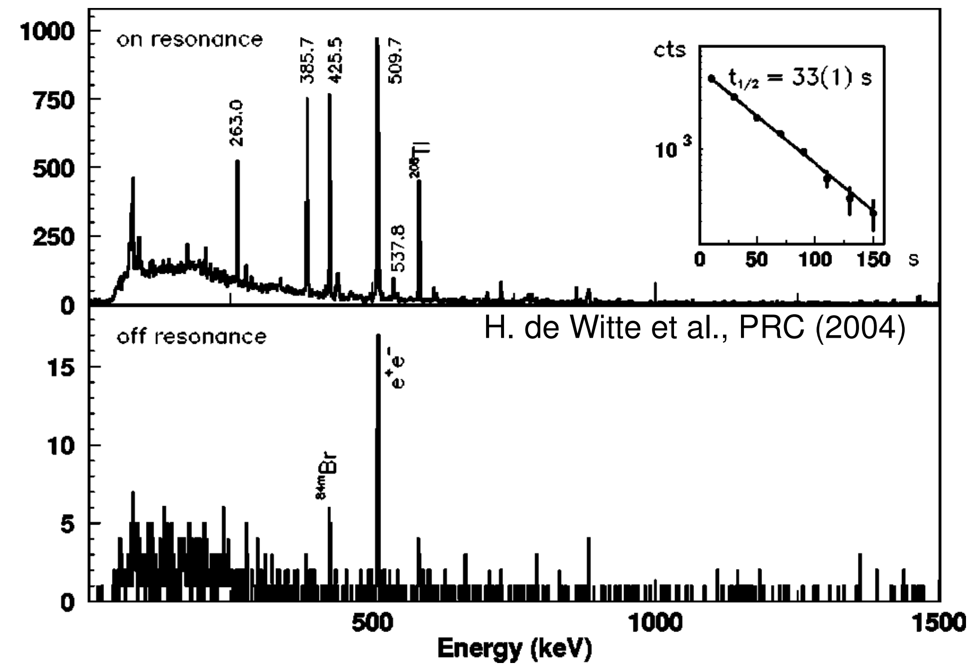

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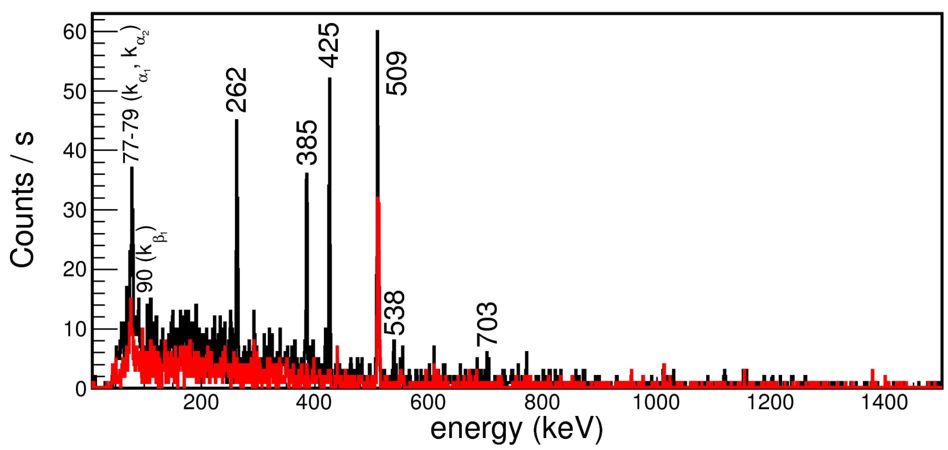

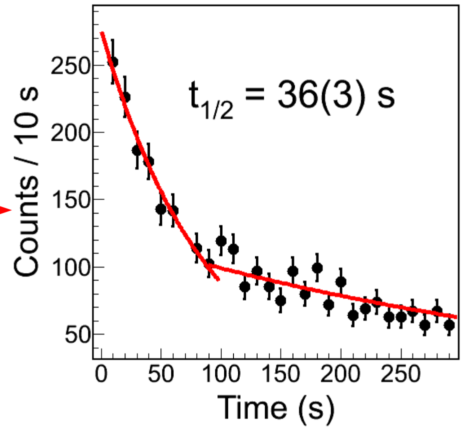

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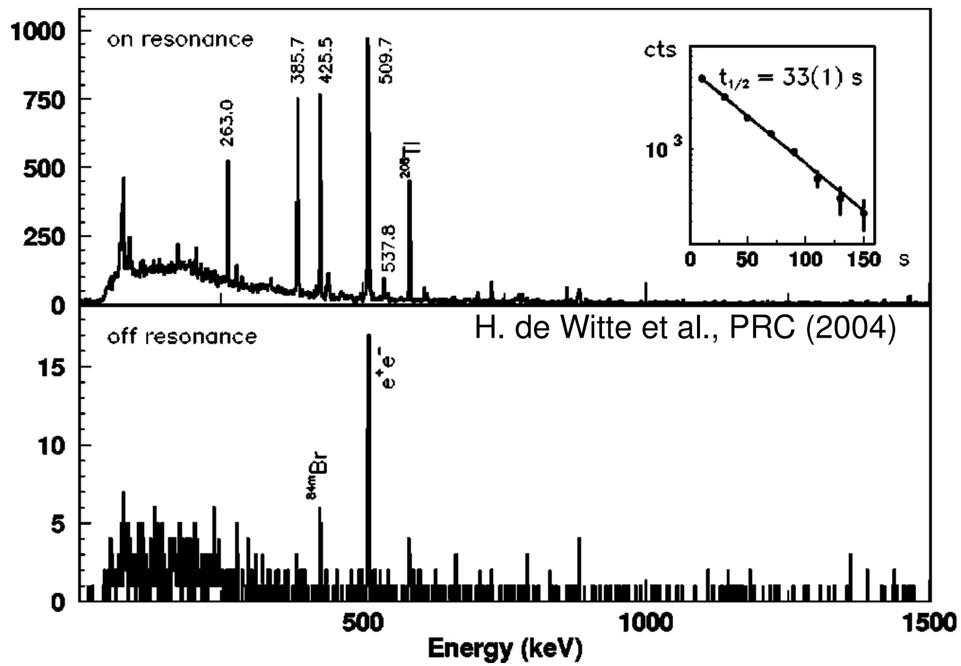

