Istituto Nazionale di Fisica Nucleare

Decay spectroscopy in the region of neutron-rich lead isotopes

Andrea Gottardo

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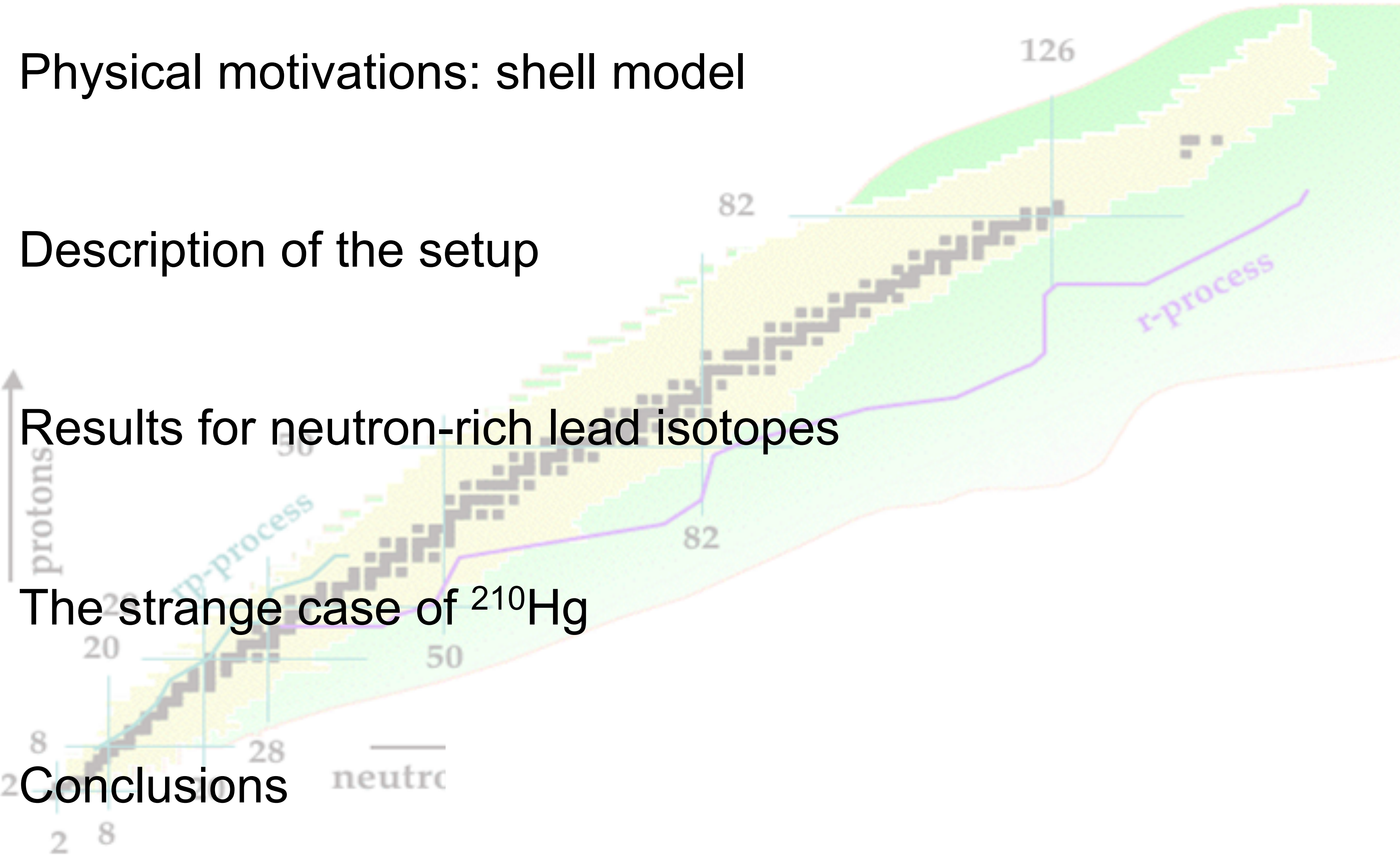
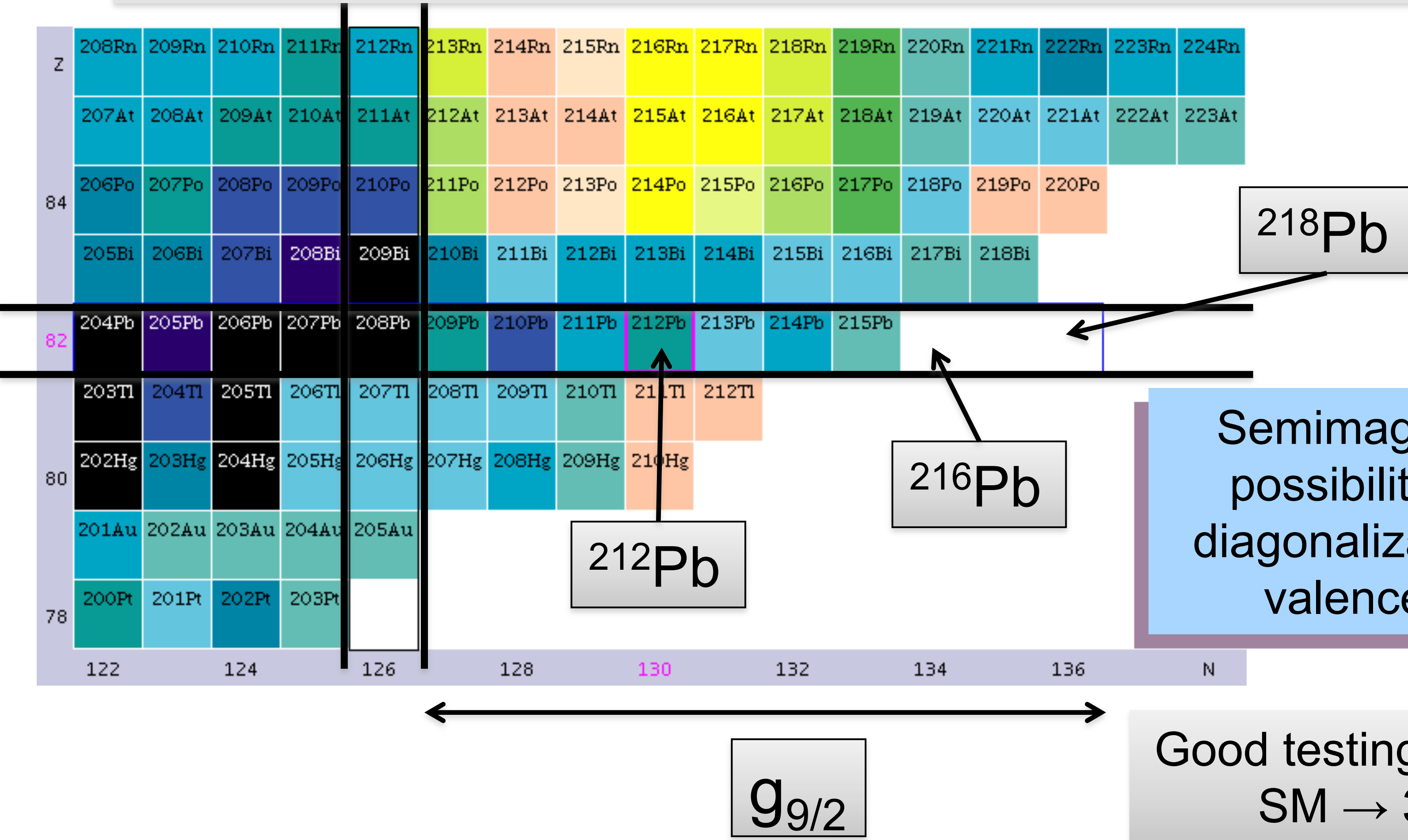


The Z=82 and beyond N=126 region

Presence of isomers involving high-j orbitals $\nu g_{9/2}$, $\nu i_{11/2}$, $\nu j_{15/2}$. Taking advantage of these isomers we want to study the developement of nuclear structure from ^{212}Pb up to ^{218}Pb and nearby nuclei



Semimagic nuclei : possibility of a full diagonalization in the valence space

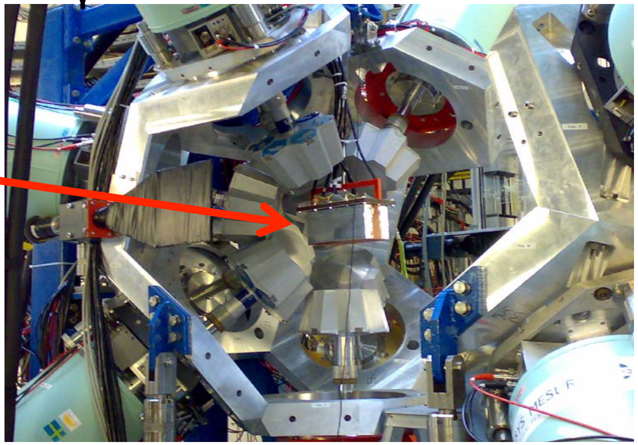
Good testing ground for SM → 3-body

Experimental setup

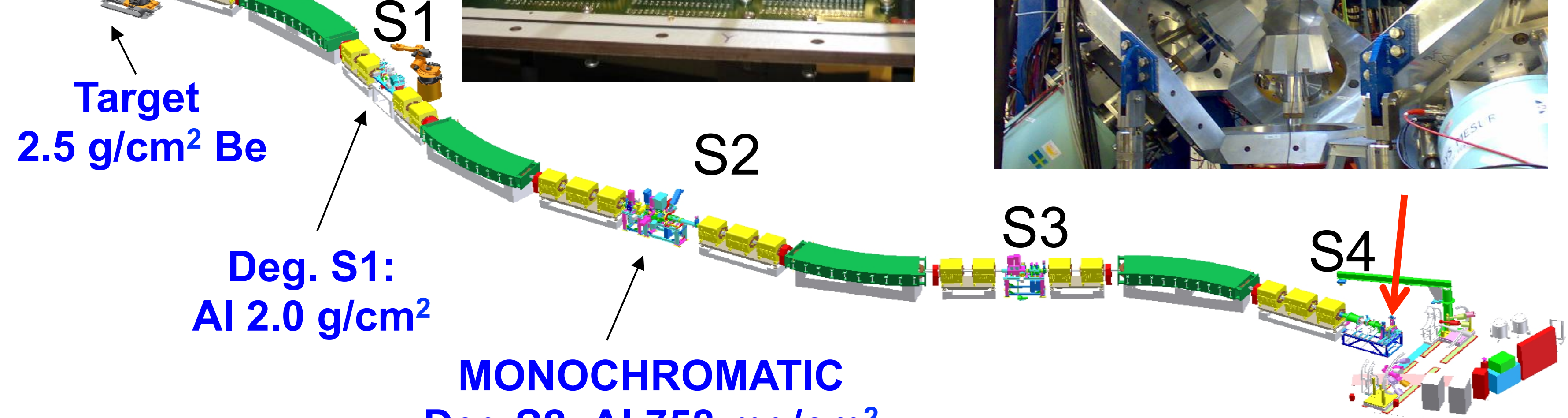
FRS-Rising at GSI: stopped beam campaign

