"Universa Universis Patavina Libertas"

INFN Istituto Nazionale di Fisica Nucleare

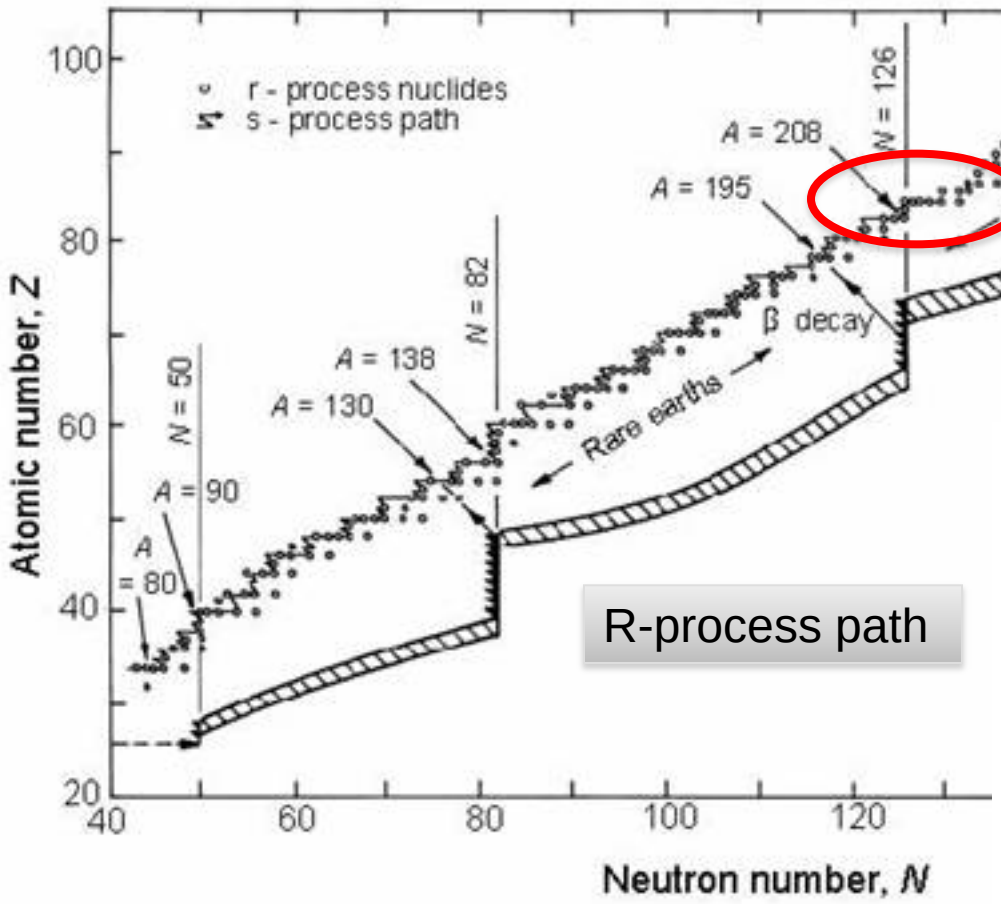
Laboratori Nazionali di Legnaro

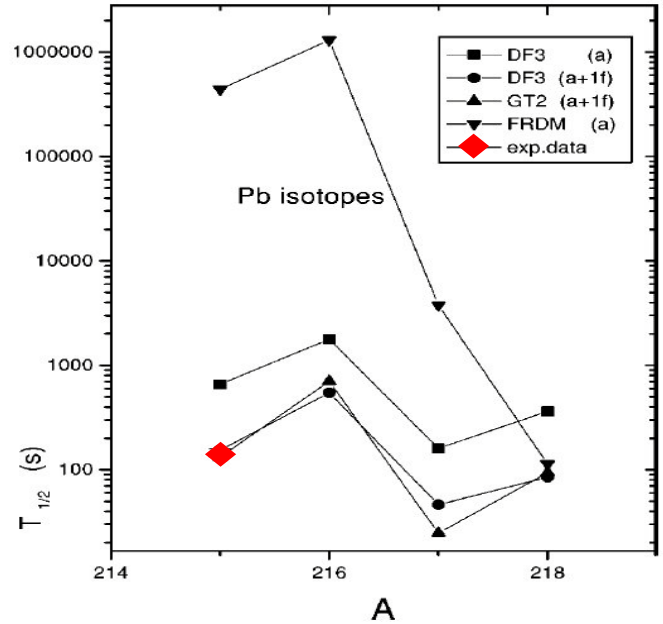
# Decay spectroscopy of neutron-rich lead isotopes

