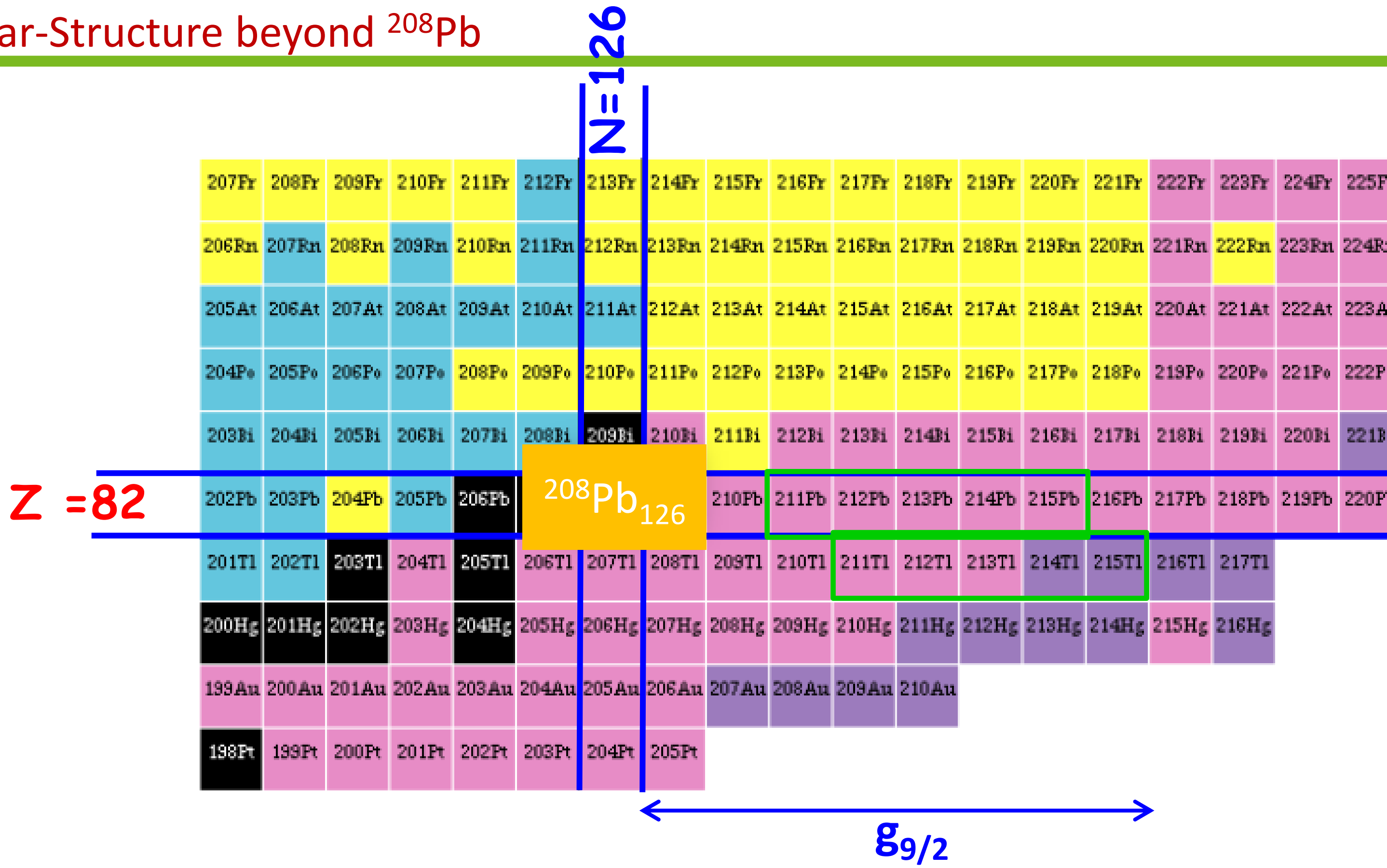
CERN-ISOLDE, Switzerland, E.Rapisarda, J.Kurcewicz, M. Kowalska, V.N. Fedosseev, S. Rothe, , B.A. Marsh
INFN, Sezione di Padova and LNL , D. Bazzacco, S. Lenzi, S. Lunardi, F. Recchia, C. Michelagnoli, A. Gottardo, G. de Angelis, J.J. Valiente-Dobón, P. John, D. Napoli, V.Modamio, D. Mengoni,
IKS-KULeuven, Belgium, H. De Witte, M.Huyse, P.Van Duppen, R. Raabe, K.Wrzosek-Lipska, C.Sotty
Instituto de Fisica Corpuscular, Universita' de Valencia, Spain A.Algora[1],
University of York, U.K., A.N. Andreyev, D. Jerkins
Department of Nuclear Physics and Biophysics, Comenius University, Slovakia S. Antalic[3],
Petersburg Nuclear Physics Institute, Gatchina, Russia, A.E. Barzakh, D.V.Fedorov, M.D. Seliverstov,
University of Köln, Germany A. Blazhev[6], P. Reiter, N. Warr, J. Jolii,
University of Manchester,U.K. J.Billowes, T.E. Cocolios, T. Day Goodacre, K.T. Flanagan, I. Strashnov,
University of Surrey, U.K., R.Carroll[8], Z.Podolyak, P.M.Waker, C. Shand, Z. Patel, P.H. Regan
University of Jyväskylä, Helsinki Institute of Physics, Finland, T. Grahn, P.T. Greenlees, Z. Janas, J.Pakarinen, P. Rahkila
University of Warsaw, Faculty of Physics, Poland, C.Mazzocchi, , M. Pfützner,
Institut fur Physik, Gutenberg Universitat, Germany, T. Kron, K.D.A.Wendt, S. Richter[14]
Department of Physics, University of Liverpool, U.K., B.Cheal, D. Joss, R. Page,
IFIN-HH, Bucharest R. Lica, N. Marginean, R. Marginean, C. Mihai, A.Negret, S. Pascu

β-decay study of neutron-rich Tl and Pb isotopes

Physical Case

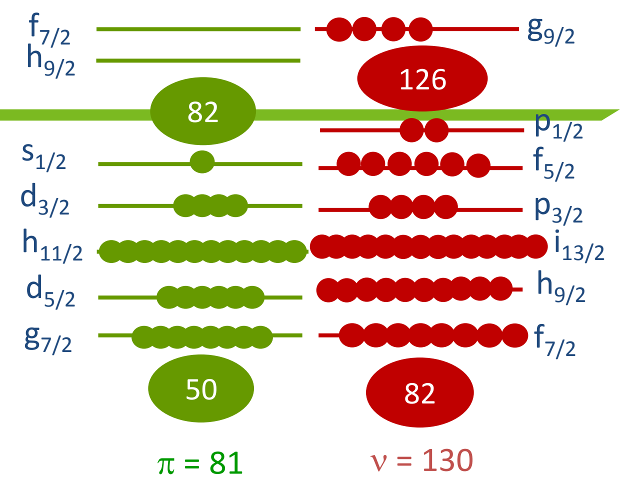
Nuclear-Structure beyond ^{208}Pb



Study the development of nuclear structure in the nuclei beyond N=126

- ❑ What the position of single particle orbitals?
- ❑ What does the effective proton-neutron interaction look like?

Physics Motivation



The region around ^{208}Pb has been very difficult to populate experimentally due to its large A and Z.

- Lifetime measurements in ^{211,212,213}Tl
- Lifetime measurements in ^{218,219}Bi

  G. Benzoni et al., Phys. Lett. B715 (2012) 293
- Three high-spin isomers in ^{211}Pb and decay scheme *G.J. Lane et al., Phys. Lett. B 606 (2005) 34*
- 8^+ isomers in ^{208}Hg and ^{210}Hg *N. Al-Dahan et al., Phys. Rev. C80 (2009) 061302; A. Gottardo et al., Phys. Lett. B725 (2013) 292*
- 8^+ isomers in ^{212,214,216}Pb *A. Gottardo et al., Phys. Rev. Lett. 109 (2012) 162502*
- $17/2^+$ isomer in ^{209}Tl (95 ns) *N. Al-Dahan et al., Phys. Rev. C80 (2009) 061302*
- β-decay of ^{215}Pb, ^{215,216,217,218}Bi *H. De Witte et al., Phys. Rev. C87 (2013) 067303; J. Kurpeta et al., Eur. Phys. J. A18 (2003) 31 H. De Witte et al., Phys.Rev. C 69, 044305 (2004)*

- Seniority scheme

  Experimental level scheme for $^{210-216}$Pb, Hg consistent with $\nu(g_{9/2})^n$ dominance