9 DSSSD, 1mm thick, 5x5 cm^2
16x16 x-y strips

15 CLUSTERs x 7 crystals
ε_γ = 11% at 1.3MeV



Beam: ^{238}U @ 1GeVA



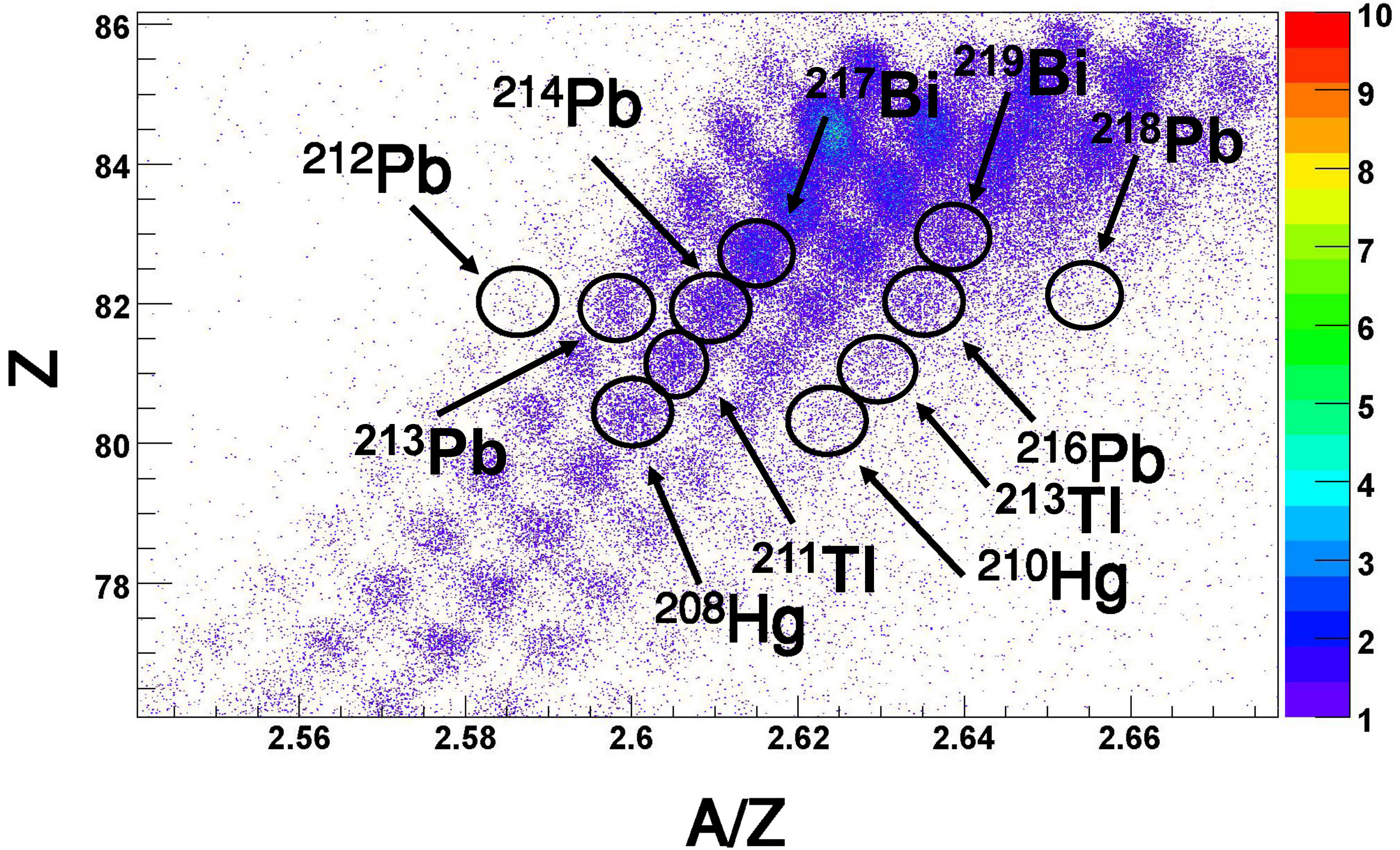
Target
2.5 g/cm^2 Be

Deg. S1:
Al 2.0 g/cm^2

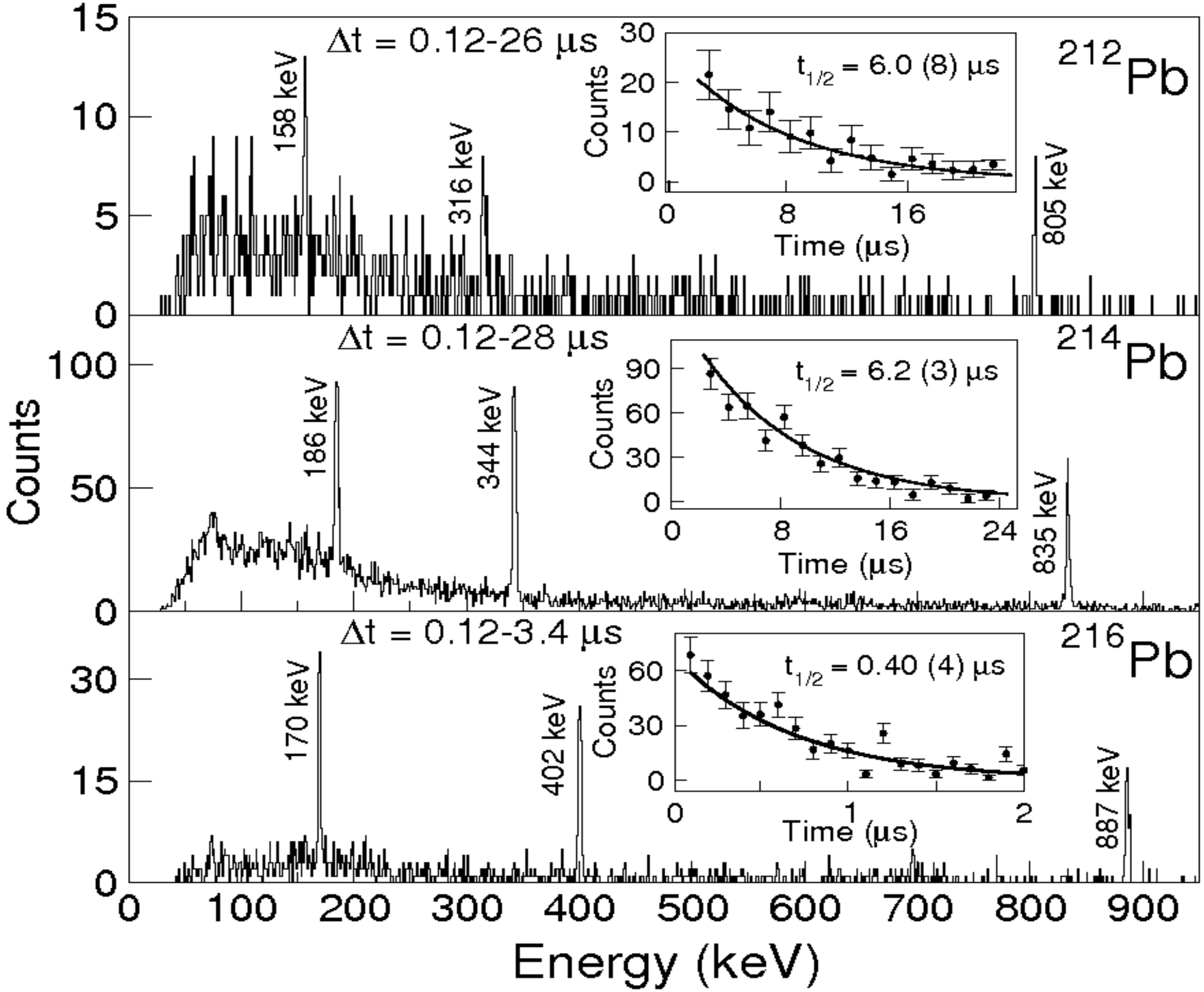
MONOCHROMATIC
Deg S2: Al 758 mg/cm^2

Nuclei populated in the fragmentation

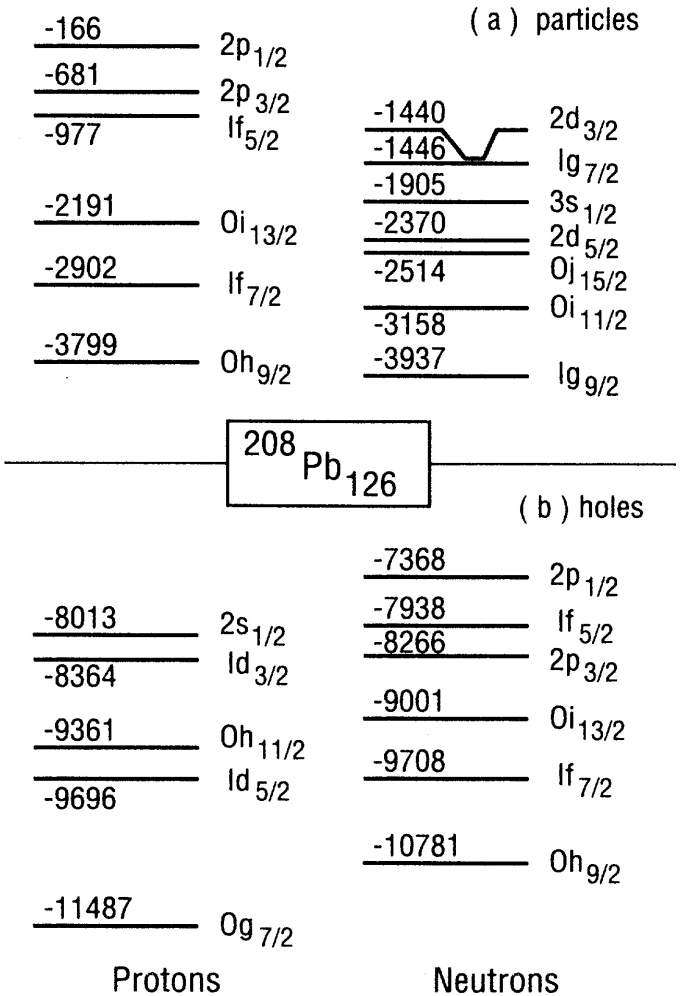
1 GeVA ^{238}U beam from UNILAC-SIS at 10^9 pps



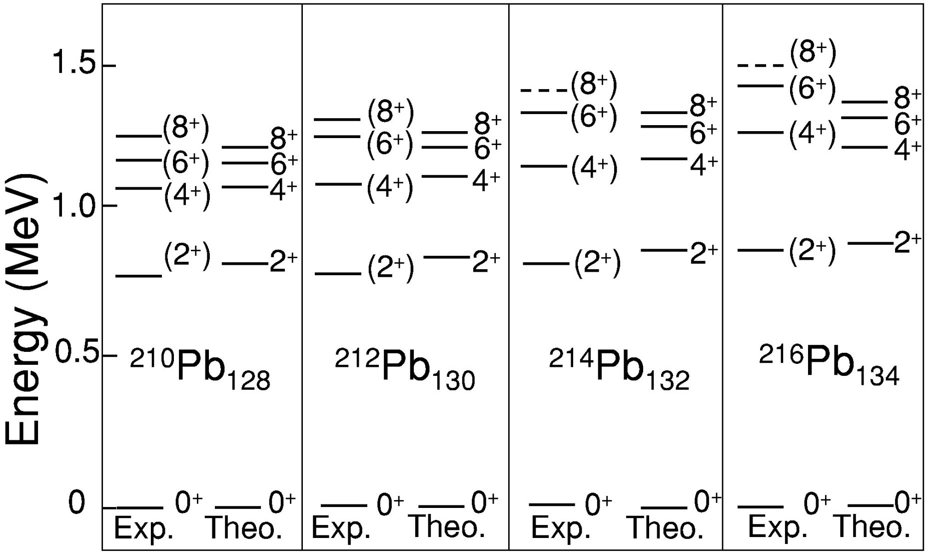
^{212,214,216}Pb: 8^+ isomer



The shell model space

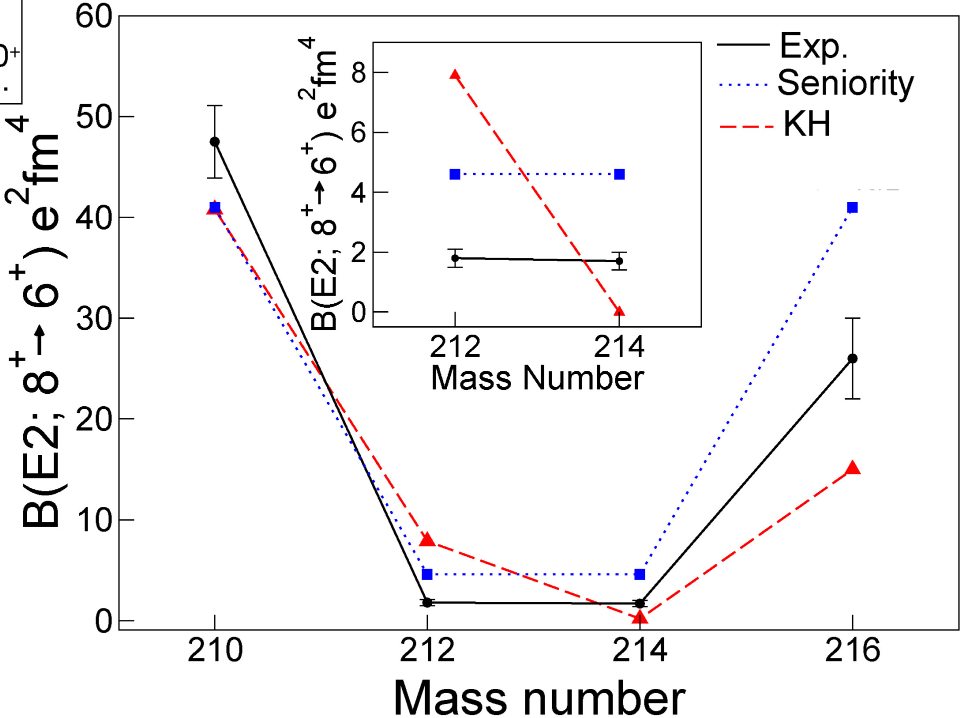


Experimental level schemes



Antoine, Nathan LSSM, KH interaction: Excellent agreement with level energies but bad reproduction of B(E2) values!

e_ν = 0.8 to reproduce ^{210}Pb, but for the other isotopes the B(E2) is wrong!