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- Suppression of δ-electrons induces slightly longer time correlations

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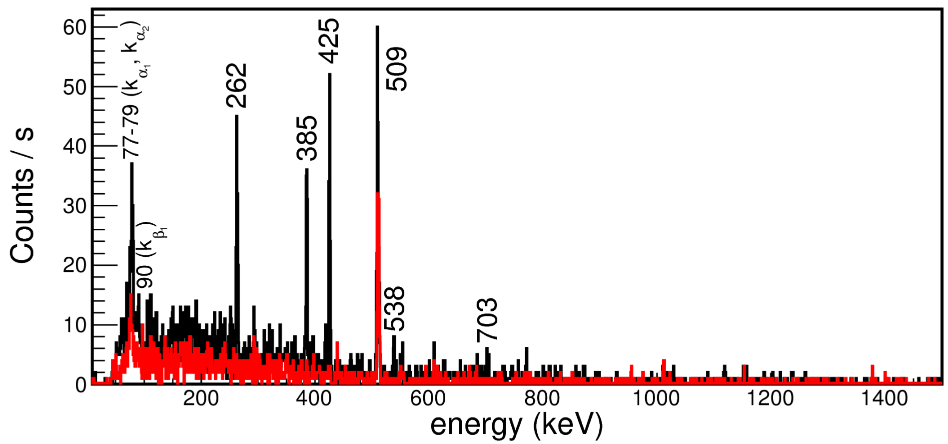

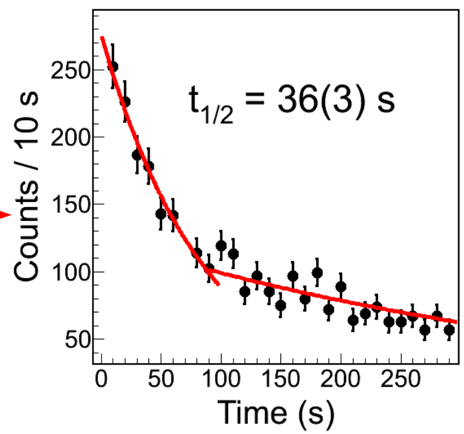

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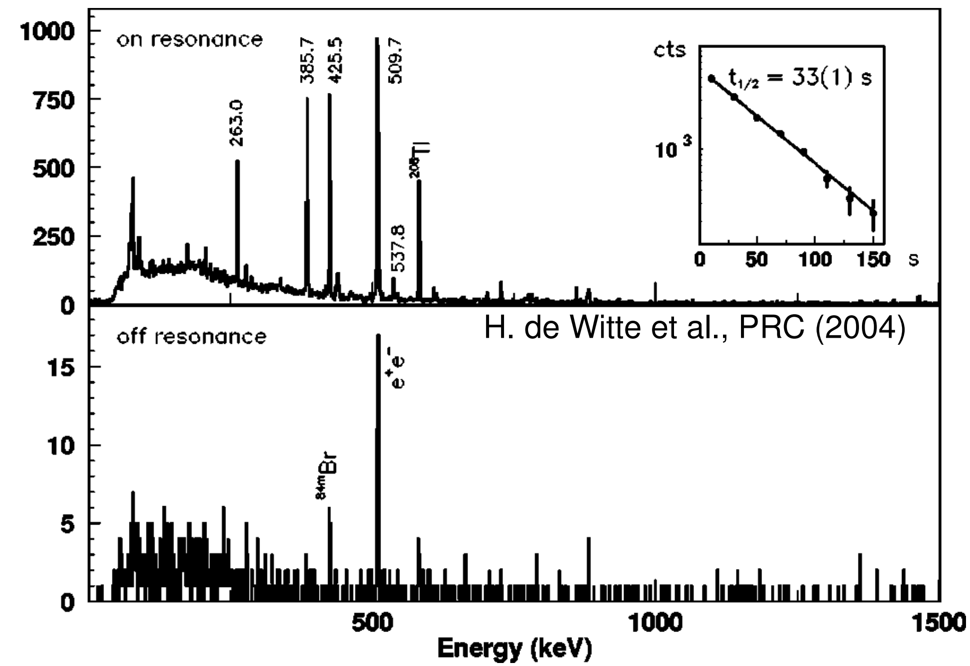