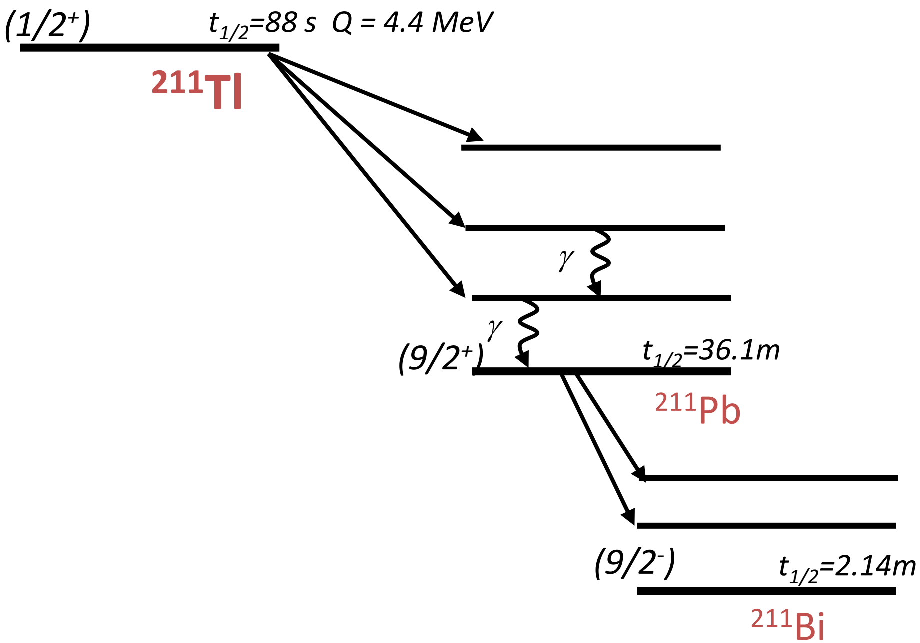
  low-lying states in odd-mass Tl described as $\nu(g_{9/2})^2 \otimes \pi(s^{-1}_{1/2})$ or $\pi(d^{-1}_{3/2})$

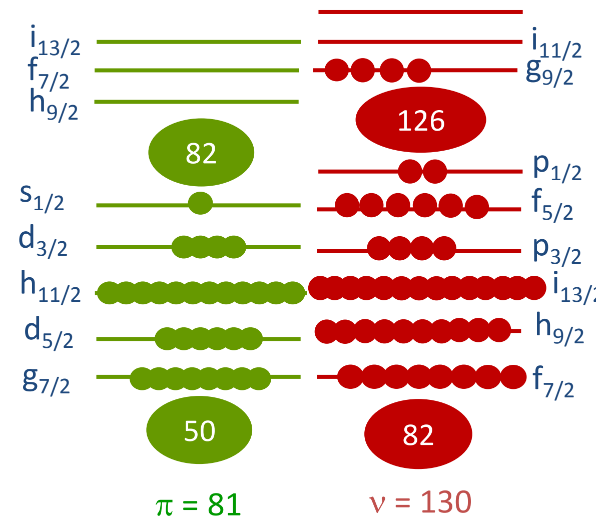
- Kuo-Herling realistic interaction *(T.T.S. Kuo ans G.H. Herling, U.S. Naval Research Laboratory Report N.2258, 1971)*

- Inclusion of the three-body forces is essential

  A. Gottardo et al. PRL109, 162502 (2012)

Half-life of $^{211-215}$Tl





^{211}Tl $t_{1/2}$=88 s → *50% uncertainty*
^{212}Tl $t_{1/2}$=96 s → *50% uncertainty*
^{213}Tl $t_{1/2}$=46 s → *100% uncertainty*

G. Benzoni et al., Phys. Lett. B715 (2012) 293

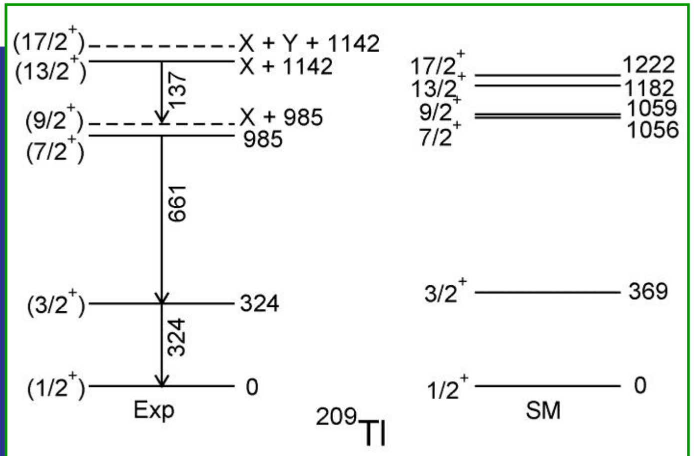
The β-decay would be dominated by Gamow-Teller transitions to high energy states (partially occupied neutron shells $3d_{5/2}$ or $4s_{1/2}$ above $g_{9/2}$)

State-of-the-art models used in r-process calculations underestimate the experimental results ⇒ Half-life measurements will shed further light on the discrepancy

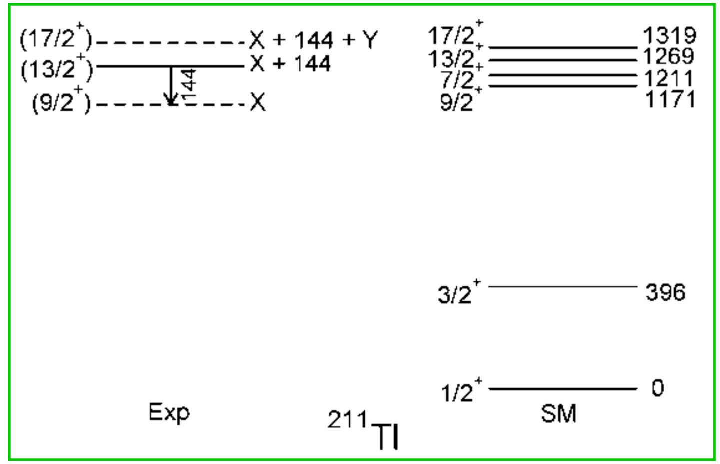
Data collected at GSI (not published) show a change in structure with respect to ^{211}Pb
Low-lying states in the daughter Pb can be populated and studied.

Long-living isomers in ^{211,213}Tl

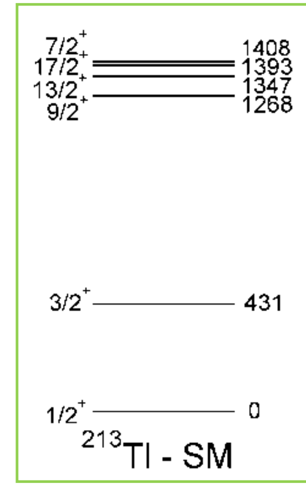
The occurrence of many high-spin single particle orbitals in the nuclei to be explored will give rise to several isomeric states