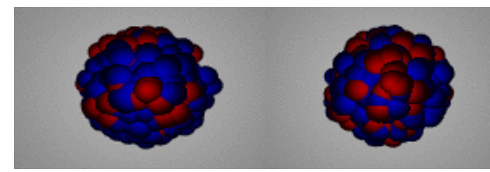
Effective three-body forces

PRL 109, 162502 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

New Isomers in the Full Seniority Scheme of Neutron-Rich Lead Isotopes: The Role of Effective Three-Body Forces

A. Gottardo,[1,2,*] J. J. Valiente-Dobón,[1] G. Benzoni,[3] R. Nicolini,[3,4] A. Gadea,[5] S. Lunardi,[2,6] P. Boutachkov,[7]

The renormalisation takes into account the coupling to high energy core excitation modes, as the giant quadrupole resonance



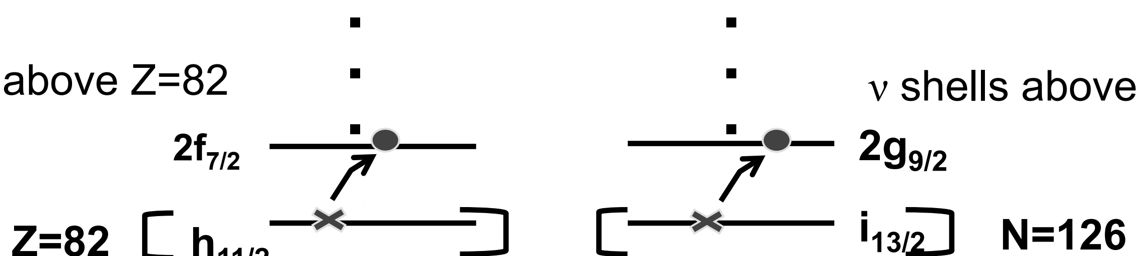
Constant effective charges $e_\nu \sim 0.5e$, $e_\pi \sim 1.5e$

Bohr and Mottleson, Nuclear Structure (1975)

Dufour and Zuker PRC 54, 1641 (1996)

π shells above Z=82

ν shells above N=126

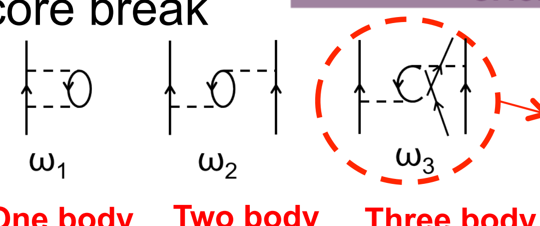


Z=82 p-h core break

N=126 p-h core break

Q-SU(3) E2 ($\Delta J=\Delta\ell=2$) partner shells: $0\hbar\omega$ excitations

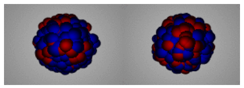
$$\langle \overline{\overline{f^n i}} | H | \overline{\overline{f^n i'}} \rangle = \langle f^n i | H | f^n i' \rangle + \langle f^n i | \omega_1 + \omega_2 + \omega_3 | f^n i' \rangle$$

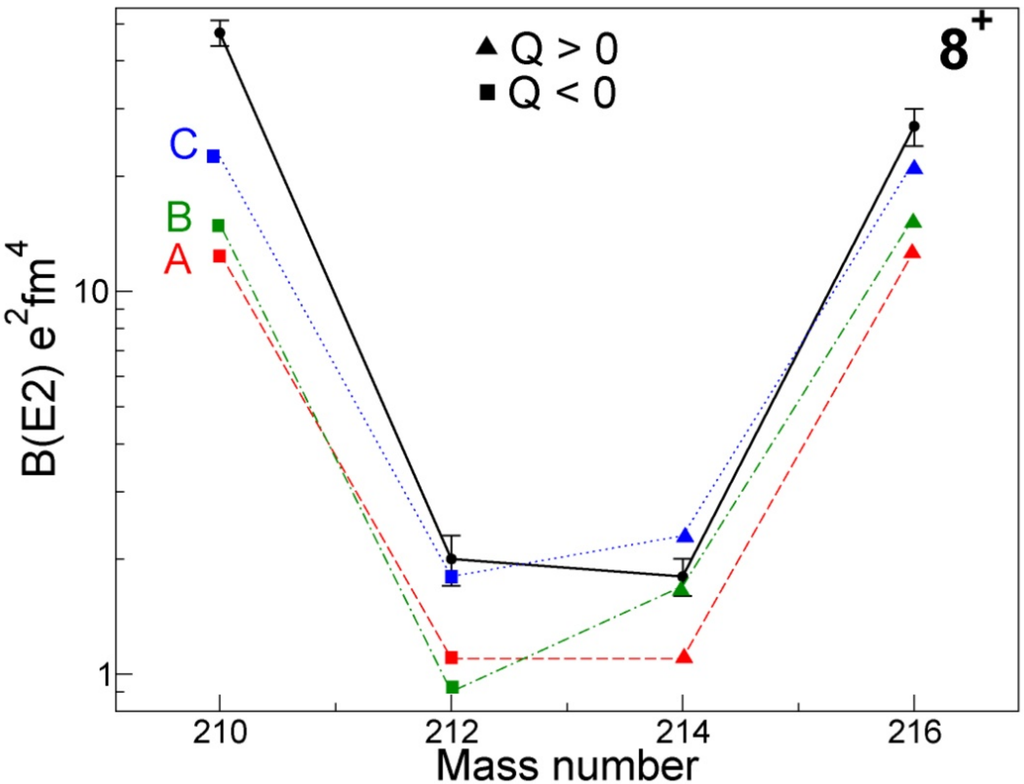


Usually neglected!

Effective 3-body interaction: results

Lee interaction for evaluating three-body effects

GQR  **+** coupling to 2^+ (and 3^-) excitations from the core



Standard eff. charges:

$e_\nu = 0.5e,\ e_\pi = 1.5e$

Exp. data

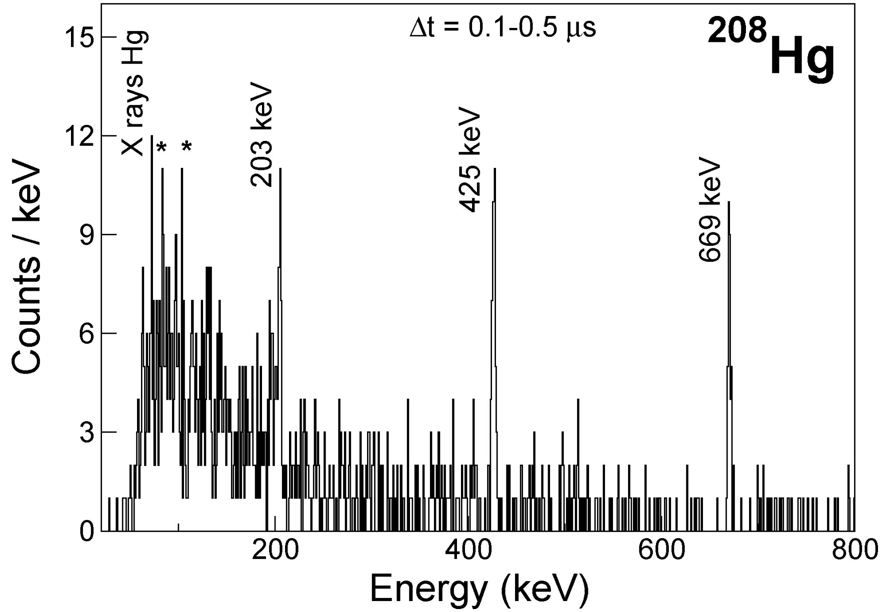
$g_{9/2}$

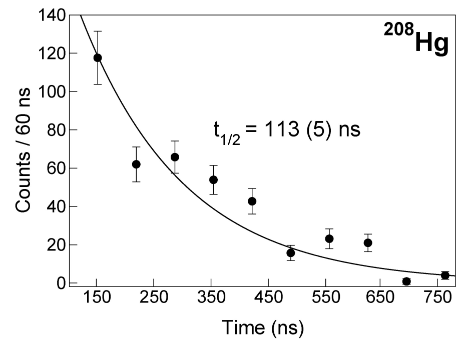
$g_{9/2}$ + ν shells above

$g_{9/2}$ + ν shells above + core exc. (**3 body**)

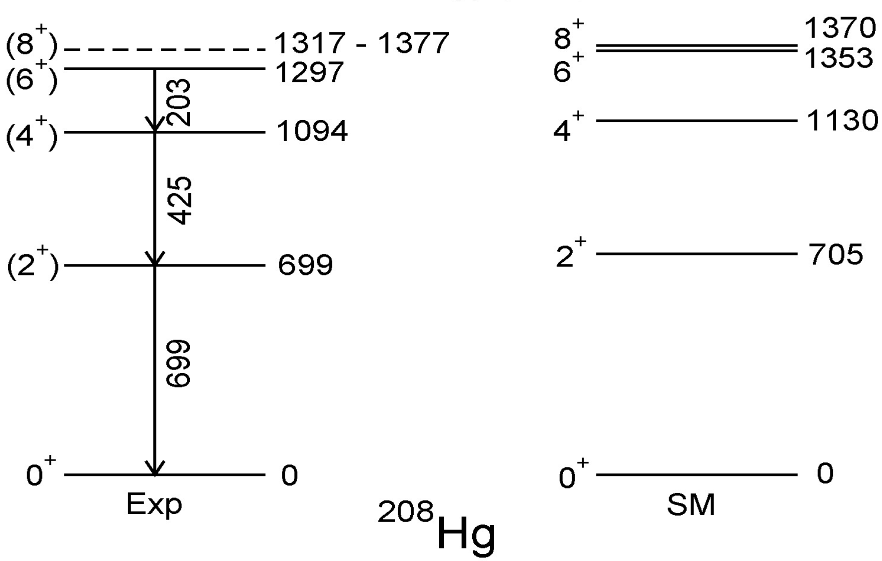
The explicit coupling to the core restores a seniority-like behaviour (midshell symmetry) and also justifies $e_\nu = 0.8e$ from the standard $e_\nu = 0.5e$

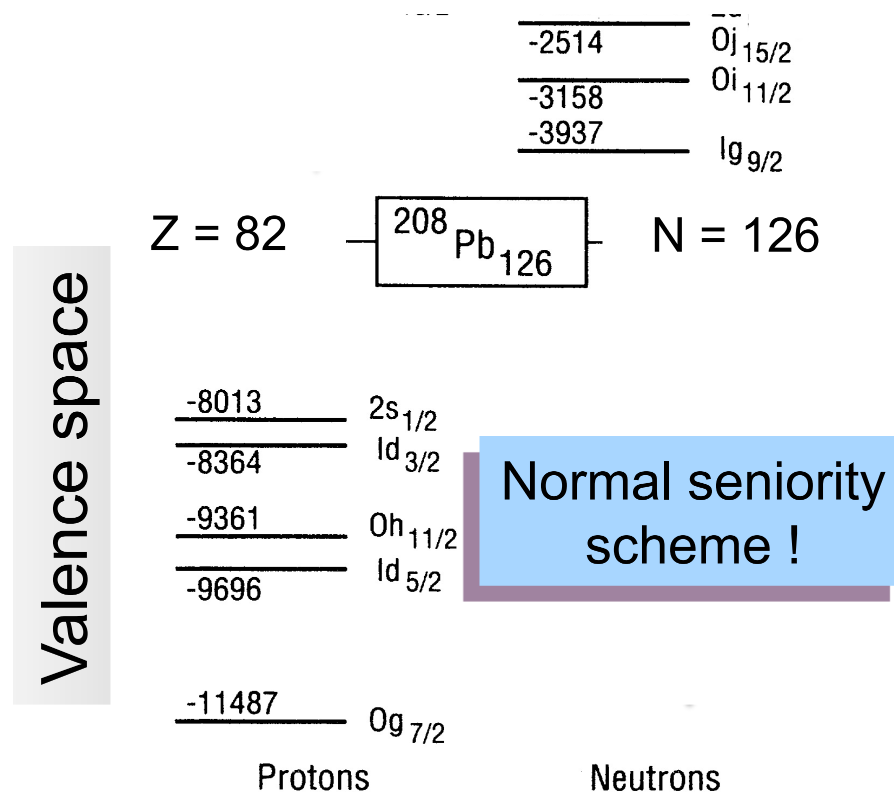
Mercury isotopes (I)