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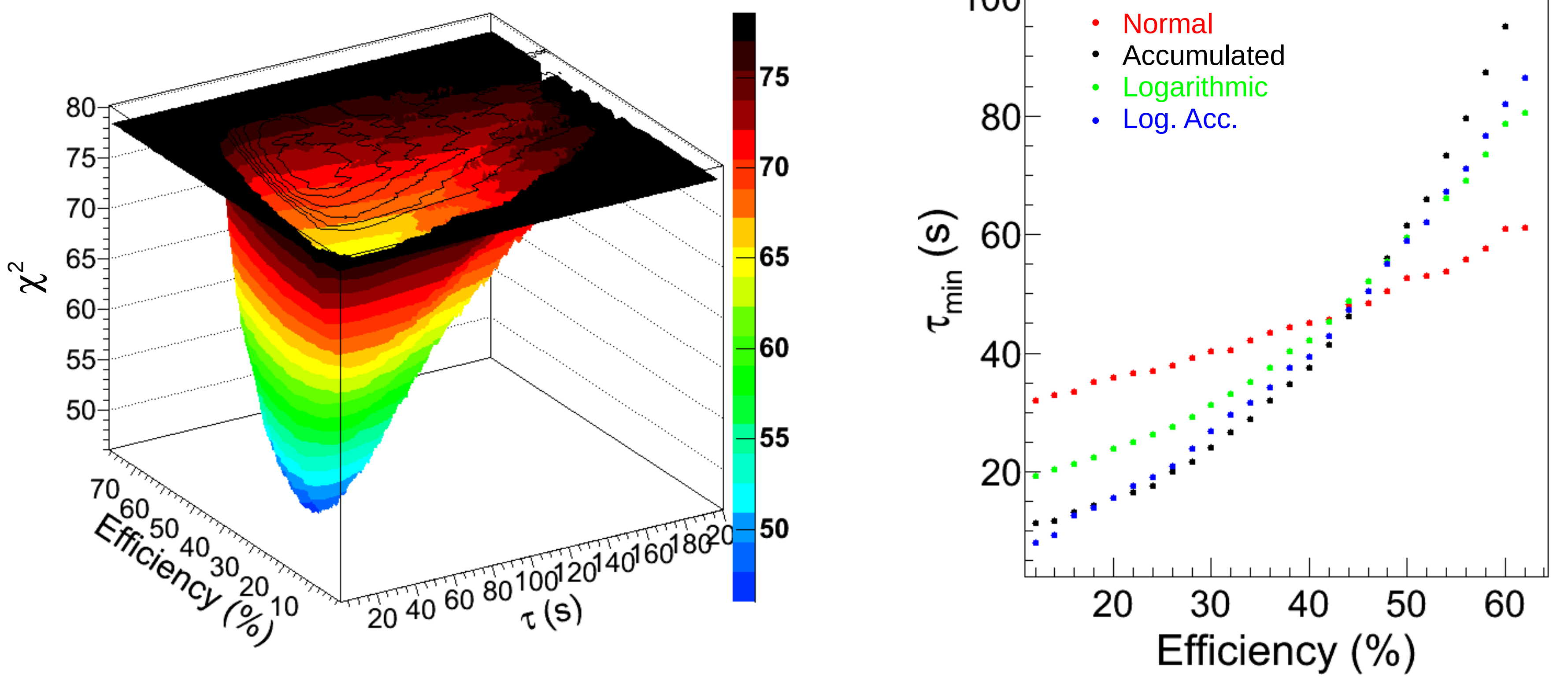
Cross-check with numerical fit

MEASUREMENT OF β–DECAY HALF LIVES

^{218}Bi: Example Of The Applicability Of The Numerical Fit



MEASUREMENT OF β–DECAY HALF LIVES

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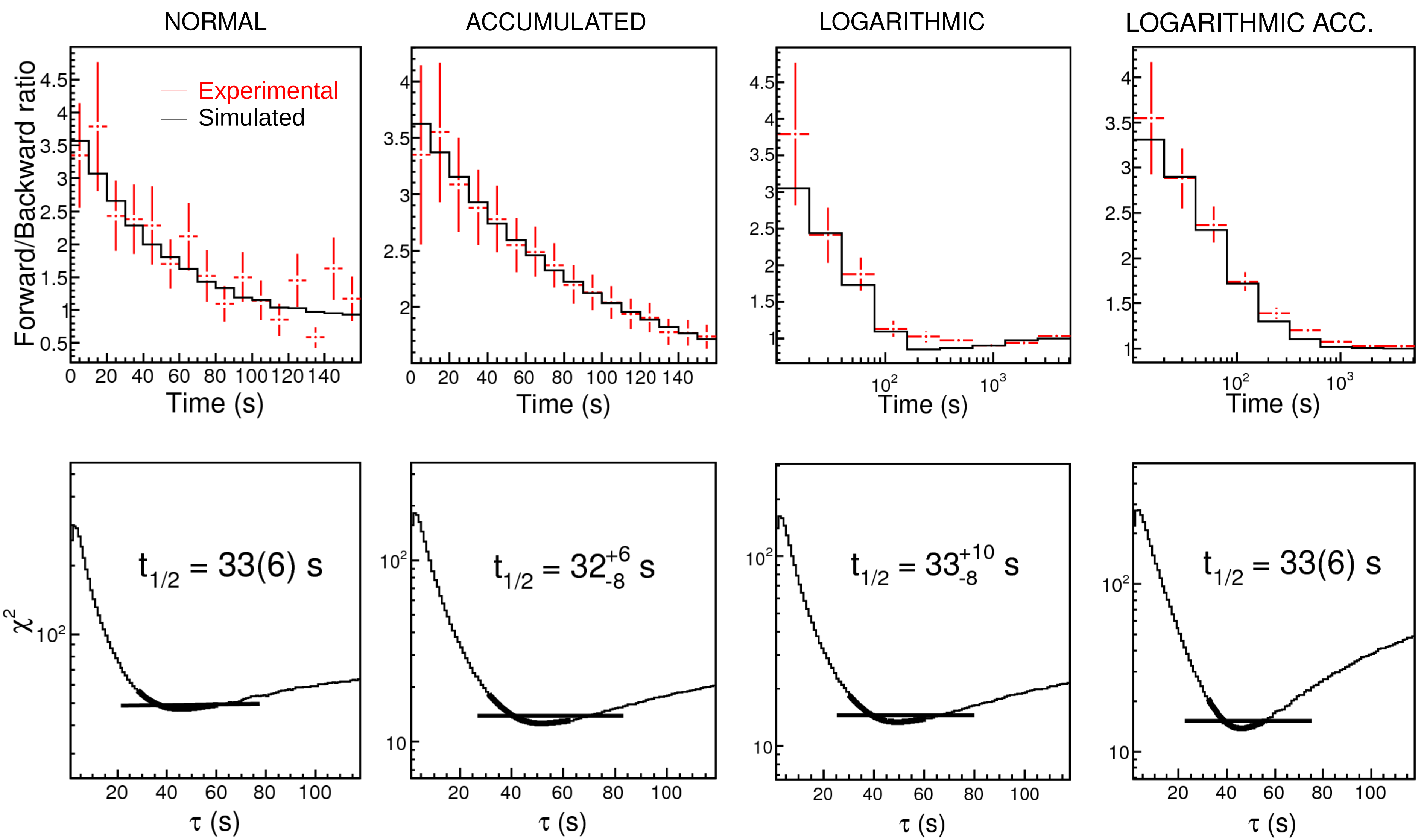

MEASUREMENT OF β–DECAY HALF LIVES

Applicability of the numerical fit

- In order to obtain a plausible value of the half live, it is essential to define a figure of merit *F*

$$F = \frac{N_{true}}{\sqrt{(N_{back})}} = 3$$

✓ For a given value of F, there is an upper limit of the half live $T_{1/2}$ measurable!!