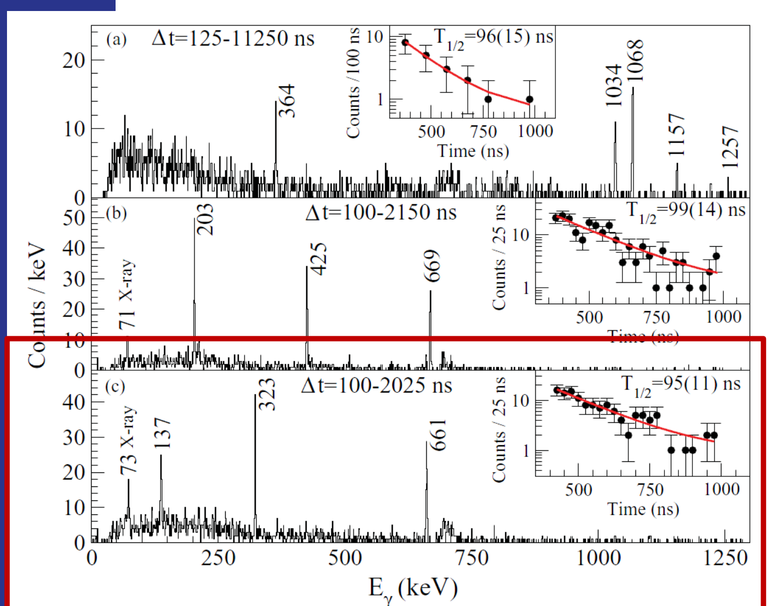


N. Al-Dahan et al., Phys. Rev. C80 (2009) 061302



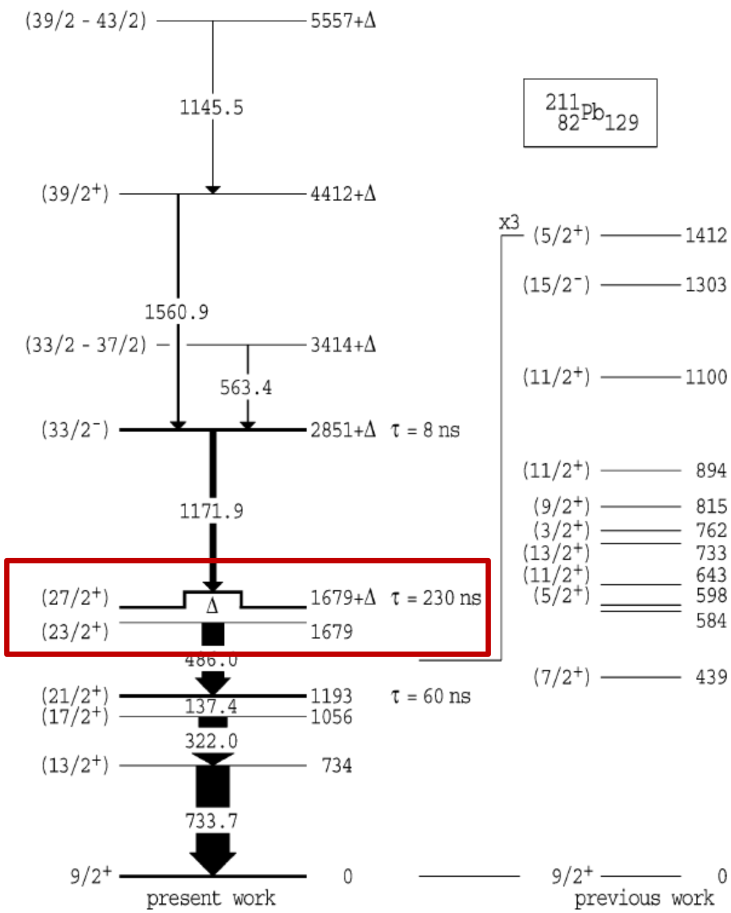
A. Gottardo, PhD thesis, unpublished



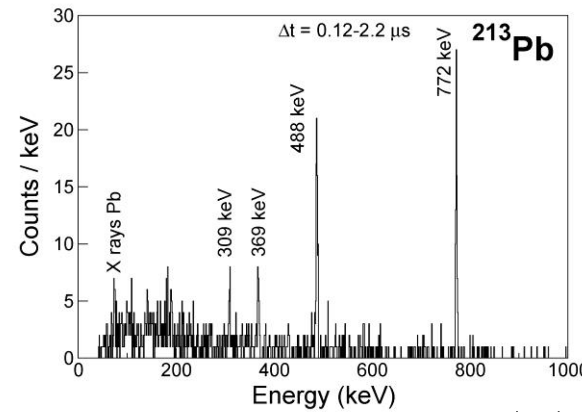


- ^{211,213}Tl: Experimental evidence (data not published) of different structure with respect to ^{209}Tl;
- Shell model calculations suggest inversion of $9/2^+$ and $7/2^+$
- SPIN TRAP → Long living isomers in ^{211,213}Tl???

Long-living isomers in ^{213}Pb



G.J. Lane et al., Phys. Lett. B 606 (2005) 34



A. Gottardo, PhD thesis, unpublished

- experimental evidence of short-lived isomeric decay;
- The decay of the isomers shows a change in nuclear structure compared to ^{211}Pb
- If $(27/2)^+$ moves below $(23/2)^+$ →SPIN TRAP → Long living isomers in ^{213}Pb ???

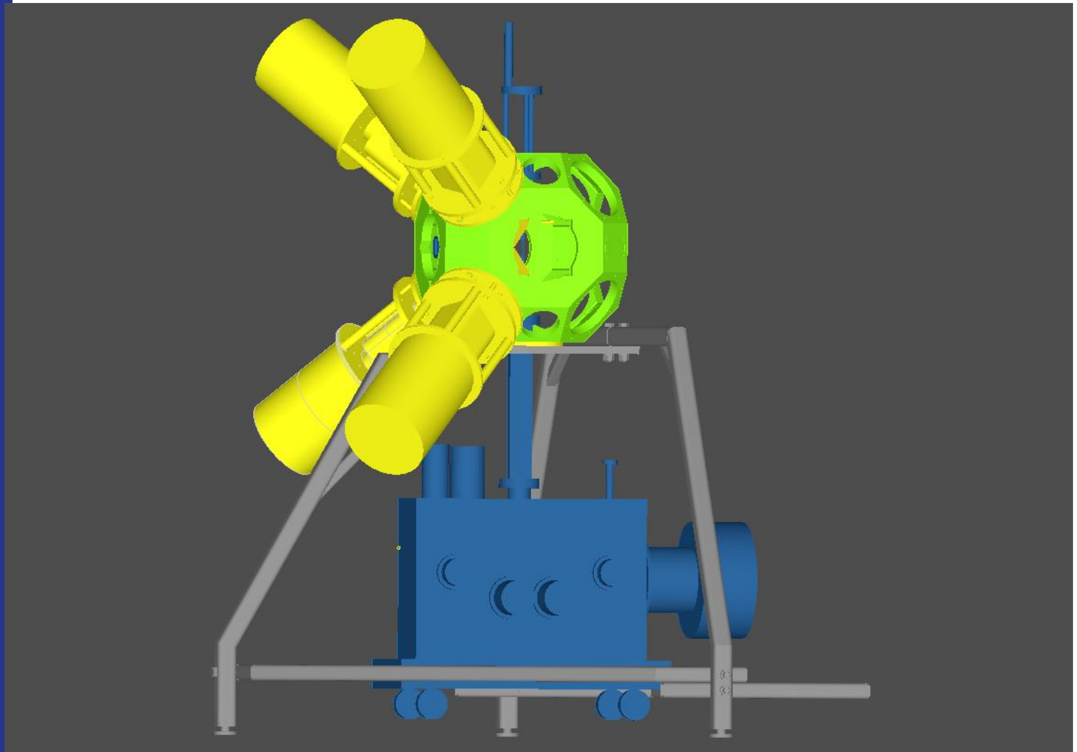
Proposed experiment

Decay Spectroscopy

AIM
- lifetime of $^{211-215}$Tl with 10% uncertainity
- decay scheme in $^{211-215}$Pb by β-decay Tl

Laser Spectroscopy

AIM
- identify long-living isomers in ^{211,213}Tl and ^{213}Pb



4 Clovers
1 Miniball Triple cluster:

Total γ detection efficiency is about 8-9% at 1.3MeV

Total β detection efficiency is about 60%

Beam Time Request

UC_x Target + quartz transfer line + LIST target → Successfully used to study ^{219}Po (IS456)

→ **up to 1000 x surface ion suppression**

- Expected strong Fr and Ra contamination
- New development in RILIS → micro beam gate **= 100 x** Surface ion suppression

  A=214-215: Pulsed-release technique → relatively longer lifetime of the β-decaying isotopes of interest compared to the significantly shorter lived Fr and Ra;

- Laser Ionization: RILIS (27% and 7% for Tl and Pb respectively)
- We request therefore:

$T_{1/2}$ measurements → 20% duty cycle

Isotope	Rate on tape /s	Time	Expected n. β-γ counts
^{211}Tl	540	1 shift	$1 \cdot 10^5$
^{212}Tl	225	1 shift	$6 \cdot 10^4$
^{213}Tl	90	1 shift	$3 \cdot 10^4$
^{214}Tl	36	3 shifts	$3 \cdot 10^4$
^{215}Tl	12	6 shifts	$2 \cdot 10^4$
^{213}Pb	250	3 shifts	$2 \cdot 10^5$
^{215}Pb Reference	47 (*)	15	

(*) H. De Witte et al., Phys. Rev. C87 (2013) 067303

2 shifts for tuning the laser to Pb and Tl

4 shifts for laser - spectroscopy

Need 21 Shifts measurement

Collaboration

CERN-ISOLDE, Switzerland, E.Rapisarda, J.Kurcewicz, M. Kowalska, V.N. Fedosseev, S. Rothe, , B.A. Marsh
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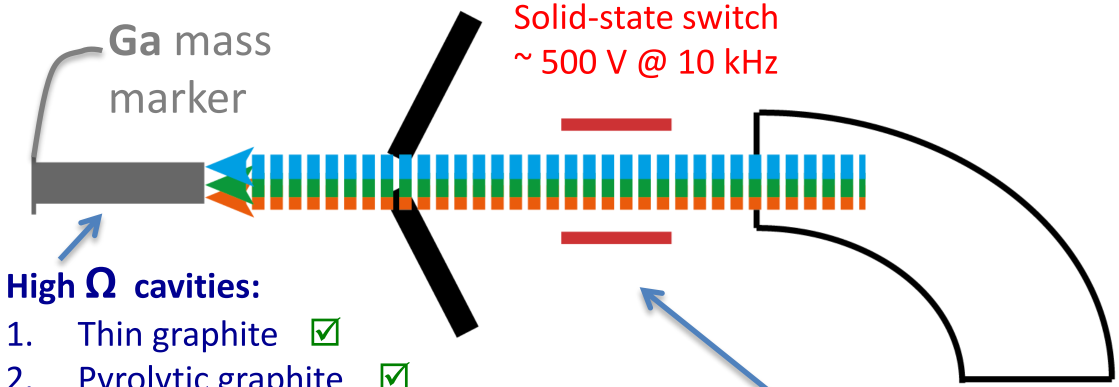
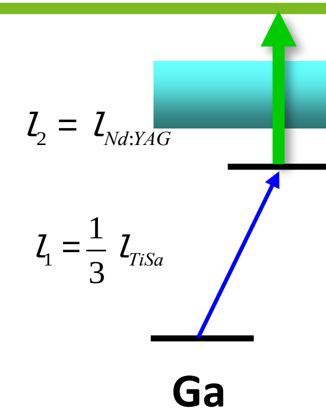
Department of Physics, University of Liverpool, U.K., B.Cheal, D. Joss, R. Page,
IFIN-HH, Bucharest R. Lica, N. Marginean, R. Marginean, C. Mihai, A.Negret, S. Pascu