Surrey group

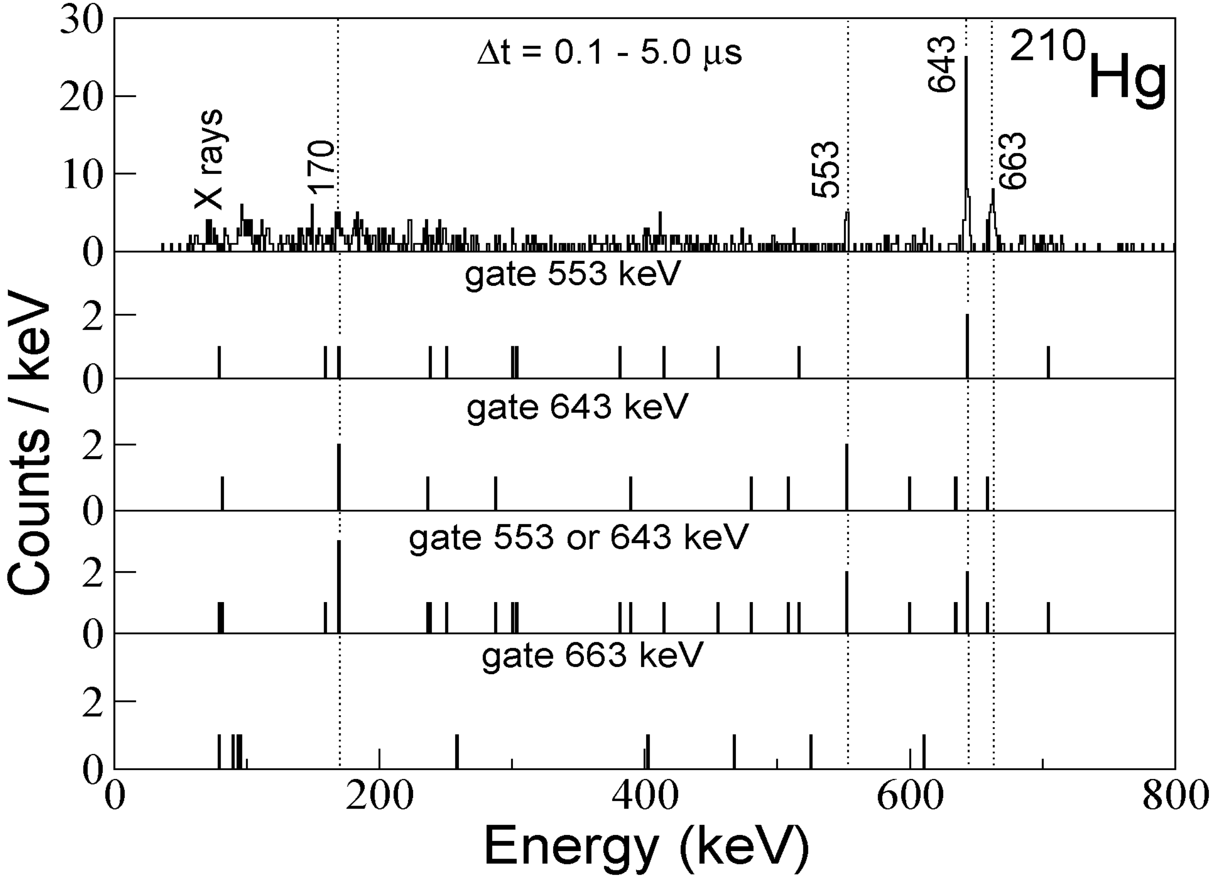




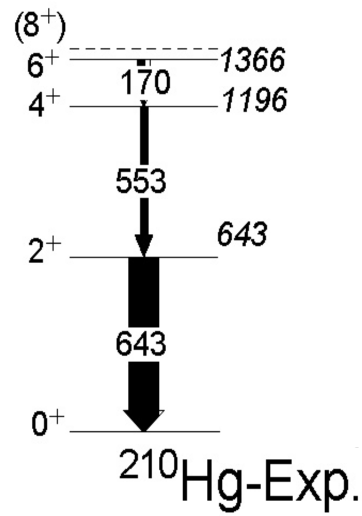
Normal seniority scheme !

Mercury isotopes (II): ^{210}Hg

Spectrum certainly different from the one of ^{208}Hg !

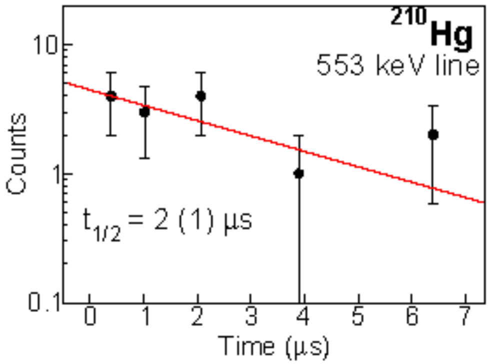


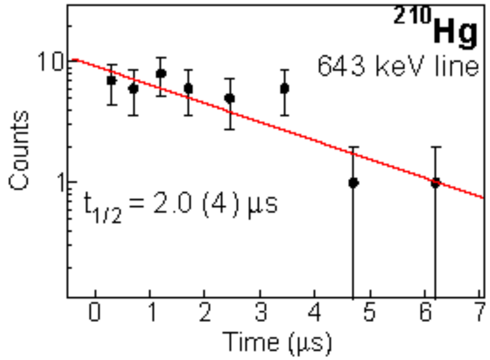
643, 553, 170 keV in coincidence!

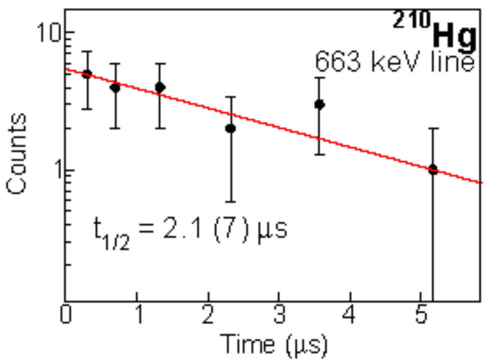


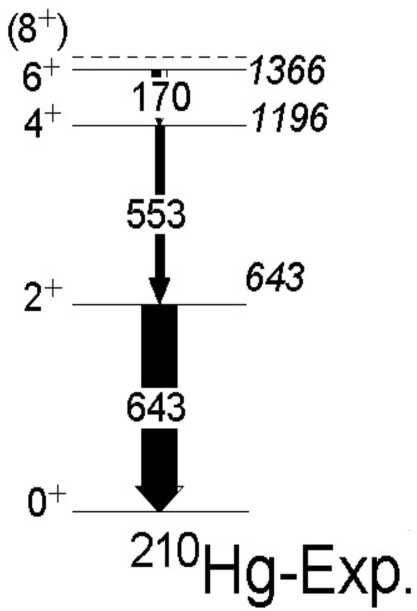
Energy	Area	Intensity
170	13 (7)	22(12)
553	12 (4)	23(8)
643	45 (7)	100(16)
663	25 (6)	65(13)

Lifetimes : a normal seniority scheme?









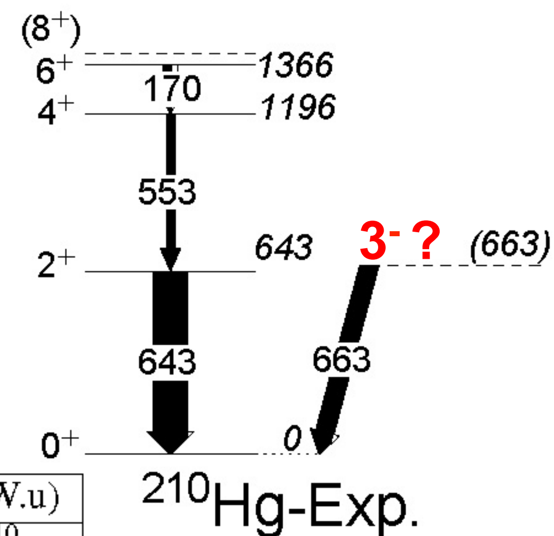
B(E2) from 553-keV line: 8 time less the one predicted by SM: as ^{212}Pb

YES, but something more…

What about the intensity of the first 2^+ (643 keV)?

Energy	Intensity
170	22(12)
553	23(8)
643	100(16)
663	65(13)

What about the 663-keV line?
It is not in coincidence!



What can we say on the spin of this state?

A state with a μs lifetime decaying to 0^+ must be 1^+,2^+, 1^-,3^-

E_γ (keV)	E,Mλ	B(E,Mλ) (W.u)
663	E1	$3(1)\cdot 10^{-10}$
663	E2	$3(1)\cdot 10^{-5}$
663	E3	4(2)
663	M1	$4(1)\cdot 10^{-8}$
20	M1	$8(3)\cdot 10^{-6}$
20	E1	$1.5(6)\cdot 10^{-6}$

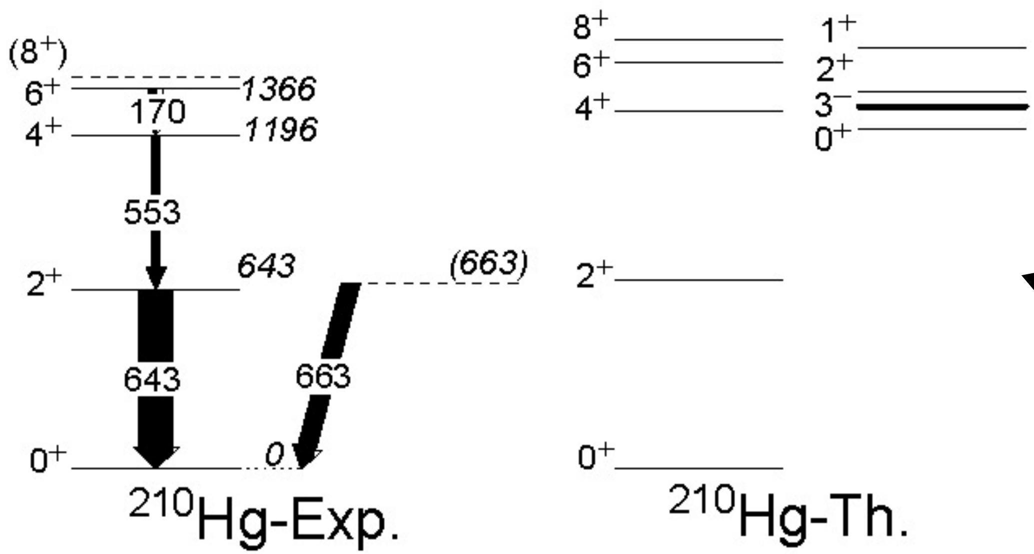
Isomeric ratio R

$R=N\downarrow Isomer\ /N$

$R\downarrow exp3-\ /R\downarrow exp8\uparrow+\ = 0.6(1)/0.11(4)$

And what about the theory?

Shell model calculations already proved effective in the Pb isotopes and ^{208}Hg (apart from the 3-body effect)



$\pi d_{3/2}^{-1}$
$\pi s_{1/2}^{-1}$

NO level close to the 2^+ !

1- Very good agreement for the seniority scheme $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$

2- $B_{exp}(E2; 8^+ \rightarrow 6^+) \sim 8 \cdot B_{theor}(E2; 8^+ \rightarrow 6^+)$: effective 3-body forces as in ^{212}Pb

3- 3^- energy by particle-vibration coupling model (impossible by shell-model)

Conclusions

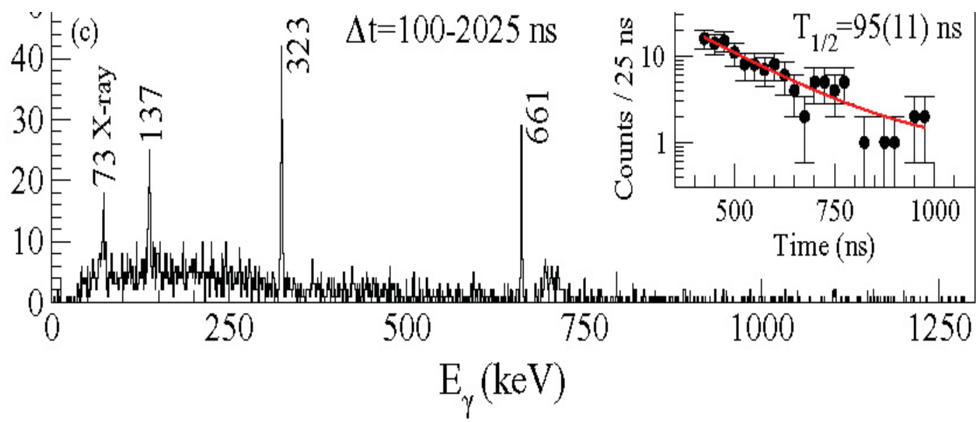
- Experiment with radioactive beam, with the in-flight technique. Several experimental challenges overcome. State-of-the-art experimental devices.
- The neutron-rich region along Z = 82 was populated, enabling to study the nuclear structure in this region up to now unknown due to experimental difficulties
- The observed shell structure seems to follow a seniority scheme. However, a closer look reveals that the B(E2) values have an unexpected behaviour. The mechanism of effective 3-body forces is general, and could be relevant also for other parts of the nuclide chart (Sn?, Ni?, Cd?).
- ^{210}Hg seems to present an unexpected deviation from standard theoretical predictions.