Results

- Previously reported half lives:
  - ✓ $t_{1/2}$ (^{218}Bi) [1] = 33 ± 1 s
  - ✓ $t_{1/2}$ (^{213}Tl) [2] = 101^{+484}_{-46} s

[1] H. de Witte et al., PRC (2004)
[2] L. Chen et al., PLB (2010)

Nucleus	E_γ (keV)	$t_{1/2}$ (s)	t_F (s)	F	$T^{max}_{1/2}$ (s) (F=3)
^{219}Bi	564	22^{+13}_{-9}	1852	17.4	653
^{218}Bi*	385	33^{+7}_{-7}	769	23.5	789
^{213}Tl*	675	46^{+55}_{-26}	3846	7.4	265
^{212}Tl	804	96^{+42}_{-28}	2128	15.0	1509
^{211}Tl	597	88^{+46}_{-29}	1470	14.9	1337

MEASUREMENT OF β–DECAY HALF LIVES

^{213}Tl: An Improved Lifetime Measurement

- Previous measurement (SMS)
  - ✓ FRS + ESR
  - ✓ Mother and daughter nuclei are counted simultaneously in their decay and appearance, respectively

L. Chen et al., PLB (2010)

- This work (delayed coincidence technique):
  - ✓ FRS + RISING set up
  - ✓ Time and position of implanted nuclei and subsequent β-decays are registered in the RISING Active Stopper

MEASUREMENT OF β–DECAY HALF LIVES

^{213}Tl: An Improved Lifetime Measurement

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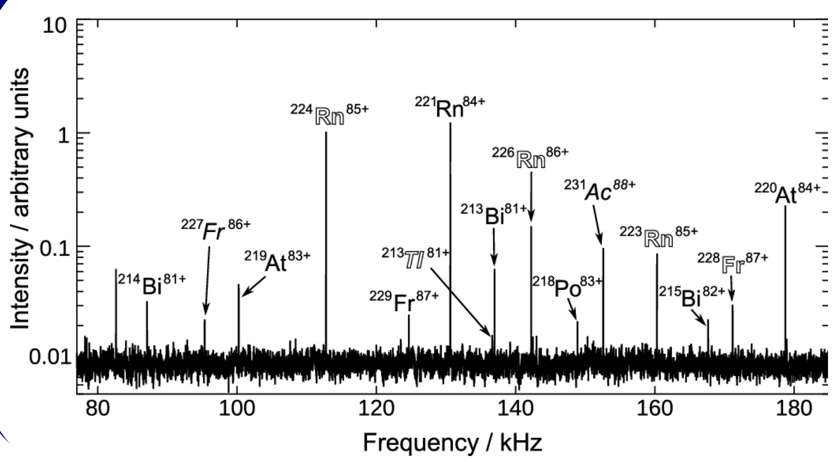

L. Chen et al., PLB (2010)

- This work (delayed coincidence technique):
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MEASUREMENT OF β–DECAY HALF LIVES

^{213}Tl: An Improved Lifetime Measurement

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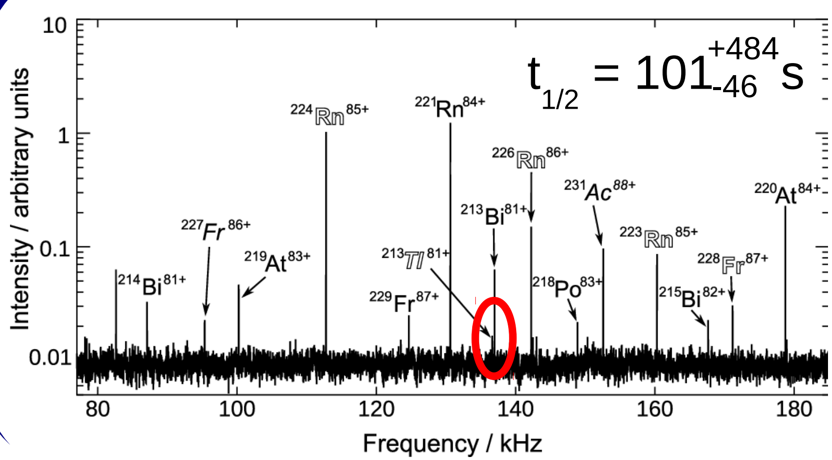

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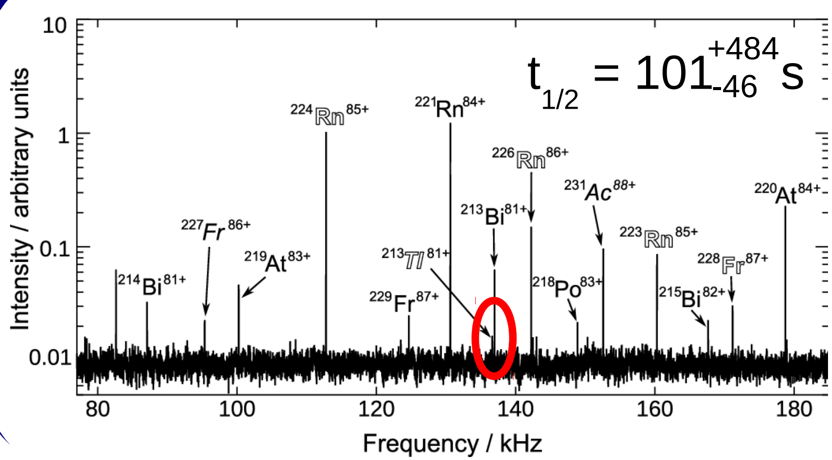