ISOLDE
CERN

Narrow laser-ion bunch width + micro beam gate tests

Courtesy of Richard Catherall

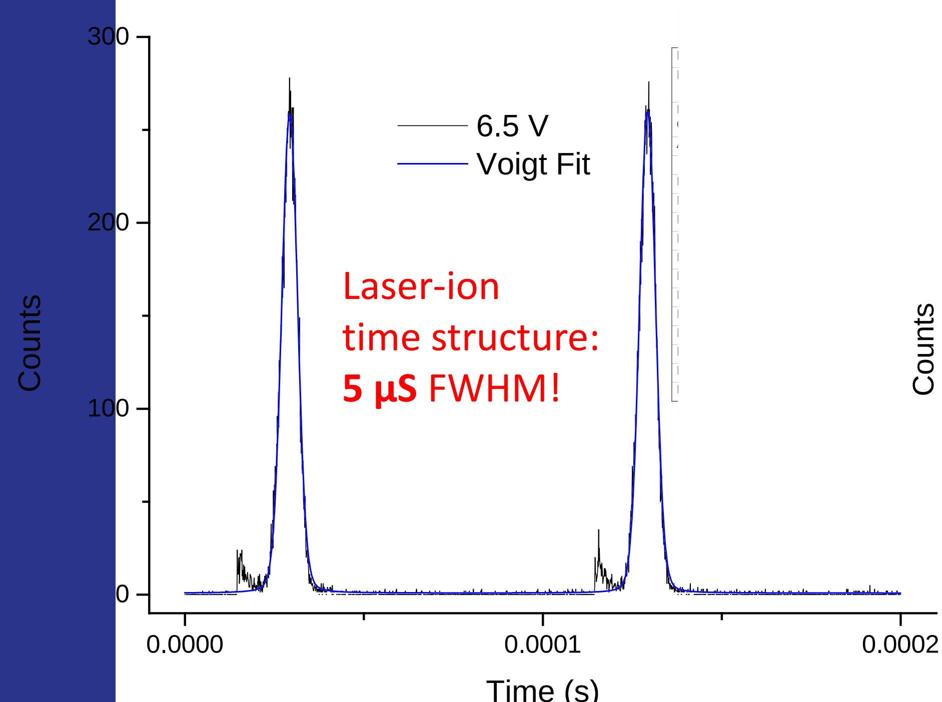




RILIS ionization scheme

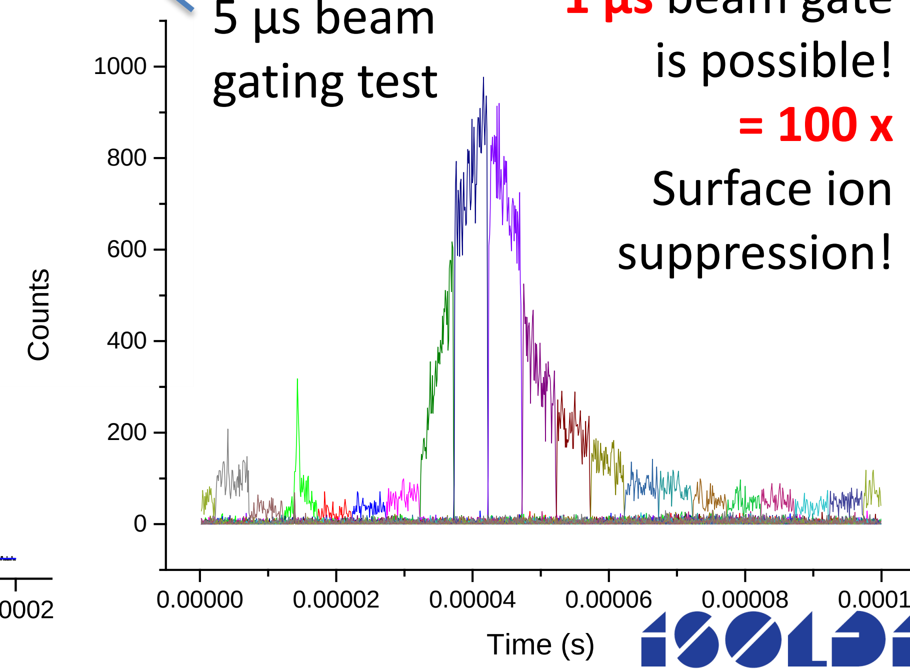
High Ω cavities:

1. Thin graphite ☑
2. Pyrolytic graphite ☑
3. Sigradur 'glassy' graphite ☐
4. Pulsed heating for higher voltage ☐



Laser-ion time structure: **5 µS** FWHM!

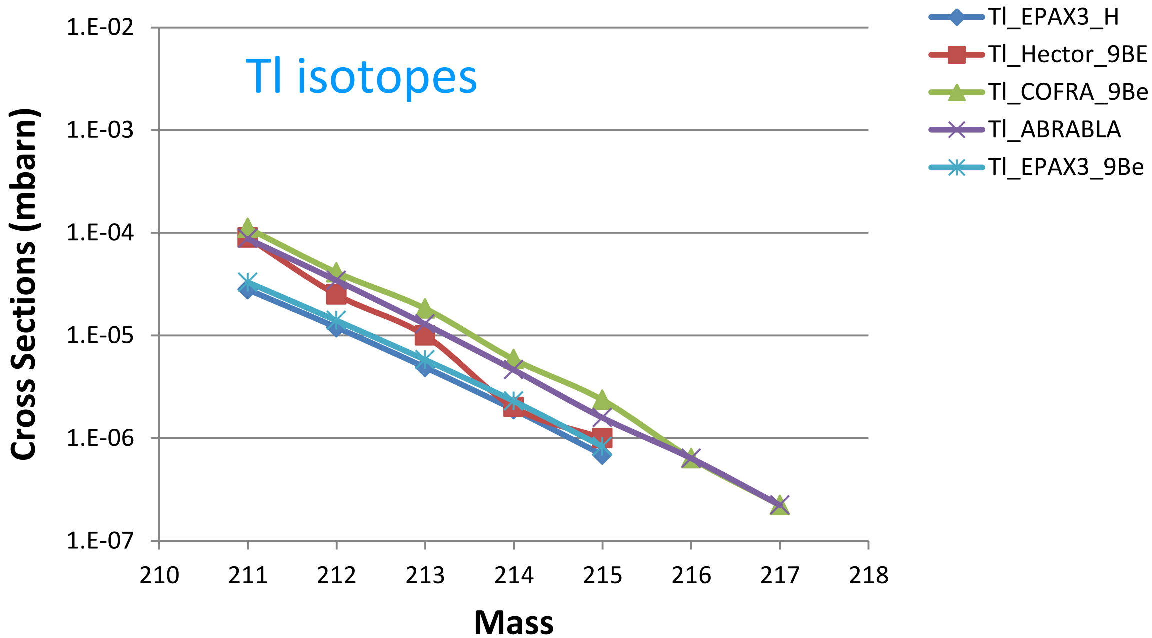
5 µs beam gating test

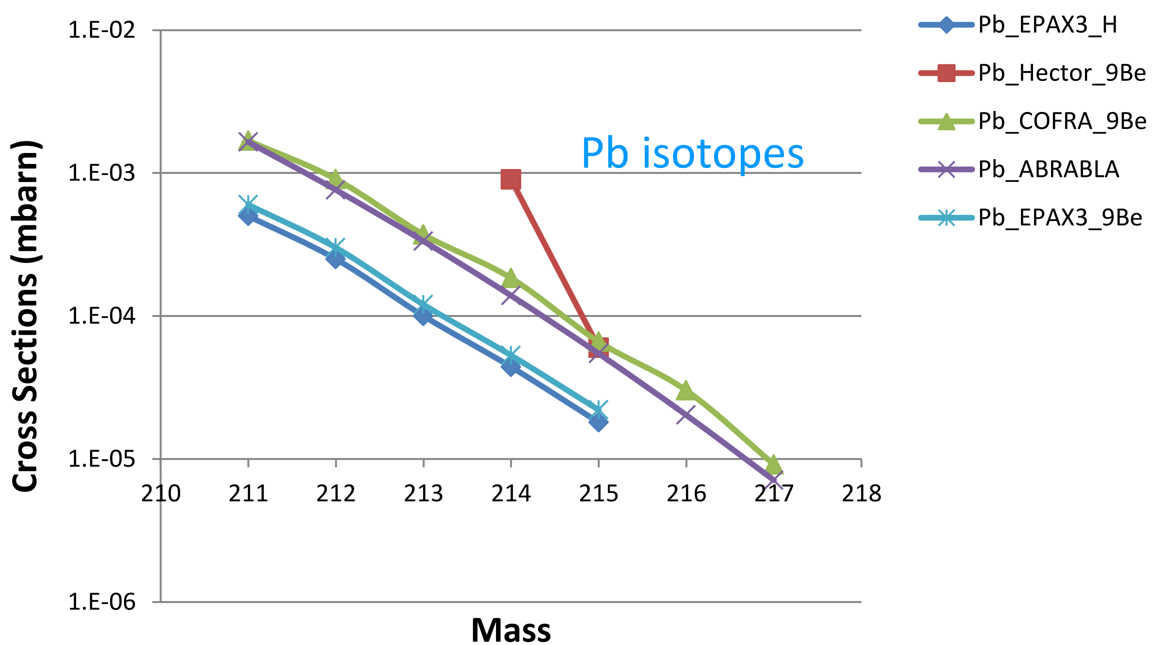


1 µs beam gate is possible!

= 100 x

Surface ion suppression!