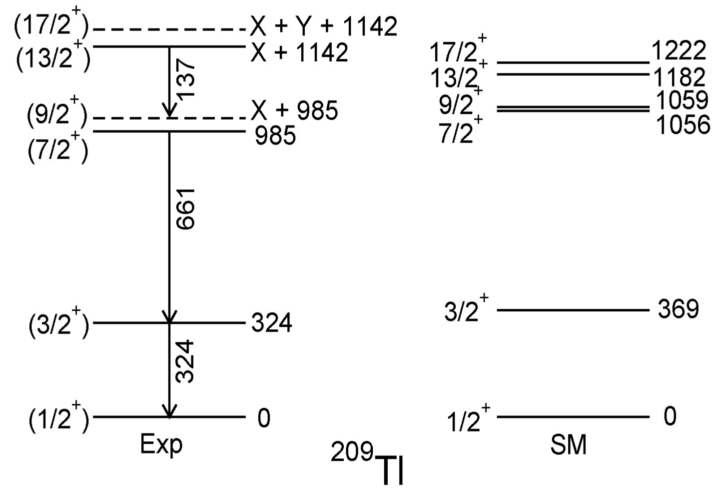
Collaboration

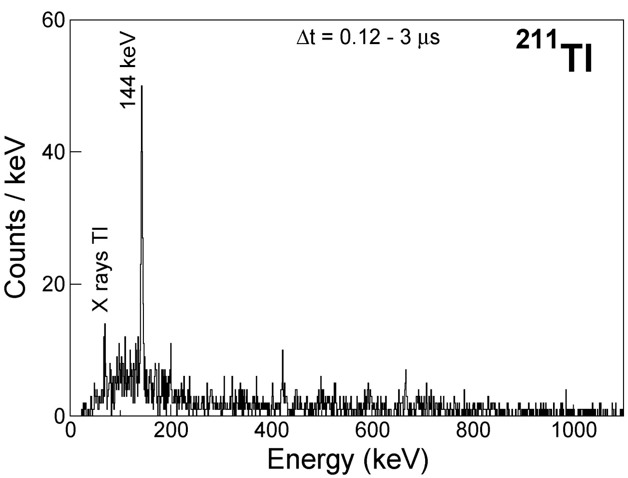
A. Gottardo, J.J. Valiente-Dobon,
A. Zuker, E. Maglione, F. Nowacki, , G. Benzoni,
A. Bracco, G. de Angelis, F.C.L. Crespi,F. Camera, A. Corsi, S. Leoni, B. Million, O. Wieland, D.R. Napoli, E. Sahin, S.Lunardi, R. Menegazzo, D. Mengoni, F. Recchia, P. Boutachkov, L. Cortes, C. Domingo-Prado,F. Farinon, H. Geissel, J. Gerl, N. Goel, M. Gorska, J. Grebosz, E. Gregor, T.Haberman,I. Kojouharov, N. Kurz, C. Nociforo, S. Pietri, A. Prochazka, W.Prokopowicz, H. Schaffner,A. Sharma, H. Weick, H-J.Wollersheim, A.M. Bruce, A.M. Denis Bacelar, A. Algora,A. Gadea, M. Pf¨utzner, Zs. Podolyak, N. Al-Dahan, N. Alkhomashi, M. Bowry, M. Bunce,A. Deo, G.F. Farrelly, M.W. Reed, P.H. Regan, T.P.D. Swan, P.M. Walker, K. Eppinger,S. Klupp, K. Steger, J. Alcantara Nunez, Y. Ayyad, J. Benlliure, Zs.Dombradi E. Casarejos,R. Janik,B. Sitar, P. Strmen, I. Szarka, M. Doncel, S.Mandal, D. Siwal, F. Naqvi,T. Pissulla,D. Rudolph,R. Hoischen, P.R.P. Allegro, R.V.Ribas, and the **Rising collaboration**

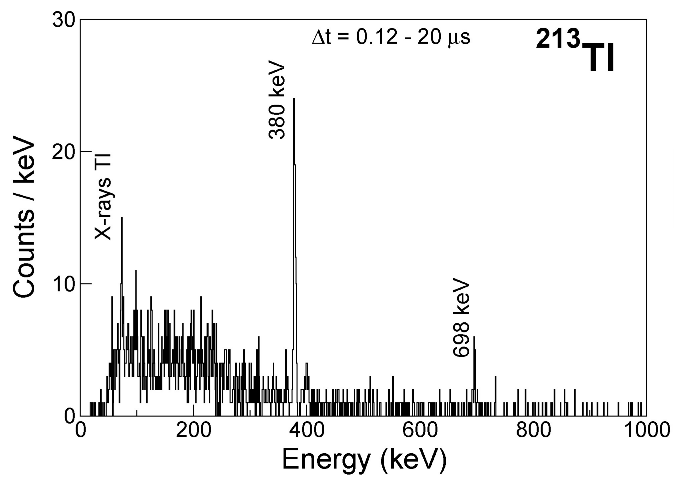
Università di Padova e INFN sezione di Padova, Padova, I; INFN-LNL, Legnaro (Pd), I; Università degli Studi e INFN sezione di Milano, Milano, I; University of the West of Scotland, Paisley, UK; GSI, Darmstadt, D; Univ. Of Brighton, Brighton, UK; IFIC, Valencia, E; University of Warsaw, Warsaw, Pl; Universiy of Surrey, Guildford, UK; TU Munich, Munich, D; University of Santiago de Compostela, S. de Compostela, E; Univ. Of Salamanca, Salamanca, E; Univ. of Delhi, Delhi, IND; IKP Koeln, Koeln, D; Lund University, Lund, S; Univ. Of Sao Paulo, Sao Paulo, Br; ATOMKI, Debrecen, H.

and ^{211,213}Tl as well…



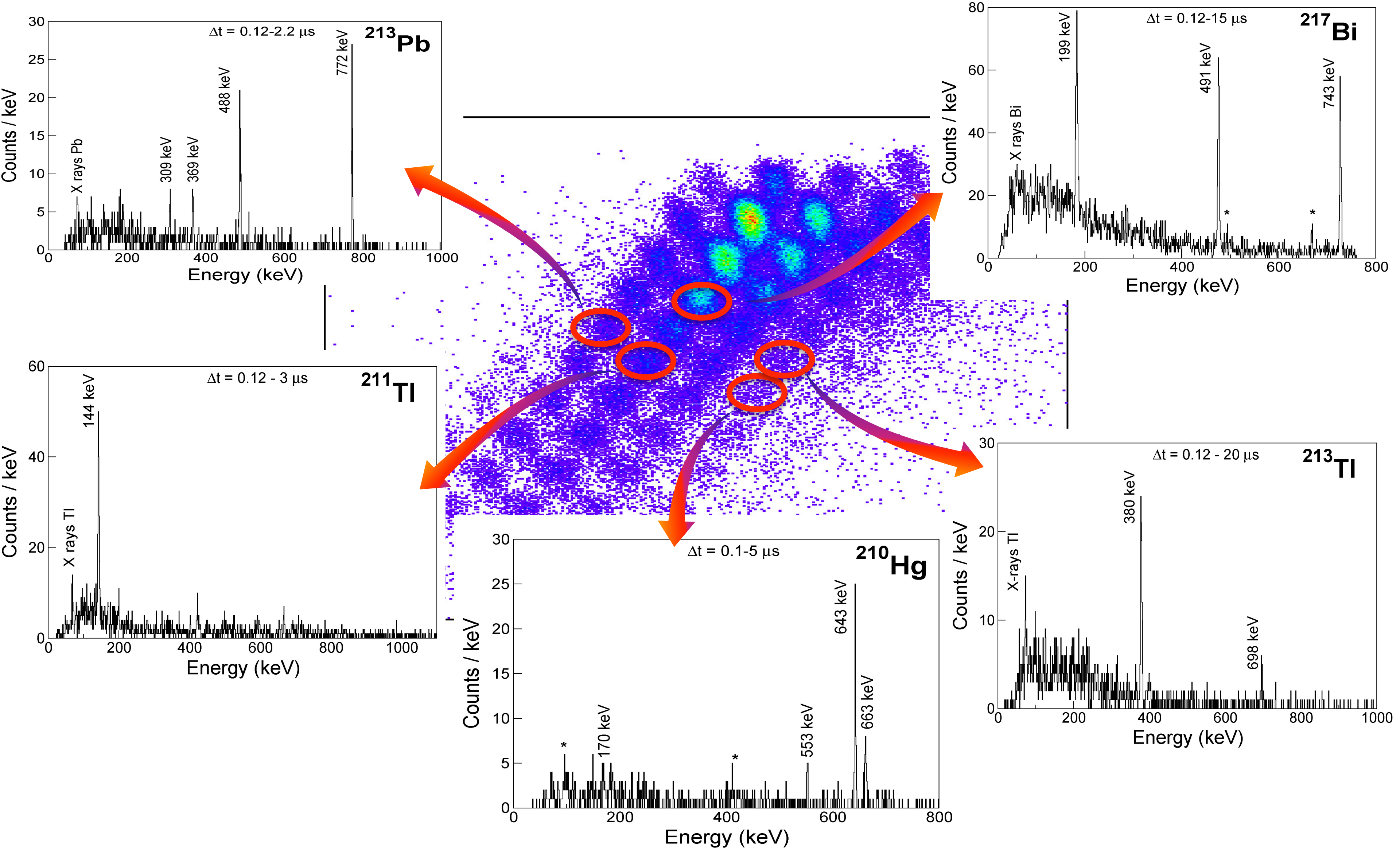




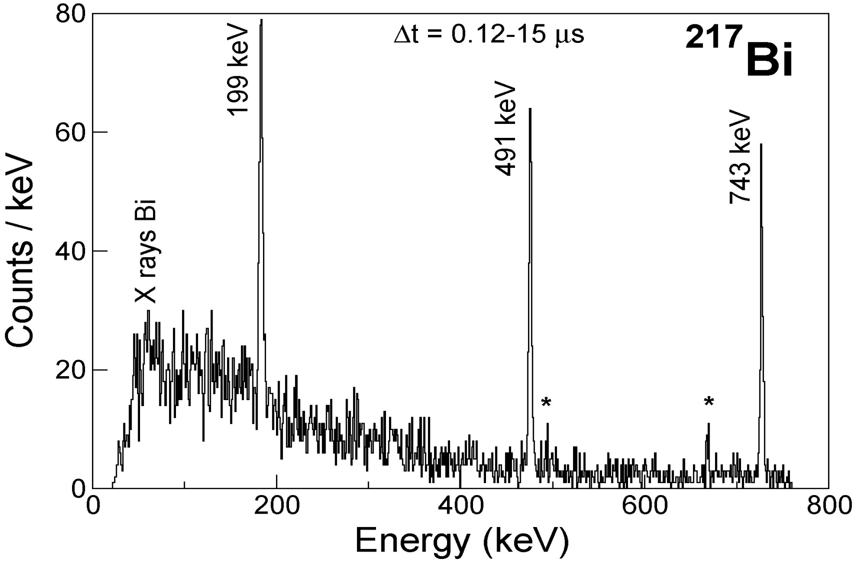


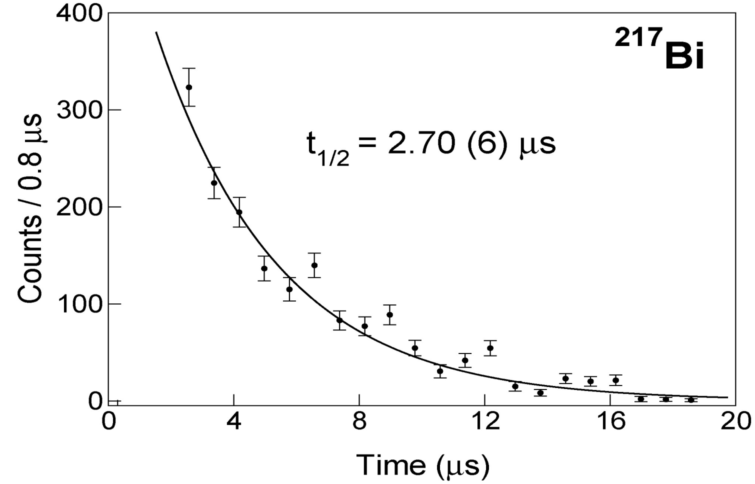
Very different structure!