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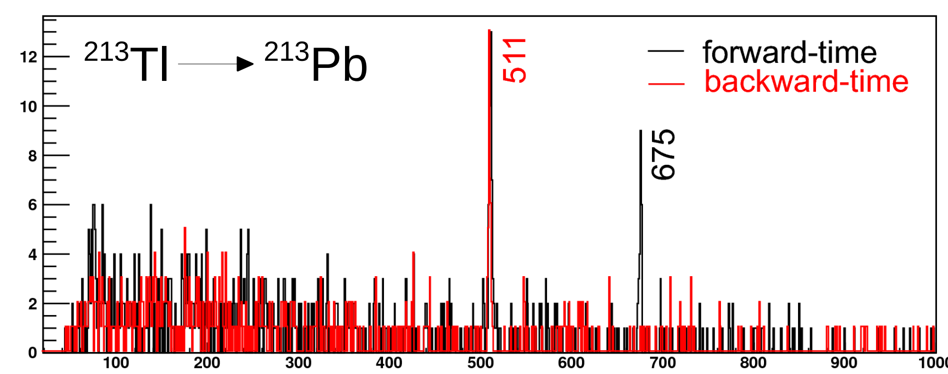

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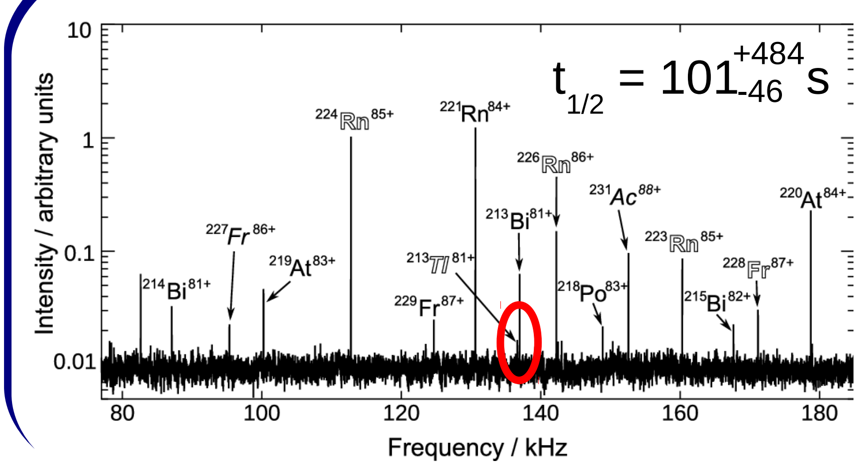

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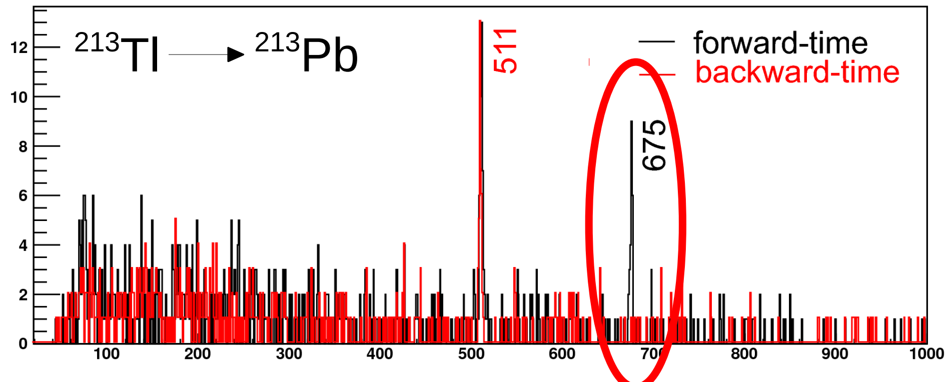

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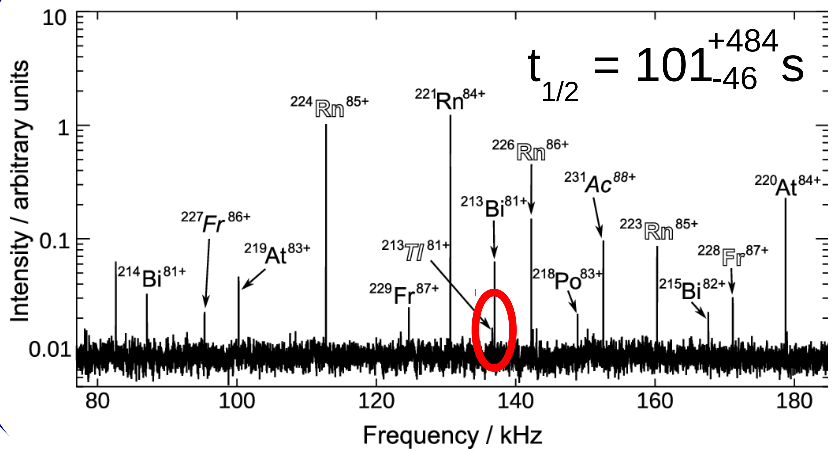