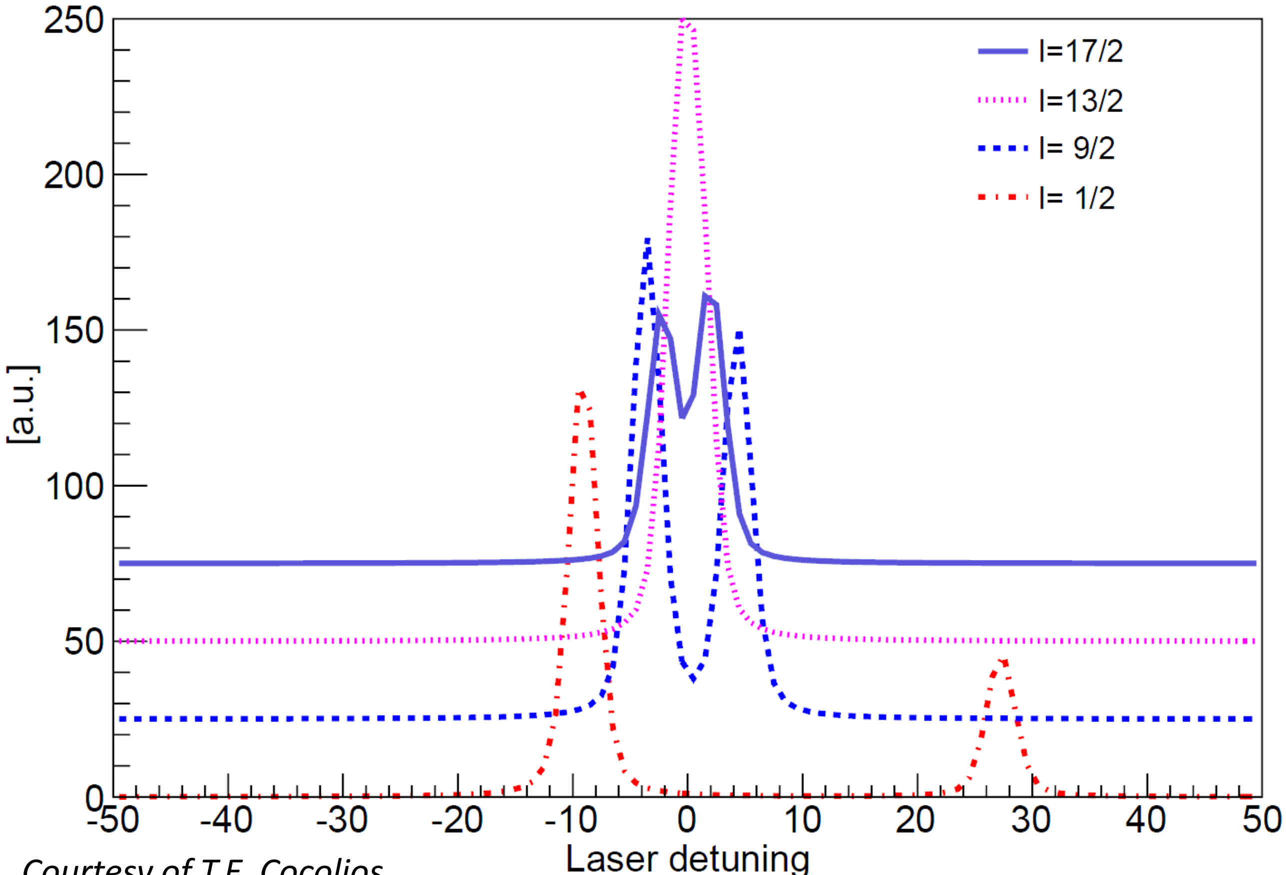




9% = gamma efficiency at 1.3 MeV
60% = beta efficiency
20% duty cycle

540 ions/sec * 8h *3600 sec * 0.09 * 0.6 * 0.2 = 1.7 * 10^5

Tl HFS scan simulation



Courtesy of T.E. Cocolios

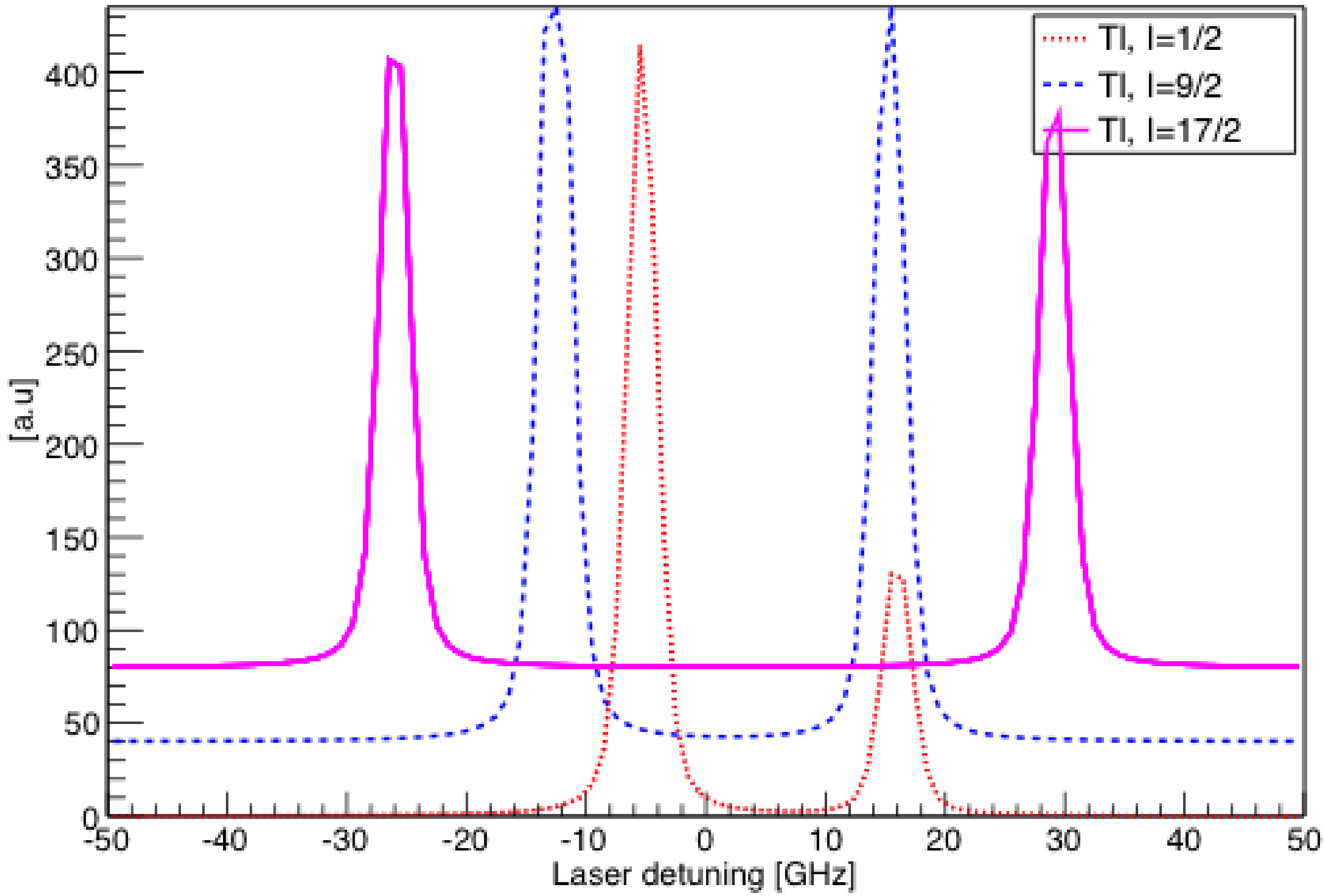
We can definitely differentiate between the ground state and an isomer, but probably not tell which isomer we have.

proton in $s_{1/2}$ => mu = + 2.793 mu_N => g-factor = + 5.586
neutron in $g_{9/2}$ => mu = - 1.913 mu_N => g-factor = - 0.429

The additivity rule is given as:
g_emp (I = Jp + Jn) = 0.5 * { gp + gn + (gp - gn) * (Jp*[Jp+1] - Jn*[Jn+1]) / (I*[I+1]) } = 2.58 + 3 * (3 - 4*Jn*[Jn+1]) / (4*I*[I+1])
g_emp (9/2 = 1/2 + 4) = + 0.24 => mu = + 1.09 mu_N
g_emp (13/2 = 1/2 + 6) = +0.04 => mu = + 0.24 mu_N
g_emp (17/2 = 1/2 + 8) = -0.07 => mu = - 0.61 mu_N

The hyperfine parameters become
A(1/2) = 36 336 MHz
A(9/2) = 1 575 MHz
A(13/2) = 240 MHz
A(17/2) = - 467 MHz

Hyperfine Structure in ^{211}Tl



Courtesy of T.E. Cocolios

J = 1/2 -> 3/2 (for the 276.8 nm transition)
Tl, I=1/2: using ^{205g}Tl, A = 21.31 GHz, mu = 1.638 mu_N
Tl, I=9/2: using ^{193m}Tl, A = 5.583 GHz (from Barzakh et al, PRC 2013)
Tl, I=17/2: using ^{215}Ac, mu = 8 mu_N => A = 6.122 GHz (using 205gTl as reference)
0 GHz isotope shift between the isomers.
1 GHz Gaussian x 1 GHz Lorentzian sigma.

LIST target performances

Table 1
Ion rates in ion guide and LIST mode for several isotopes, which are measured using either the tape station ($*$, ions per μC proton beam current), the Leuven Windmill detector setup ($\circ$, counts per proton supercycle) or a Faraday cup (∇, pA). The detector background level (b) and calculated suppression factors S are shown. The statistical uncertainty ($\sqrt{N}$) of the background measurement is given in brackets.