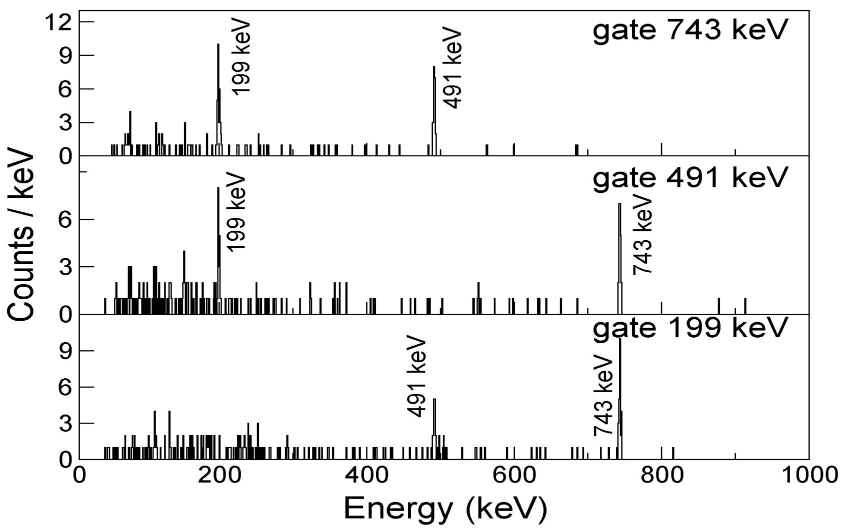
A glimpse of the other results

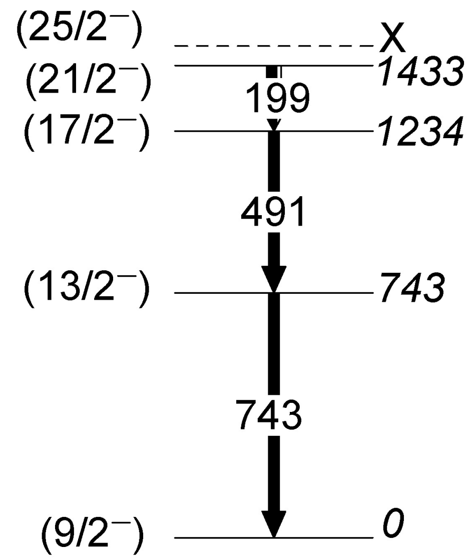


Bismuth isotopes (I)

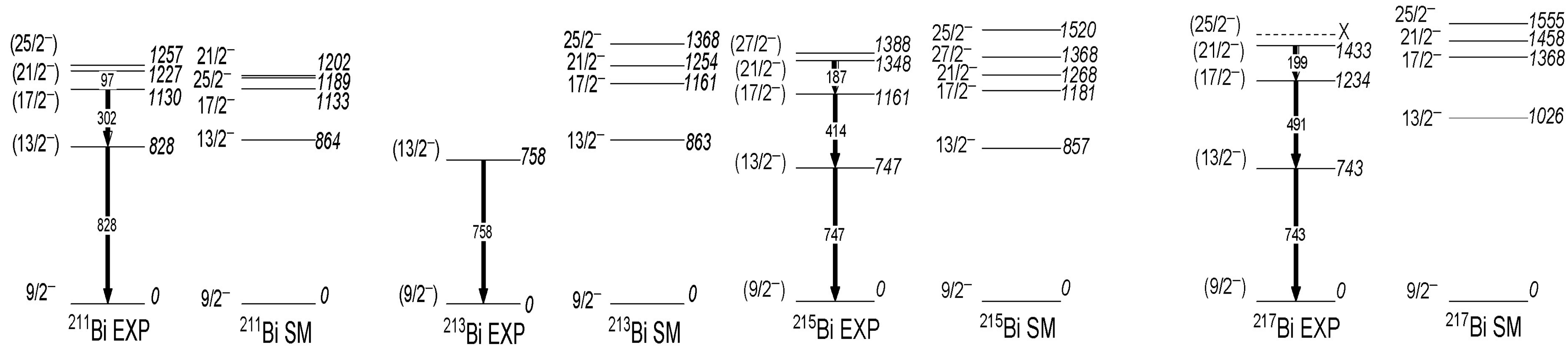


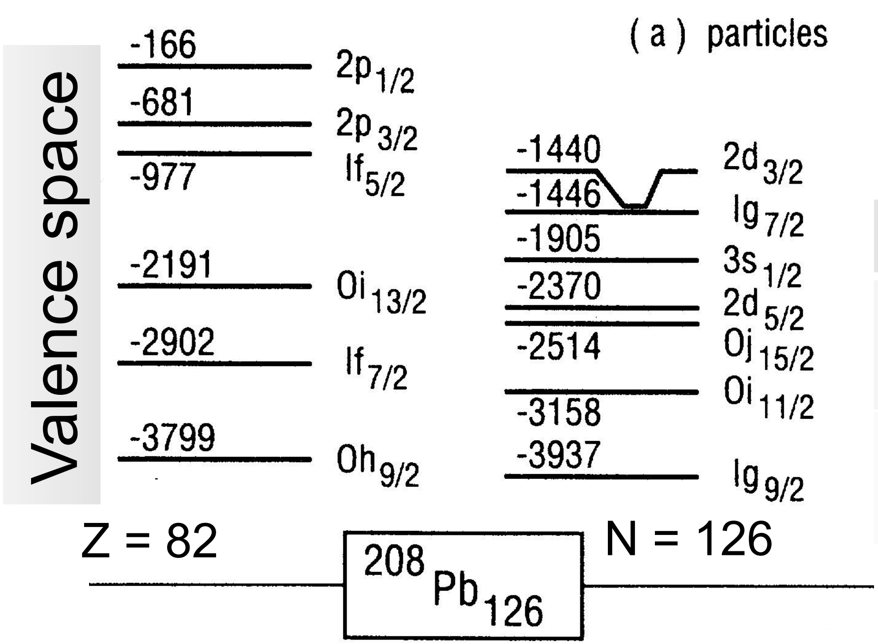






Bismuth isotopes (II)

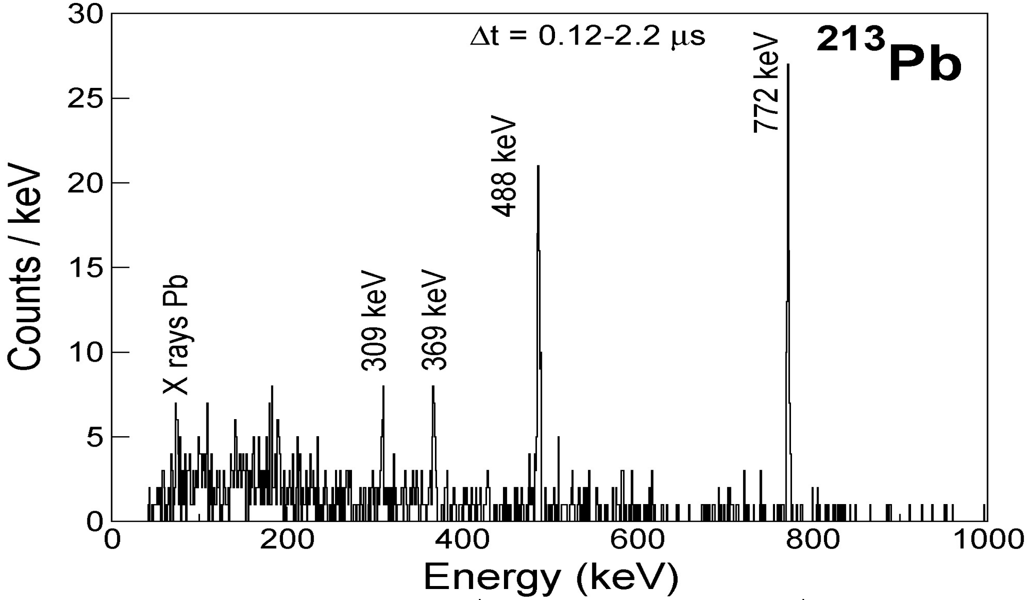


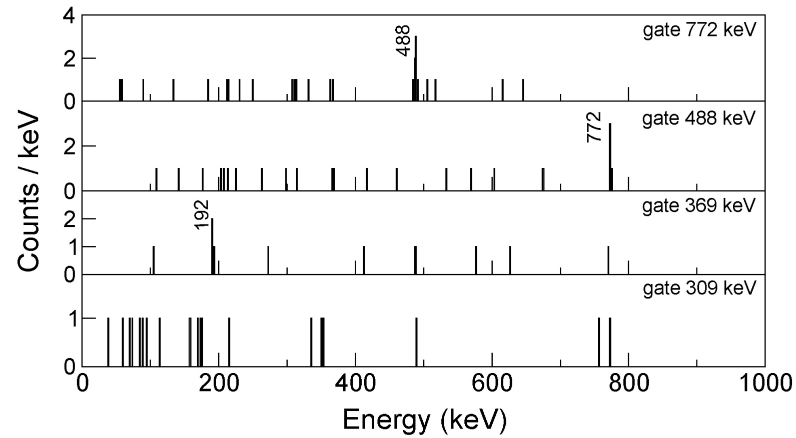


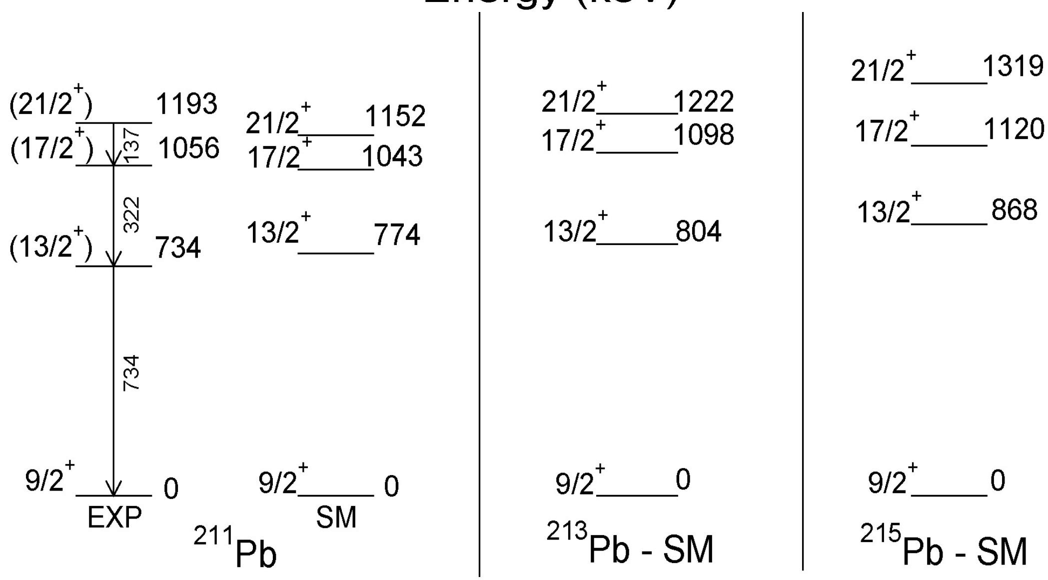
$e_\nu = 0.8,\ e_\pi = 1.5$

	^{211}Bi	^{217}Bi
B(E2; 25/2$^-$ →21/2$^-$) EXP.	8 (2) e^{2}fm^4	4.4 (3.6) e^{2}fm^4
B(E2; 25/2$^-$ →21/2$^-$) KH	92 e^{2}fm^4	1.0 e^{2}fm^4