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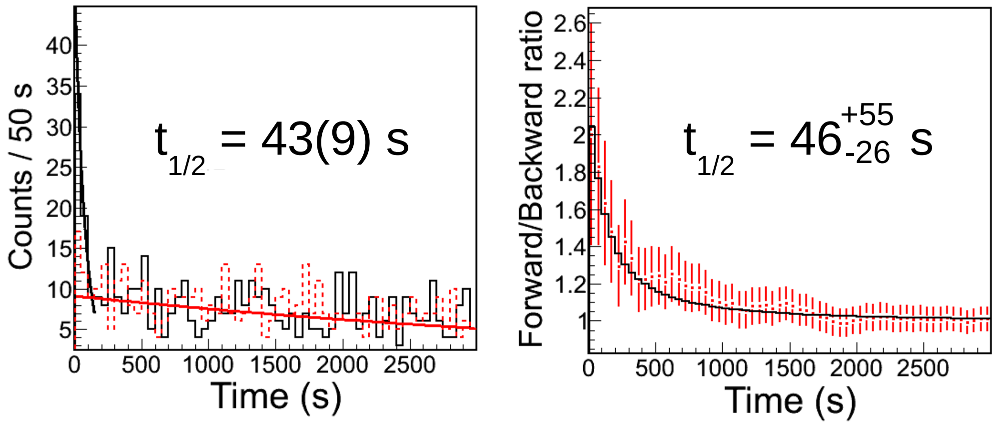
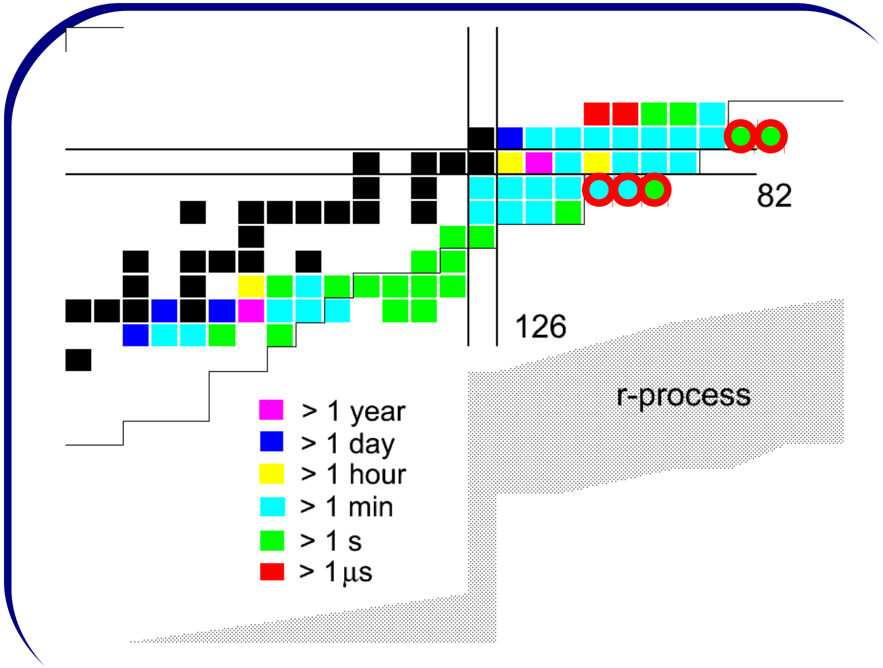


COMPARISON WITH THEORETICAL PREDICTIONS



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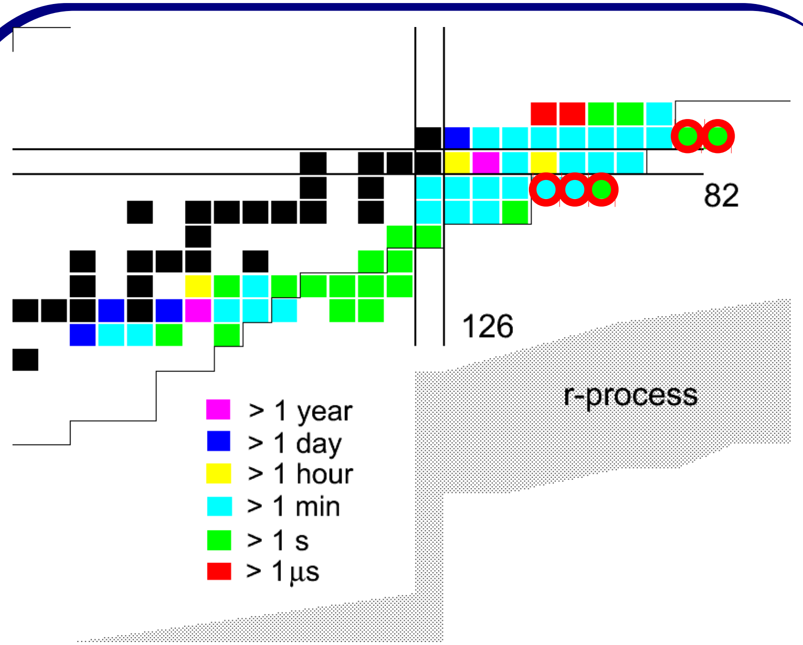