Isotope	I_{IG}	I_{LIST}	b ($\sqrt{N}$)	S
$^{26}Na^{*}$	75000	50	50(7)	$\geqslant$ 10700
$^{30}Na^{*}$	1437	125	125(11)	$\geqslant$ 130
$^{46}K^{*}$	13000	50	50(7)	$\geqslant$ 1850
$^{205}Fr^{\circ}$	63520	25	0	2540
$^{212}Fr^{\nabla}$	80	2	0.85	70
$^{220}Fr^{\circ}$	15379	412	412(20)	$\geqslant$ 770

D.A. Fink et al. submitted to NIMB

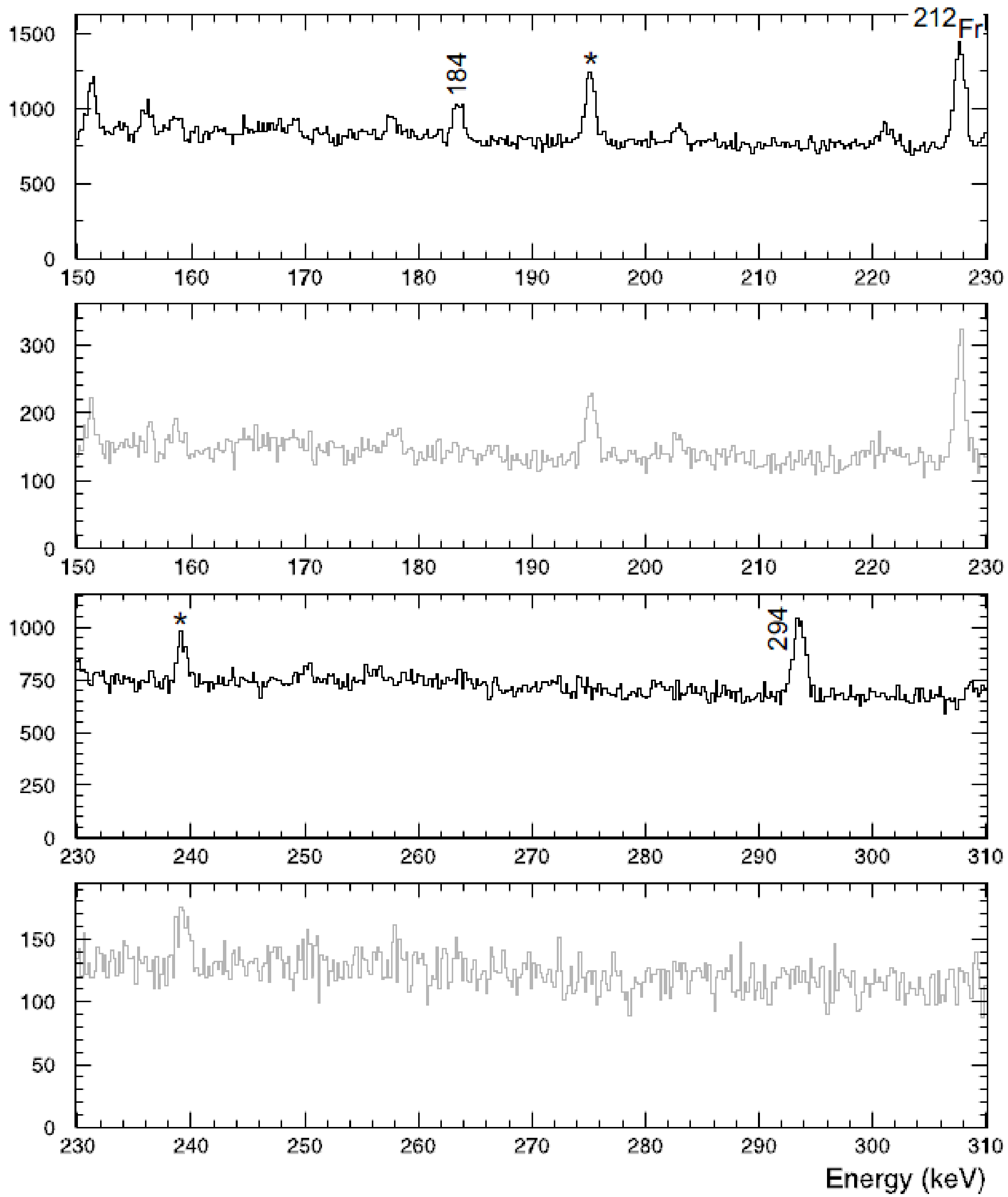


Figure 4.5a: β-gated LEGe spectrum obtained at mass 215. On-resonance, with laser tuned to Pb (black) versus lasers off (gray). Data from run II. Lines marked with $\star$ belong to ^{209}At, present as the daughter of the contaminant ^{213}Fr.

Old run at ISOLDE in 2000

GPS separator

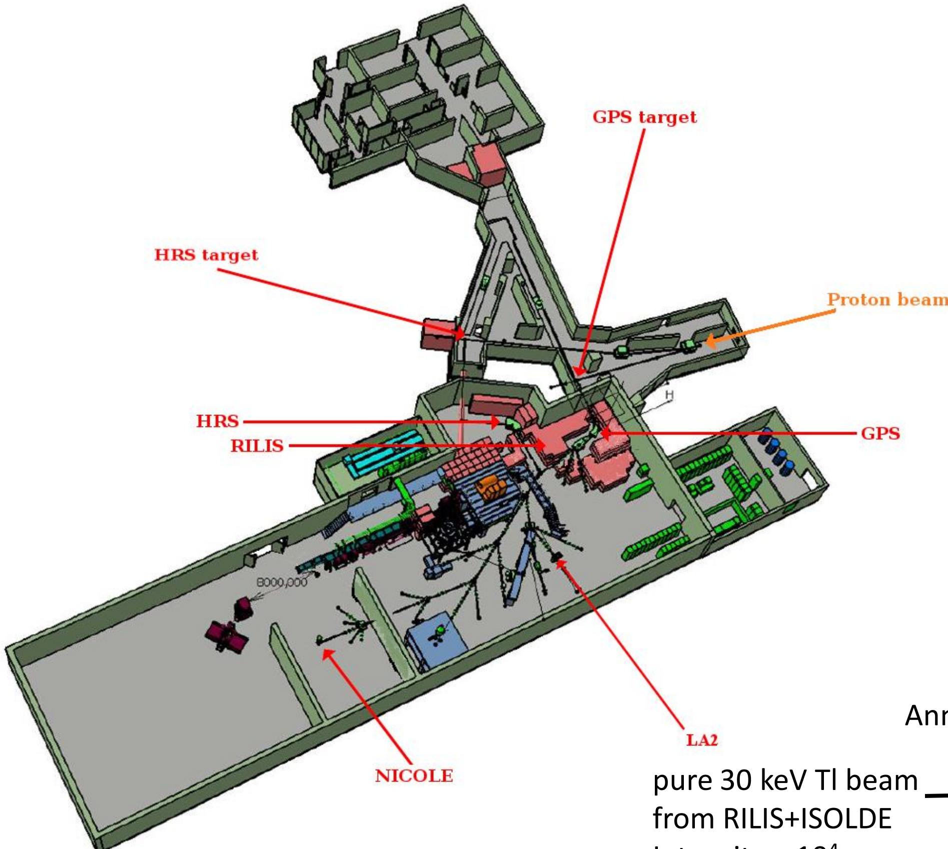
A= 215

Laser tuned on Pb

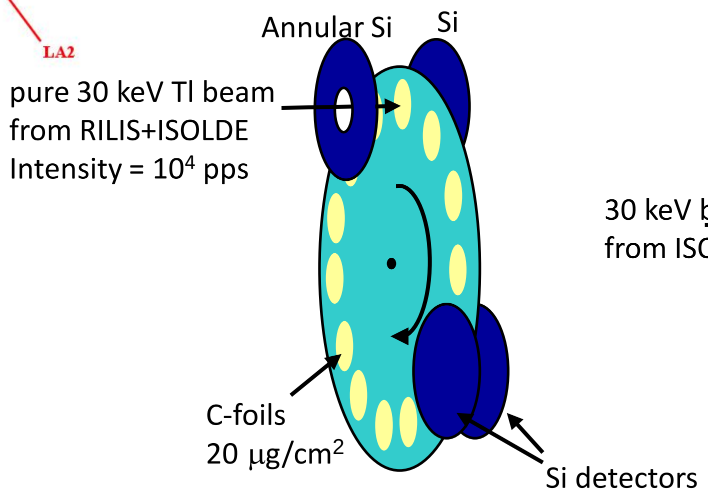
Hilde de Witte, PhD thesis, KULeuven 2004