Andrea Gottardo

- Neutron-rich Pb nuclei beyond N=126
- Experimental setup
- Seniority Pb isomers → the B(E2) probes

# The Z=82 and beyond N=126



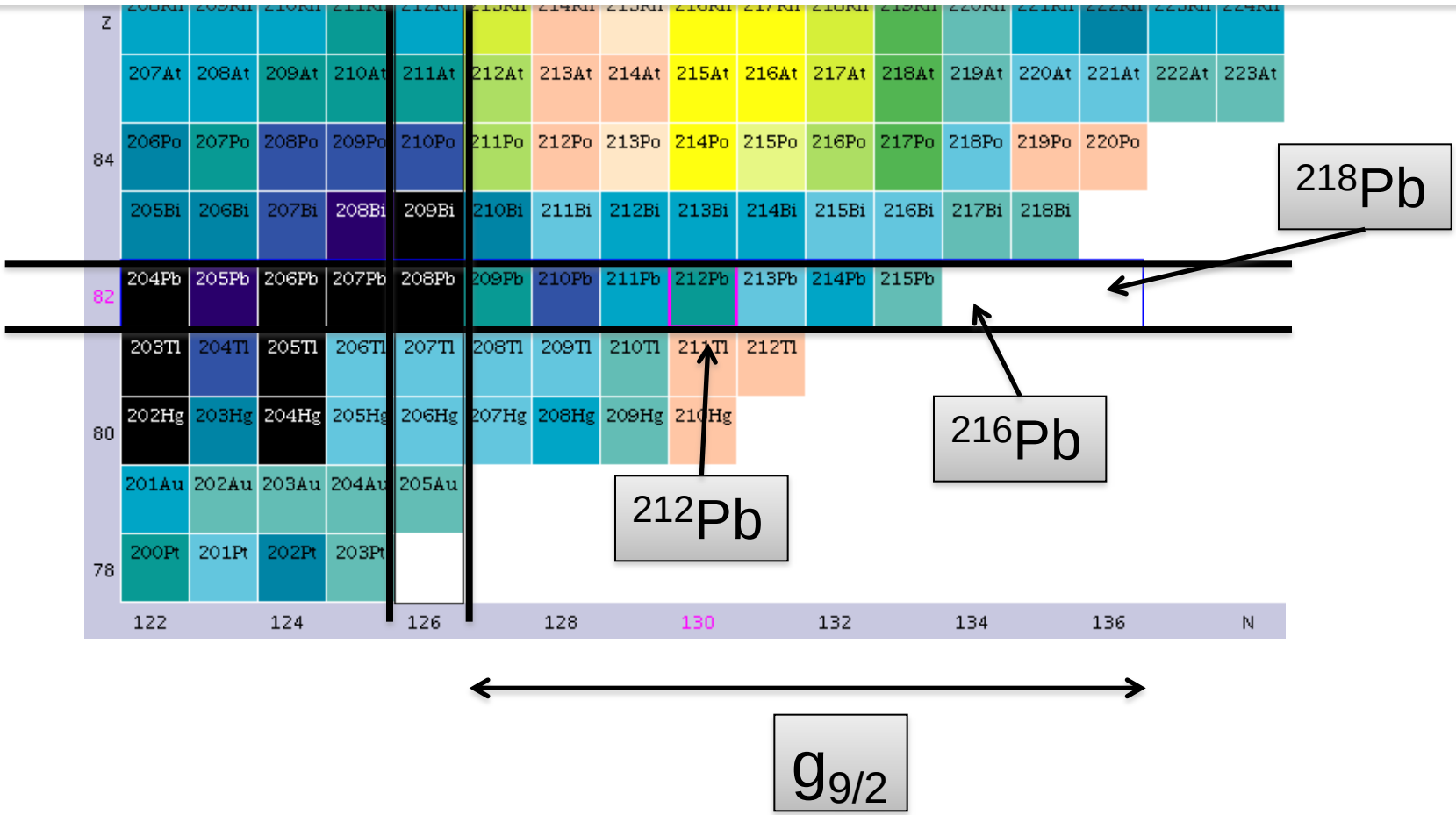




Experimental β-decay data needed around $^{208}$Pb to validate theoretical models.