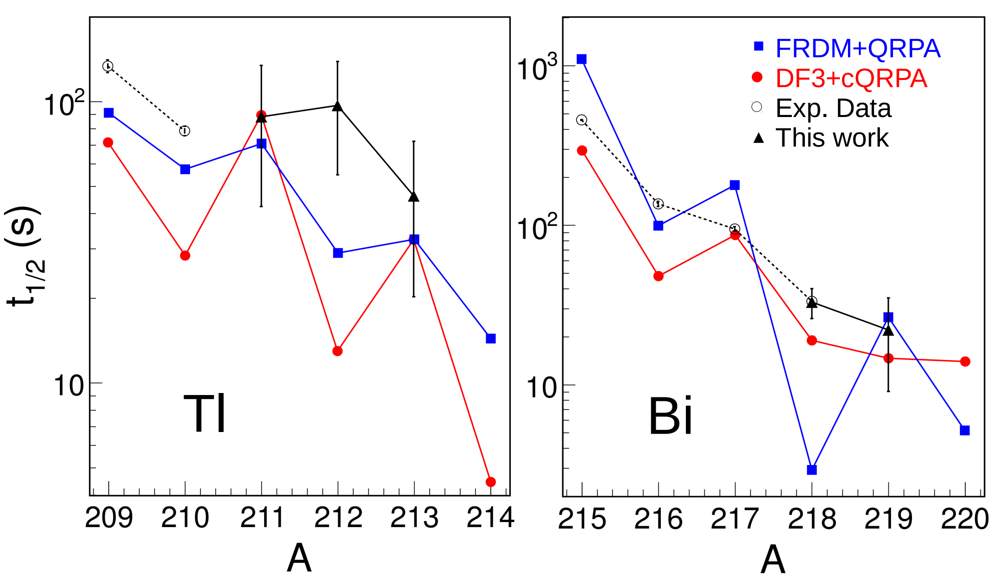

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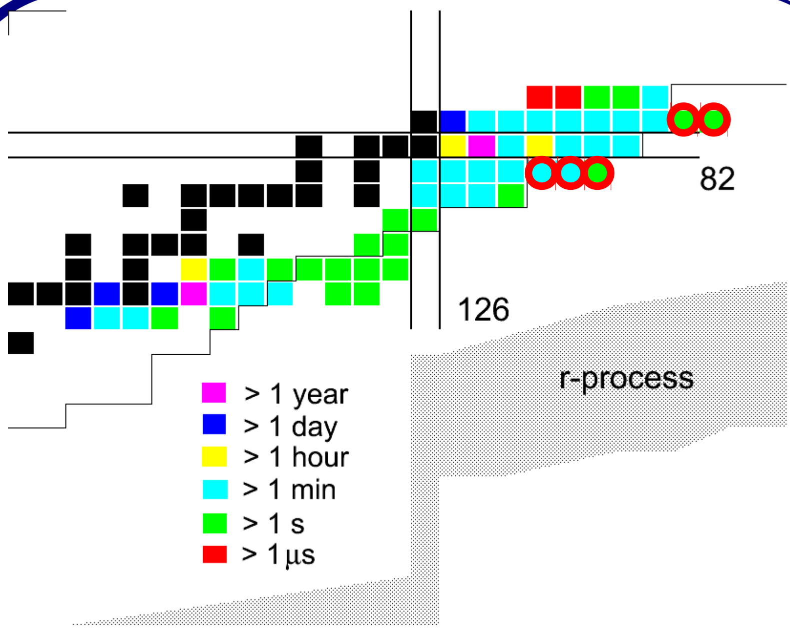