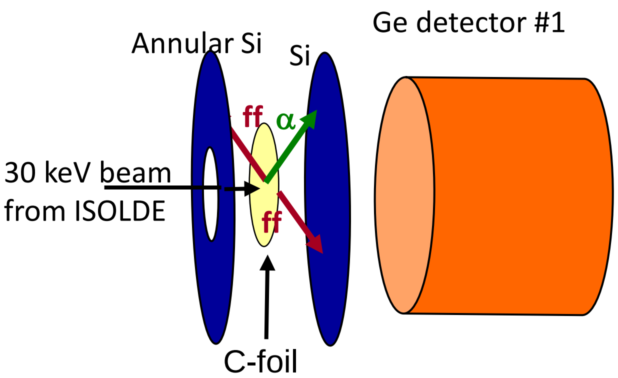
Ac207 300 ms 7/2- EC,α	Ac208 1.3 s 3+,4+ EC,α	Ac209 1.3 s 7/2- EC,α	Ac210 1.1 s 3+,4+ EC,α	Ac211 230 ms 13/2+ EC,α	Ac212 1.1 s 5-,8- EC,α	Ac213 4 s 3/2- EC,α	Ac214 50 s 1+,2+ EC,α	Ac215 600 ms 5/2- EC,α	Ac216 30 us 3-,6- EC,α	Ac217 120 ns 9/2- EC,α	Ac218 500 ns 1+,2+ EC,α	Ac219 160 ns 9/2+ EC,α	Ac220 160 ms 0+,5+ EC,α	Ac221 1.2 m 5/2+ EC,α	Ac222 30 m 0+,5+ EC,α	Ac223 13 m 5/2+ EC,α
Ra206 600 ms 0+ EC,α	Ra207 7 s 1/2- EC,α	Ra208 1.9 s 0+ EC,α	Ra209 9 s 1/2- EC,α	Ra210 2.1 s 0+ EC,α	Ra211 13 s 3/2- EC,α	Ra212 11 s 0+ EC,α	Ra213 5 m 1/2- EC,α	Ra214 300 ms 0+ EC,α	Ra215 70 us 9/2+ EC,α	Ra216 30 ns 0+ EC,α	Ra217 230 ns 3/2+ EC,α	Ra218 30 ns 0+ α	Ra219 14 ms 5/2+ EC,α	Ra220 120 ms 0+ α	Ra221 20 m 5/2+ α	Ra222 9 h 0+ α
Fr205 5 s 13/2+ EC,α	Fr206 6 s 6-,7- EC,α	Fr207 8 s 13/2+ EC,α	Fr208 8 s 6-,7- EC,α	Fr209 5 m 5/2- EC,α	Fr210 1.6 m 2+,3+ EC,α	Fr211 6 m 5/2- EC,α	Fr212 1.4 h 0+,1+ EC,α	Fr213 18 s 5/2- EC,α	Fr214 200 us 2-,3- EC,α	Fr215 500 ns 5/2- EC,α	Fr216 400 ns 1+,4+ EC,α	Fr217 190 ns 5/2- EC,α	Fr218 900 us 0+,5+ EC,β-,α,...	Fr219 230 ms 1/2+ α	Fr220 1.1 h 2+,3+ EC,β-,α,...	Fr221 6 h 1/2+ β-,α
Rn204 5 s 0+ EC,α	Rn205 1.9 m 1/2- EC,α	Rn206 21 s 0+ EC,α	Rn207 2.4 m 1/2- EC,α	Rn208 4 m 0+ EC,α	Rn209 4 m 1/2- EC,α	Rn210 14 m 0+ EC,α	Rn211 6 h 1/2- EC,α	Rn212 18 s 0+ α	Rn213 600 us 9/2+ EC,α	Rn214 150 ns 0+ α	Rn215 400 ns 3/2+ EC,α	Rn216 90 ns 0+ α	Rn217 80 us 5/2+ α	Rn218 230 us 0+ α	Rn219 11 s 1/2+ β-,α	Rn220 1.6 m 0+ α
At203 17 s 3/2- EC,α	At204 7 m 3+,4+ EC,α	At205 3 m 3/2- EC,α	At206 13 m 3+,4+ EC,α	At207 4 h 7/2- EC,α	At208 40 m 3+,4+ EC,α	At209 4 d 7/2- EC,α	At210 4 d 3+,4+ EC,α	At211 5 h 3/2- EC,α	At212 20 ms 1-,2- EC,β-,α,...	At213 10 us 3/2- EC,α	At214 7 us 0-,3- EC,β-,α,...	At215 6 us 3/2- α	At216 70 us 1-,2- EC,β-,α,...	At217 5 ms 3/2+ β-,α	At218 20 s 1+,2+ β-,α	At219 3 m 3/2+ β-,α
Po202 5 m 0+ EC,α	Po203 3 m 3/2- EC,α	Po204 40 m 0+ EC,α	Po205 12 m 3/2- EC,α	Po206 4 h 0+ EC,α	Po207 23 m 1/2- EC,α	Po208 22 d 0+ EC,α	Po209 6 d 1/2- EC,α	Po210 30 d 0+ α	Po211 4 s 9/2+ α	Po212 130 us 0+ α	Po213 400 us 7/2+ α	Po214 50 us 0+ α	Po215 4 ms 5/2+ β-,α	Po216 6 ms 0+ α	Po217 40 s 7/2+ β-,α	Po218 4 m 0+ β-,α
Bi201 5 h 9/2- EC,α	Bi202 15 h 4+,5+ EC,α	Bi203 4 d 9/2- EC,α	Bi204 3 d 4+,5+ EC,α	Bi205 220 y 9/2- EC,α	Bi206 300 d 4+,5+ EC,α	Bi207 220 y 9/2- EC	Bi208 220 y 4+,5+ EC	Bi209	Bi210 2.4 y 0-,9- β-,α	Bi211 1.4 m 9/2- β-,α	Bi212 1.0 m 1-,8- β-,α	Bi213 50 s 9/2- β-,α	Bi214 11 m 2-,3- β-,α	Bi215 6 h 9/2- β-,α	Bi216 6 m 3+,4+ β-,α	Bi217 1.8 h 1/2+ β-,α
Pb200 220 y 0+ EC	Pb201 11 h 3/2- EC	Pb202 220 y 0+ EC	Pb203 80 y 3/2- EC		Pb205 220 y 1/2- EC	Pb206	Pb207	Pb208	Pb209 220 y 9/2+ β-	Pb210 220 y 0+ β-,α	Pb211 5 y 3/2+ β-,α	Pb212 220 y 0+ β-,α	Pb213 3 h 5/2+ β-,α	Pb214 220 y 0+ β-,α	Pb215 5 d 7/2+ β-	Pb216 16 d 0+ β-
Tl199 1.4 y 1/2+ EC	Tl200 70 y 0-,1- EC	Tl201 220 y 1/2+ EC	Tl202 220 y 1-,2- EC		Tl204 110 y 0-,1- EC,β-	Tl205	Tl206 220 y 0-,1- β-	Tl207 300 y 1/2+ β-	Tl208 7 h 4+,5+ β-	Tl209 4 d 1/2+ β-	Tl210 1.5 h 3+,4+ β-	Tl211 1.1 d 1/2+ β-	Tl212 1.0 h 2+,3+ β-	Tl213 12 m 1/2+ β-	Tl214 4 m 1+,2+ β-	Tl215 20 s 1/2+ β-
				Hg202 0+	Hg203 220 y 3/2- β-	Hg204 0+	Hg205 3 y 1/2- β-	Hg206 220 y 0+ β-	Hg207 50 m 9/2+ β-	Hg208 15 y 0+ β-	Hg209 3 h 9/2+ β-	Hg210 2.0 d 0+ β-	Hg211 5 m 5/2+ β-	Hg212 40 s 0+ β-	Hg213 16 s 5/2+ β-	Hg214 6 s 0+ β-
	Au198 110 y 0-,1- EC,β-	Au199 2.5 y 1/2+ β-	Au200 300 d 0-,1- β-	Au201 40 d 1/2+ β-	Au202 20 d 1-,2- β-	Au203 21 d 1/2+ β-	Au204 30 d 0-,1- β-	Au205 190 d 3/2+ β-	Au206 30 m 4+,5+ β-	Au207 1.5 h 1/2+ β-	Au208 3 m 3+,4+ β-	Au209 1.5 m 1/2+ β-	Au210 400 ms 5+,6+ β-	Au211 5 s 1/2+ β-	Au212 5 s 2+,3+ β-	Au213 1.4 s 1/2+ β-
	Pt197 3 d 1/2- β-		Pt199 1.5 h 1/2- β-	Pt200 14 d 0+ β-	Pt201 50 m 3/2- β-	Pt202 11 d 0+ β-	Pt203 3 d 1/2- β-	Pt204 220 y 0+ β-	Pt205 40 m 9/2+ β-	Pt206 13 h 0+ β-	Pt207 3 m 3/2+ β-	Pt208 4 m 0+ β-	Pt209 23 s 5/2+ β-	Pt210 10 s 0+ β-	Pt211 1.9 s 1/2+ β-	Pt212 700 ms 0+ β-

β-spectroscopy: Experimental Setup



Windmill Chamber



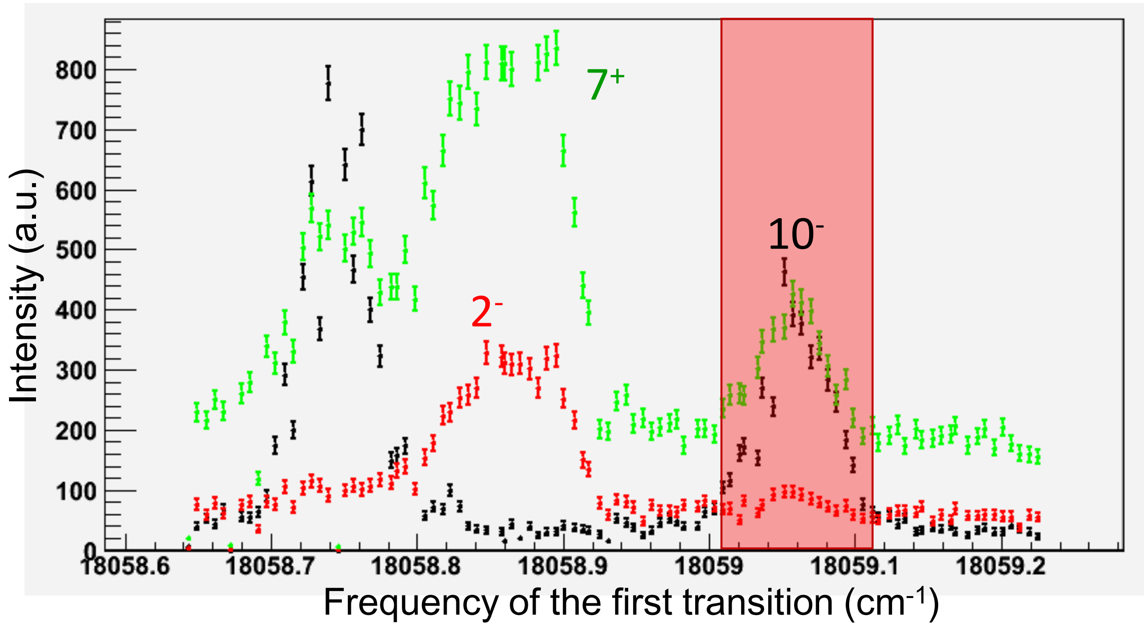


ISOLDE

Isomeric Beams @ ISOLDE

- technique based on in-source laser spectroscopy
(Ü. Köster et al., NIM B, 160, 528(2000); L. Weissman et al., PRC65, 024315(2000)).