^{213}Pb: a strange case

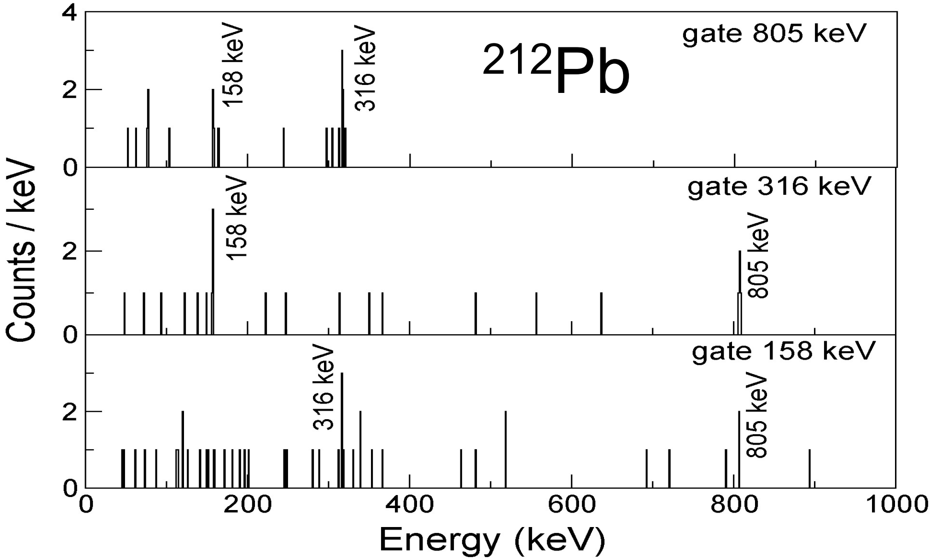


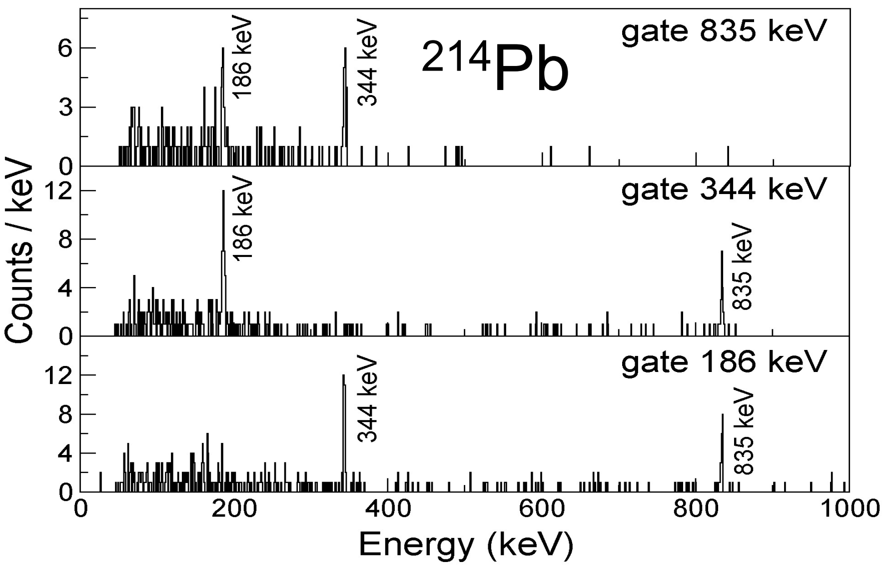


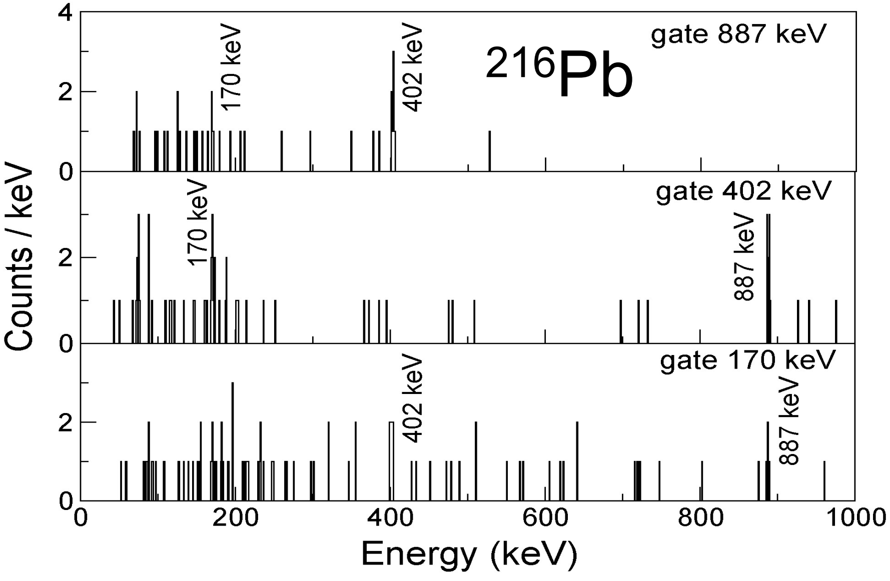


What are we observing in ^{213}Pb ? More than one isomer, but appearantly NOT the seniority isomer

$\gamma\gamma$ coincidences







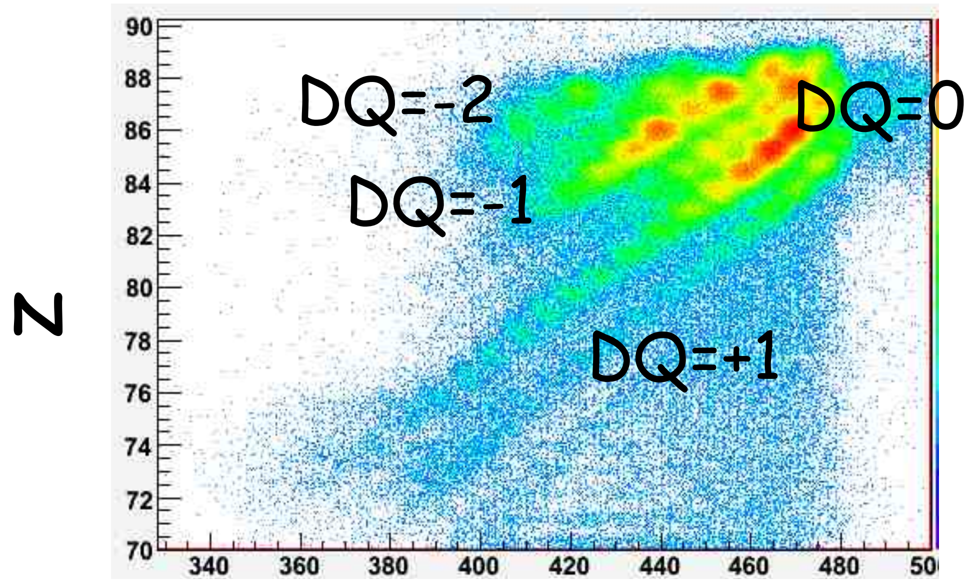
Charge state identification

Formation of many charge states owing to interactions with materials

➔Isotope identification is more complicated

➔ Need to disentangle nuclei that change their charge state after S2 deg.

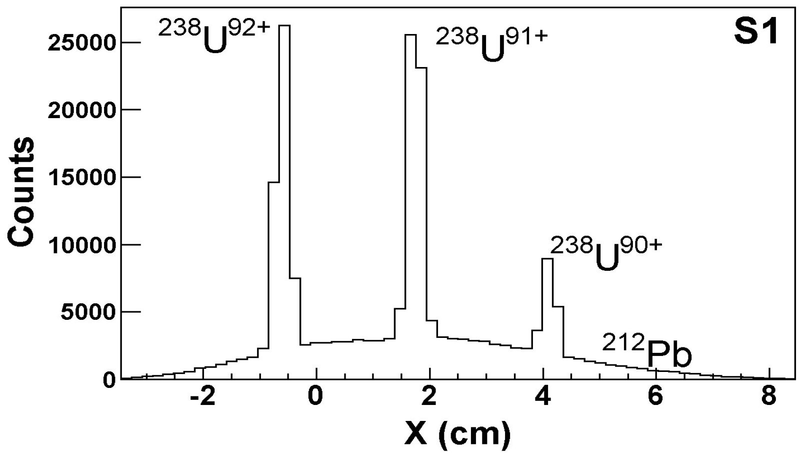
$(B\rho)_{TA\text{-}S2} - (B\rho)_{S2\text{-}S4}$