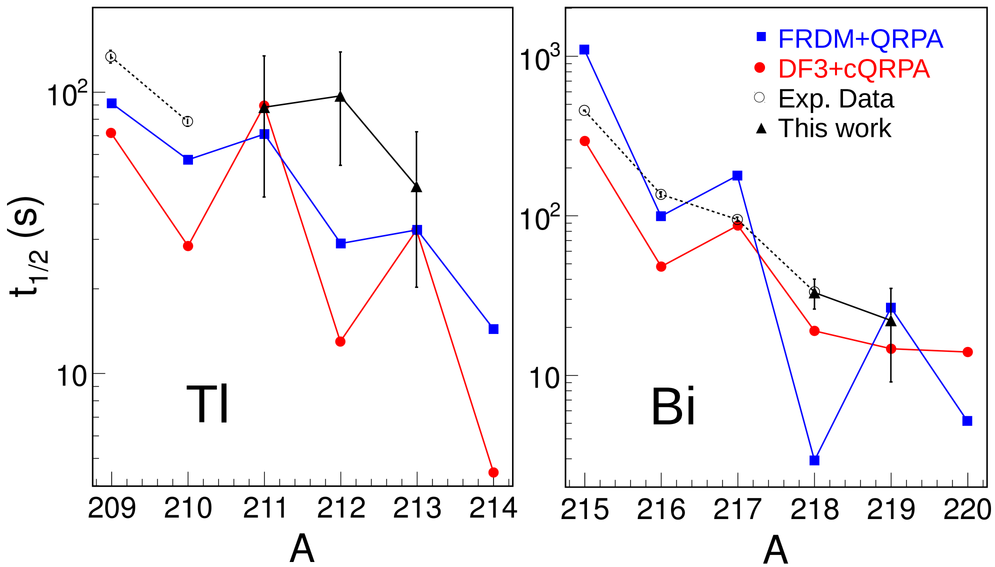

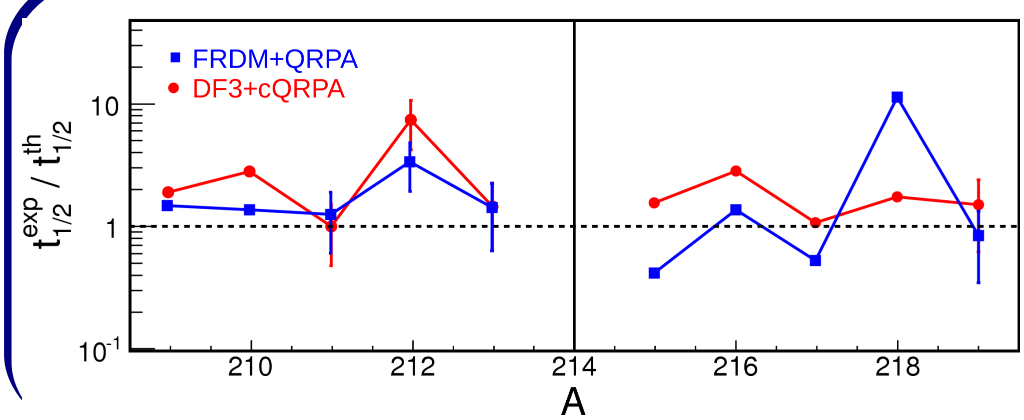

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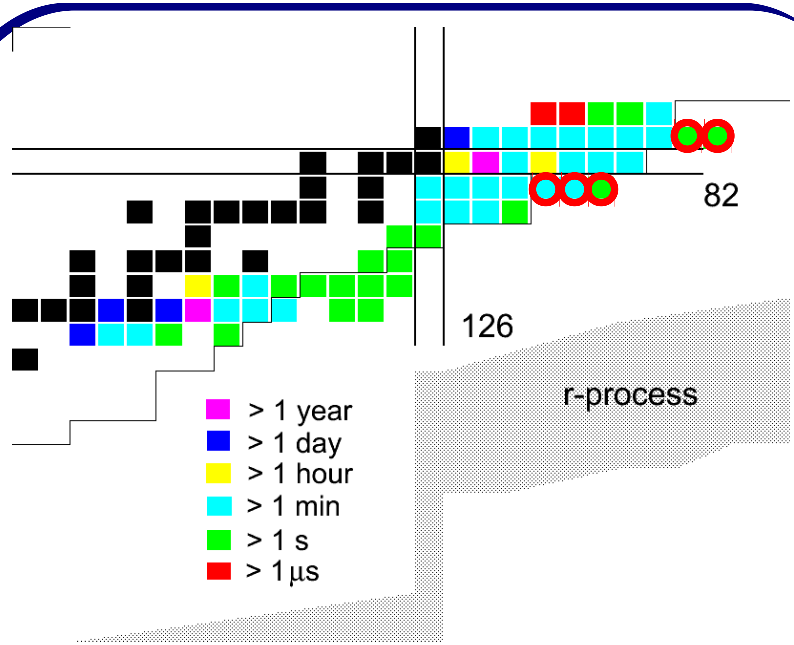
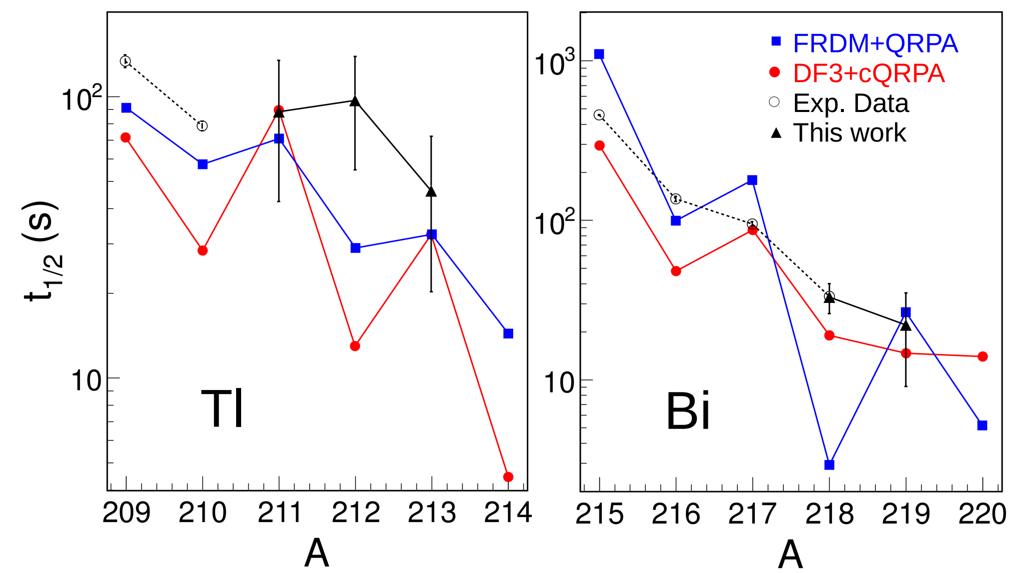
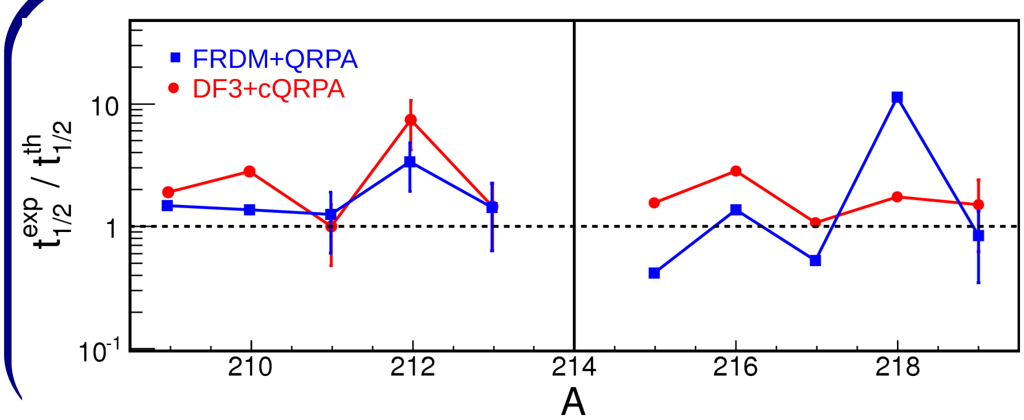




The description of
first-forbidden (ff) transitions
using macroscopic statistical models
seems a good approach
for these nuclei



CONCLUSIONS

- The β-decay half lives of five heavy nuclei have been measured with a novel numerical method
  - ✓ Complex background structures
  - ✓ ^{218}Bi: the benchmark of the analysis

- (Mic-mac) FRDM+QRPA and (self-consistent) DF3 + QRPA models are in agreement with our measurements: describing ff transitions in a macroscopic statistical model seems a good approximation in β-decay processes governed by GT strength.

- This work represents a step forward in the investigation of nuclei in the vicinity of the neutron-rich Lead isotopes, of main importance to understand the evolution of the Z=82 shell closure towards the neutron drip-line and the r-process matter flow to heavier fissioning nuclei

- Further expectations to investigate the production of nuclei at extreme conditions of isospin and the astrophysical processes that lead to the formation of the heaviest nuclei in the Universe rely on the new generation of in-flight secondary beam facilities, like RIKEN or FAIR.

S350-EXPERIMENT COLLABORATION

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