- set the laser frequency to select and maximize the production of the isomer of interest.

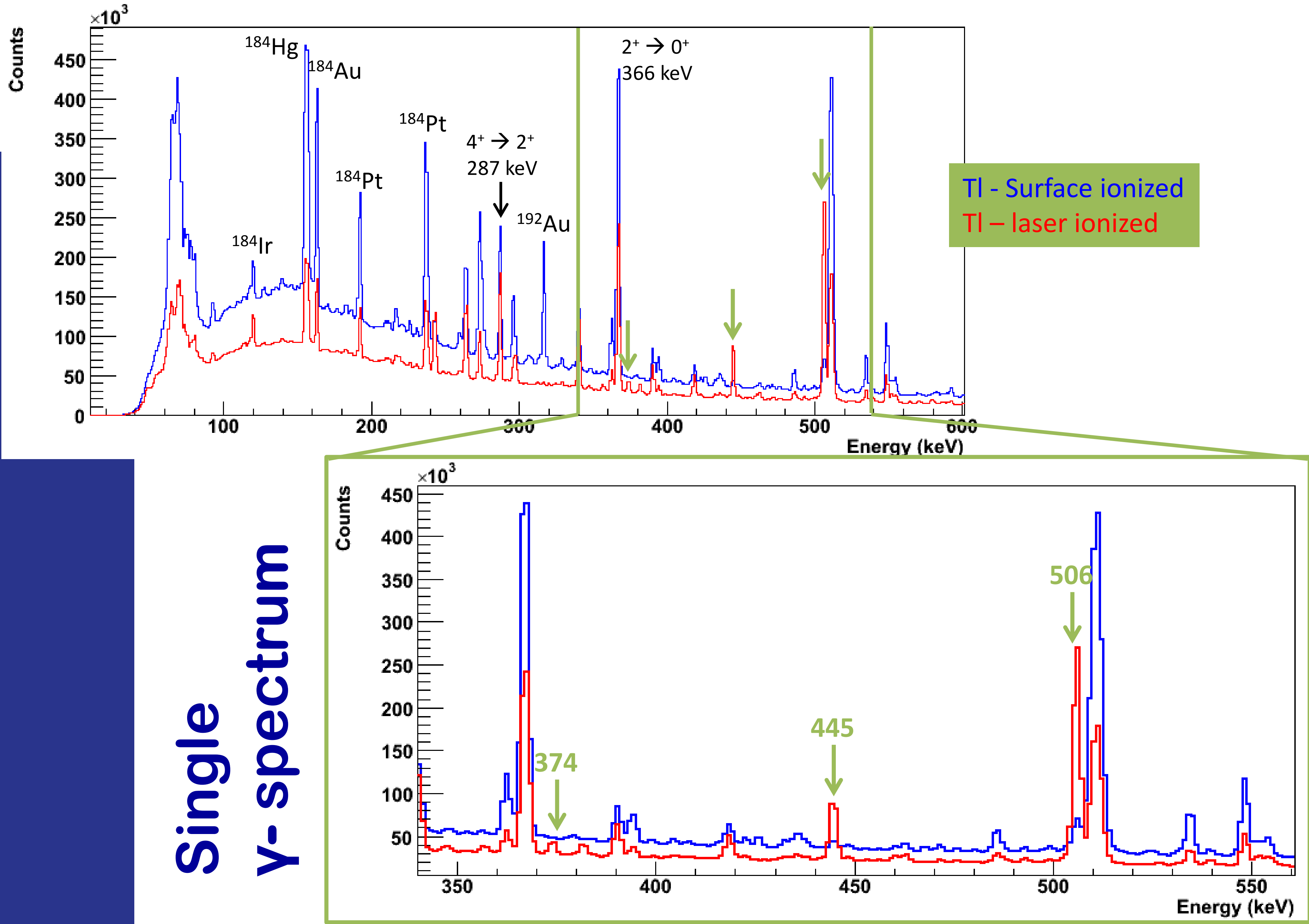


Two SET of DATA

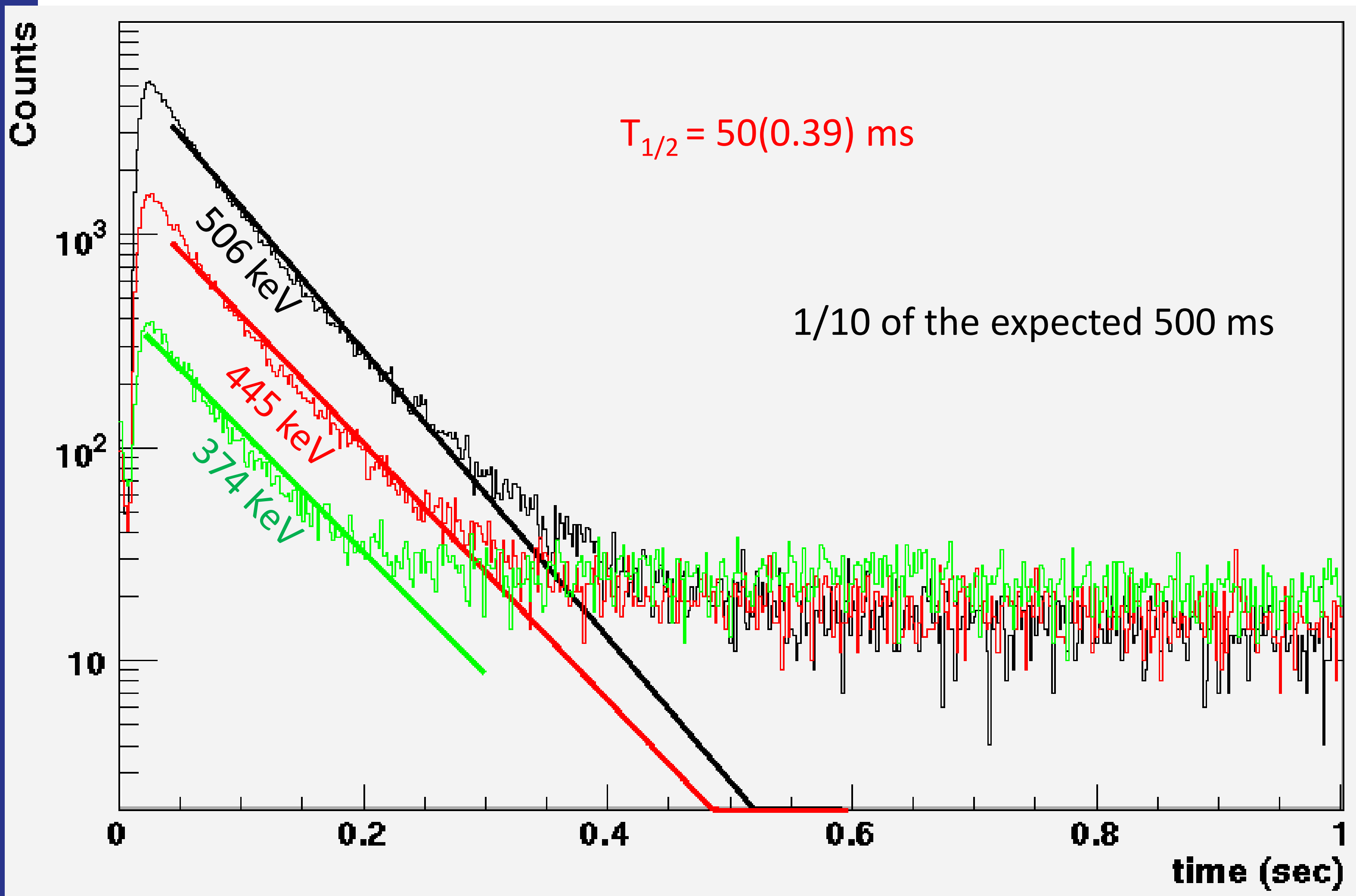
No laser: Tl is Surface Ionized
mixture of 2^-, 7^+, 10^-

With laser: Laser set on 10^-
enhanced 10^- state

Single γ- spectrum



LifeTime II



Counts
10^3
10^2
10
0
0.2
0.4
0.6
0.8
1
time (sec)
506 keV
445 keV
374 KeV
$T_{1/2}$ = 50(0.39) ms
1/10 of the expected 500 ms