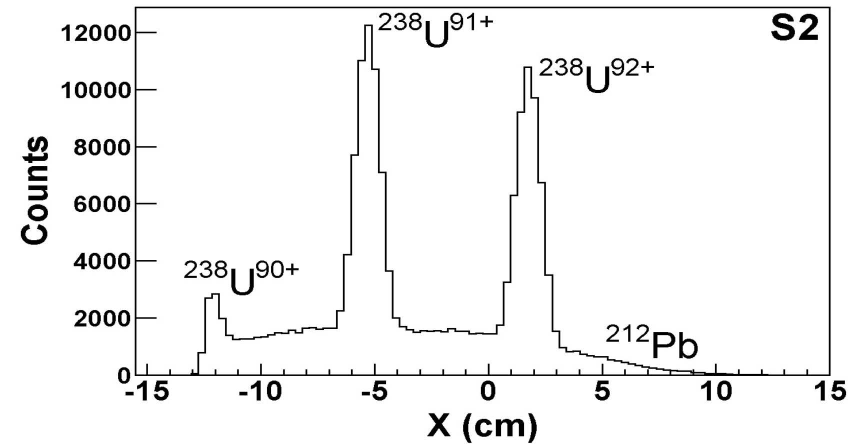


$B\rho_1 - B\rho_2$

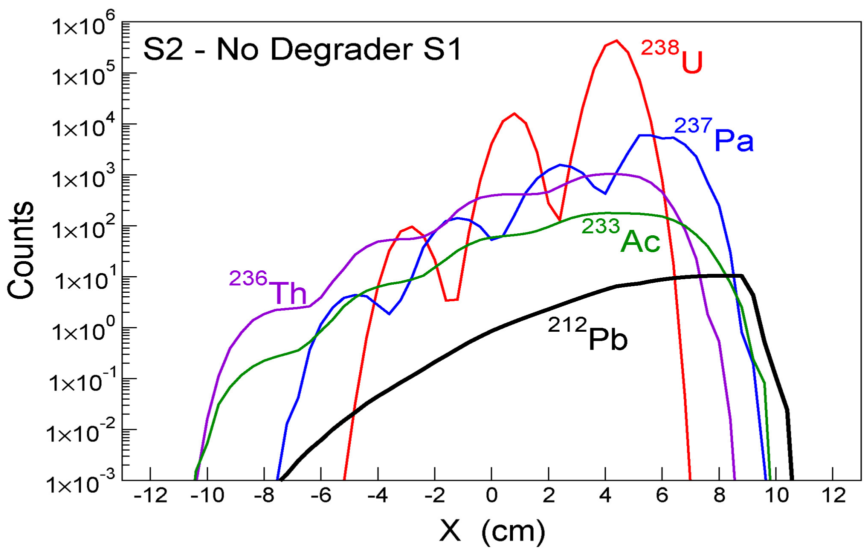
^{238}U charge-state problem

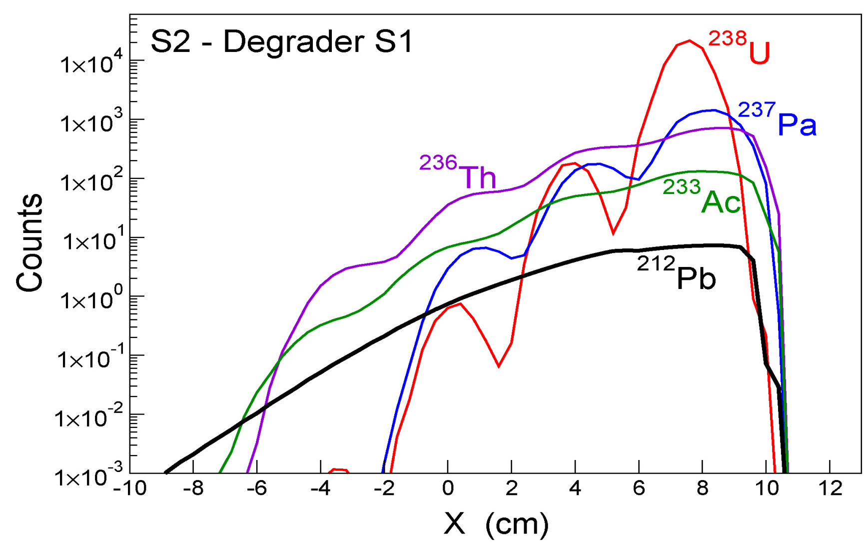
Mocadi simulation





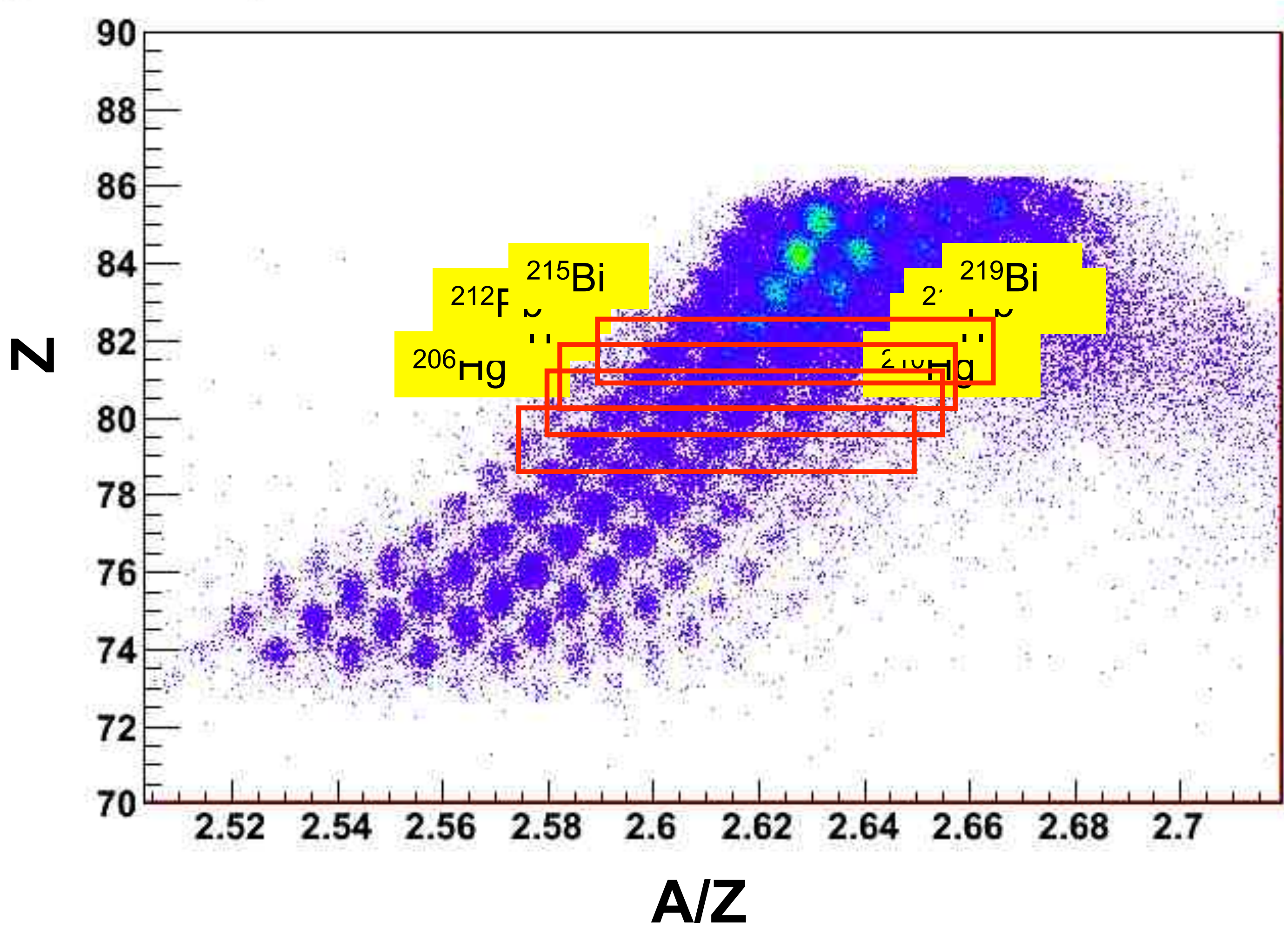
LISE++ simulation





Nuclei populated in the fragmentation

1 GeVA ^{238}U beam from UNILAC-SIS at 10^9 pps



FRS setting

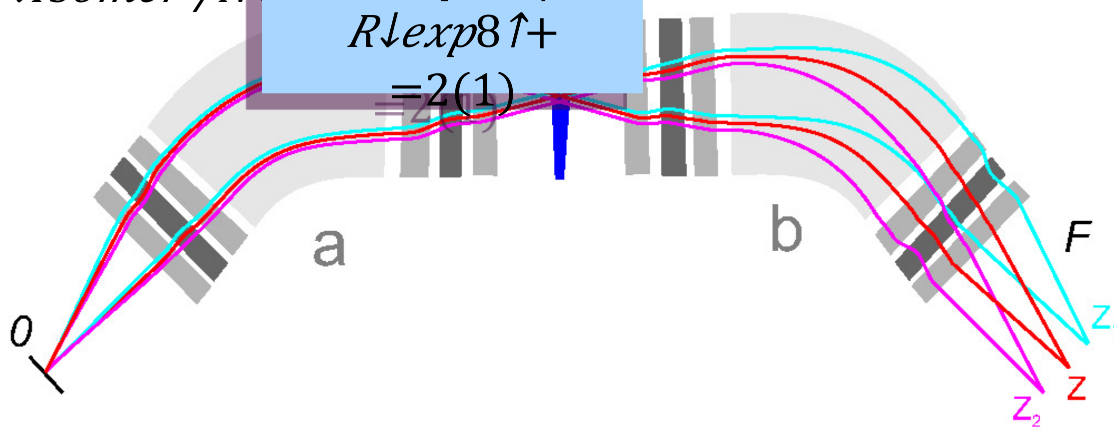
Isomeric ratio R

$R=N_{Isomer}/N$

$R_{exp}3^{-} / R_{exp}8^{+} = 2(1)$

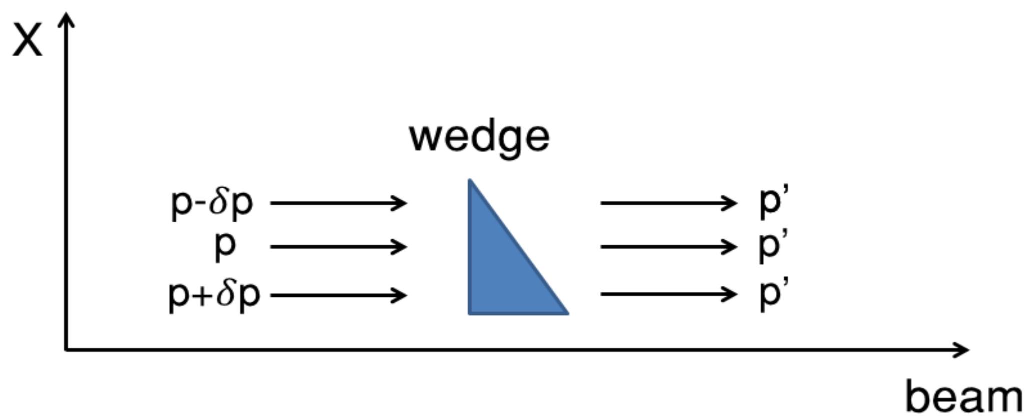
Achromatic setting for the S2 degrader:

x_4 depends only on the A/q, not on momentum



Monochromatic setting for the S2 degrader:

Same velocity for all the ions with a certain Z

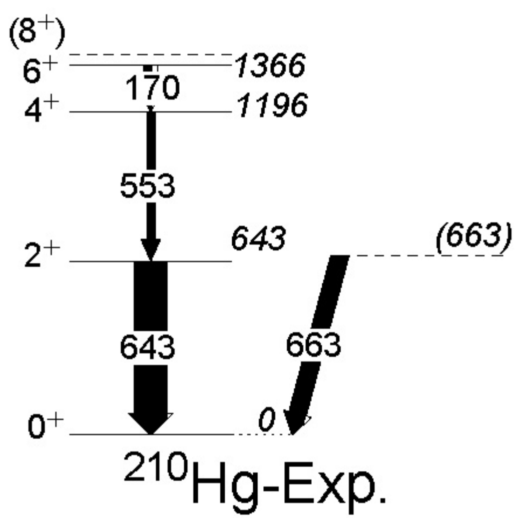


Some old good γ spectroscpy

A state with a μs lifetime decaying to 0^+ must be $1^+,2^+,1^-,3^-$

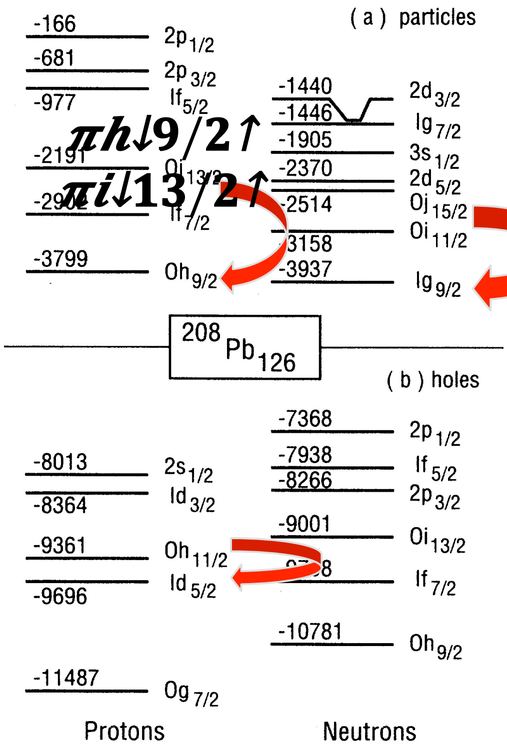
But in the systematics there are very well known limits for the various multipolarities

Energy	E,Mλ	B(E,Mλ) (W.u)
663 keV	E1	$5(1)\cdot10^{-10}$
663 keV	E2	$2.7(7)\cdot10^{-5}$
663 keV	E3	2.7(7)
663 keV	M1	$2.2(5)\cdot10^{-3}$
20 keV	M1	$7(2)\cdot10^{-5}$
20 keV	E1	$1.4(4)\cdot10^{-6}$



3^- seems the only resonable assumption…

The octupole states in the Pb region



The 3^- of ^{208}Pb at 2.6 MeV is a very fragmented state coming from different p-h excitations across the core

$\nu g_{9/2}$
$\nu j_{15/2}$

In nuclei above N=126 the 3^- energy drops due to octupole correlations betwen the $\Delta J=\Delta \ell=3$ shells

Z	206Po 8.8 D ε: 94.55% α: 5.45%	207Po 5.80 H ε: 99.98% α: 0.02%	208Po 2.898 Y α: 100.00% ε: 4.0E-3%	209Po 102 Y α: 99.52% ε: 0.48%	210Po 138.376 D α: 100.00% 2386.78	211Po 0.516 S α: 100.00%	212Po 0.299 μS α: 100.00%	213Po 3.72 μS α: 100.00%	214Po 164.3 μS α: 100.00% 1274.766
83	205Bi 15.31 D ε: 100.00%	206Bi 6.243 D ε: 100.00%	207Bi 31.55 Y ε: 100.00%	208Bi 3.68E+5 Y ε: 100.00%	209Bi STABLE 100%	210Bi 5.012 D β-: 100.00% α: 1.3E-4%	211Bi 2.14 M α: 99.72% β-: 0.28%	212Bi 60.55 M β-: 64.06% α: 35.94%	21[illegible]Bi 45.5[illegible] M β-: [illegible].80% α: [illegible].20%
82	204Pb ≥1.4E+17 Y 1.4% α 2620.60	205Pb 1.73E+7 Y ε: 100.00%	206Pb STABLE 24.1% 2647.80	207Pb STABLE 22.1%	208Pb STABLE 52.4% 2614.522	209Pb [illegible]53 H β-: 100.00%	210Pb 22.20 Y β-: 100.00% α: 1.9E-6% 1870	211Pb 36.1 M β-: 100.00%	212Pb 10.64 H β-: 100.00% 1820
81	203Tl STABLE 29.524%	204Tl 3.783 Y β-: 97.08% ε: 2.92%	20[illegible]Tl STA[illegible]LE 70[illegible]8%	206Tl 4.202 M β-: 100.00%	207Tl 4.77 M β-: 100.00%	208Tl 3.053 M β-: 100.00%	209Tl 2.161 M β-: 100.00%	210Tl 1.30 M β-: 100.00% β-n: 7.0E-3%	211Tl >300 NS β-
80	202Hg STABLE 29.86% 2356.83	203Hg 46.594 D β-: 100.00%	204Hg STABLE 6.87% 2675.25	205Hg 5.14 M β-: 100.00%	206Hg 8.32 M β-: 100.00%	207Hg 2.9 M β-: 100.00%	208Hg 41 M β-: 100.00%	209Hg 35 S β-: 100.00%	210Hg >300 NS β-
	122	123	124	125	126	127	128	129	N

- 0.7 MeV

0.5 MeV

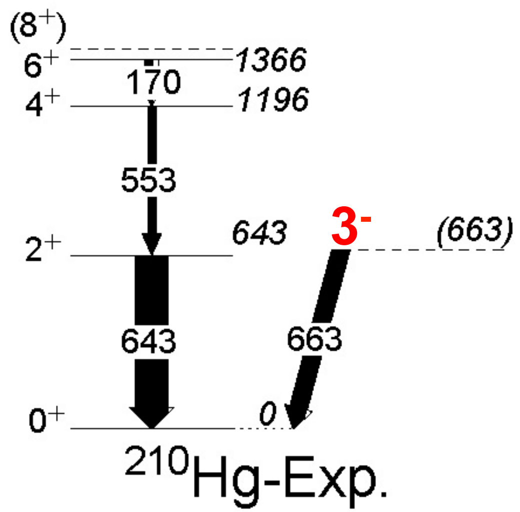
=

$\pi h_{11/2}^{-1}$
$\pi d_{5/2}^{-1}$
correlations?

correlations?

^{210}Hg: a summary

An isomeric state must exist above the 2^+, very close in energy: the 663-keV line may be this level. From all the experimental evidences it looks like it is 3^- state



From a theoretical point of view, no state is predicted so close to the first 2^+ for a spherical nucleus

Isomeric ratios and other possibilities

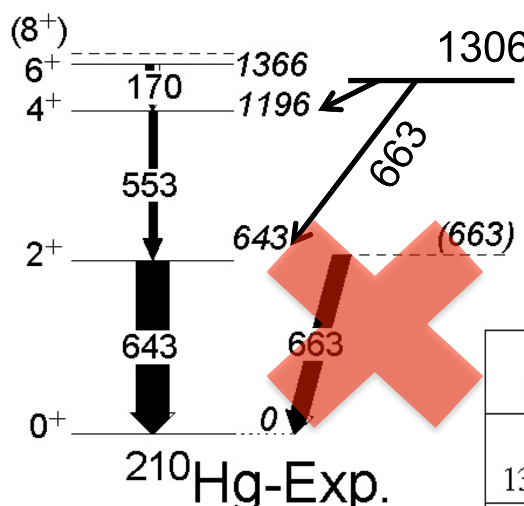
Isomeric ratio R

$R = N_{Isomer} / N$

$R_{exp}^{3-} / R_{exp}^{8+} = 2(1)$

Spin cut off-model: $R_{exp}^{3-} / R_{exp}^{8+} = 1.7$

Maybe we missed the coincidence? There are few events…



Maybe this 1306-keV is a 3^- or 5^- (at the right energy) BUT…

Energy	E,Mλ	B(E,Mλ) (W.u)
663 keV	E1	$5(1)\cdot10^{-10}$
663 keV	E2	$2.7(7)\cdot10^{-5}$
663 keV	E3	2.7(7)
663 keV	M1	$2.2(5)\cdot10^{-3}$

State (keV)	Decays	Exp. branch. ratio	W. branch. ratio
3^- 1306 keV	663 keV to 2^+ 110 keV to 4^+	$\frac{E1(663)}{E1(110)} > 4$	$\frac{E1(663)}{E1(110)} = 191$
5^- 1306 keV	663 keV to 2^+ 110 keV to 4^+	$\frac{E3(663)}{E1(110)} > 4$	$\frac{E3(663)}{E1(110)} = 2\cdot10^{-4}$