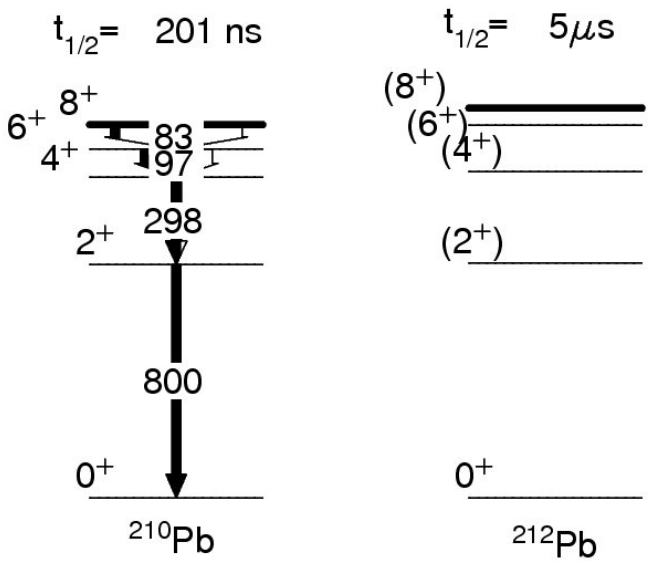
I.N. Borzov PRC67, 025802 (2003)

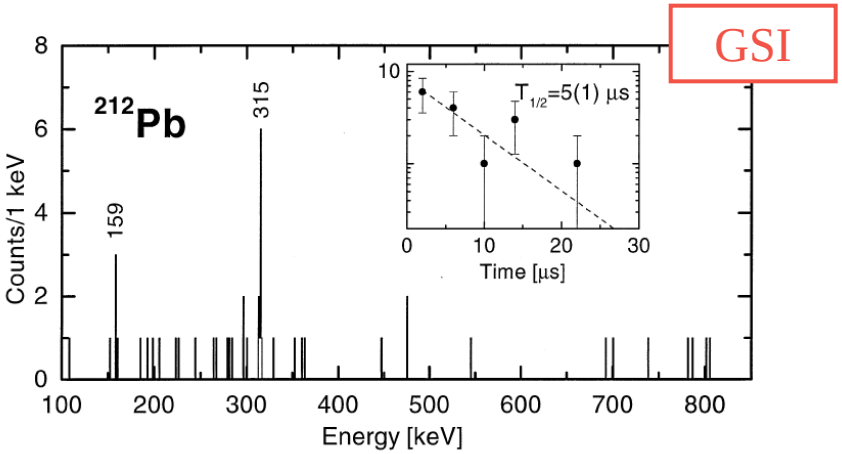
# The Z=82 and beyond N=126

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 developmet of nuclear structure from $^{212}$Pb up to $^{220}$Pb and nearby nuclei



# Experimental challenges




5x10$^6$ pps

- 2 HPGe detectors (Eff$_\gamma$=1%)
- 350 ions implanted

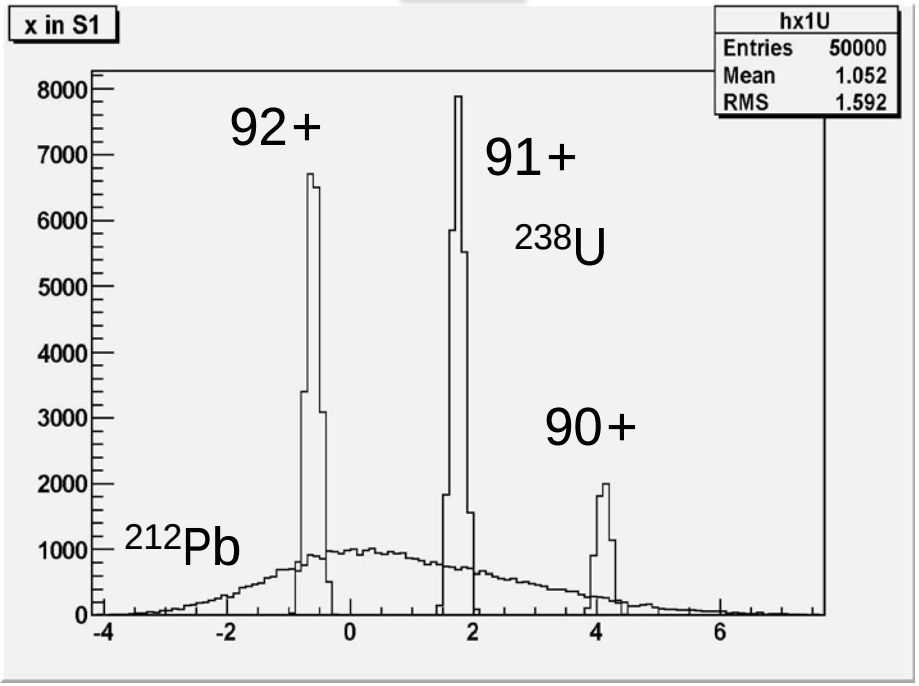
M. Pfutzner, PLB 444 (1998) 32

| | $COFRA(mb)$ |
|---|---|
| $^{212}$Pb | $9.05\times10^{-4}$ |
| $^{214}$Pb | $1.84\times10^{-4}$ |
| $^{216}$Pb | $3.01\times10^{-5}$ |
| $^{218}$Pb | $3.69\times10^{-6}$ |
| $^{220}$Pb | $3.17\times10^{-7}$ |

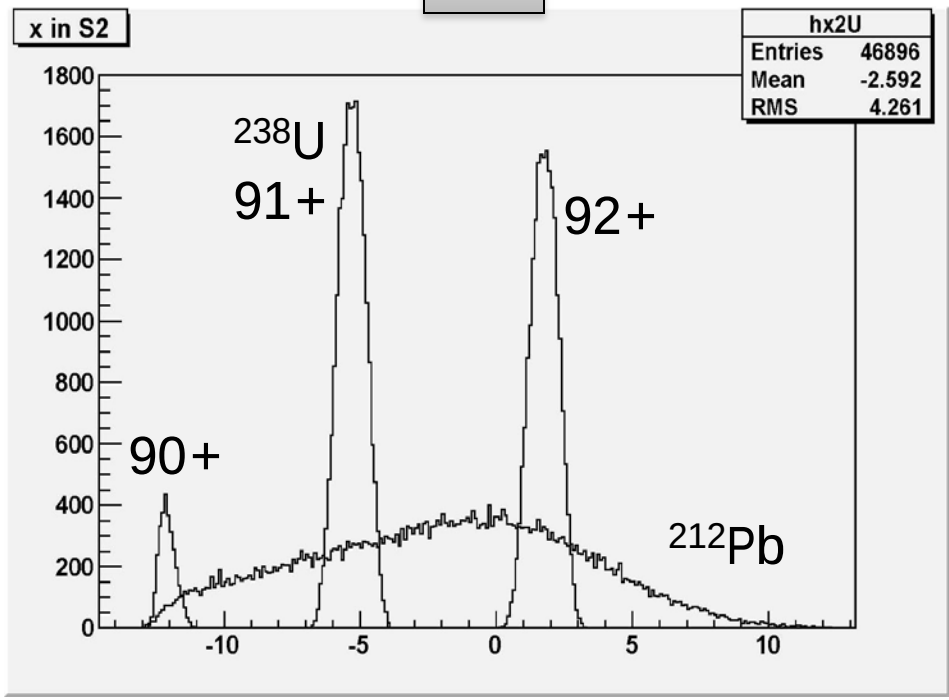
Difficult region to explore: only fragmentation possible, primary beam charge states!

# Charge state problem

S1




S2



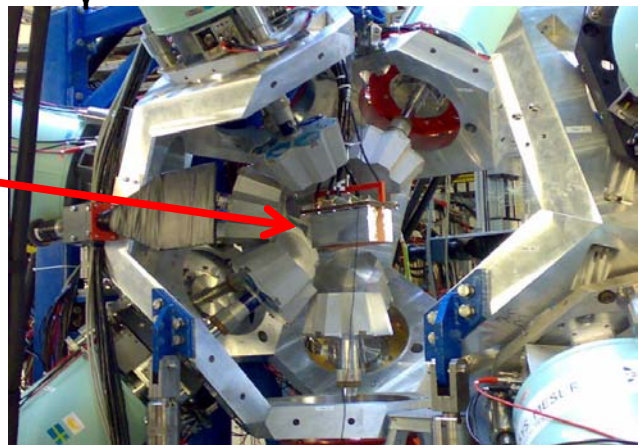

The $^{238}U$ beam intensity is $10^9$ pps!

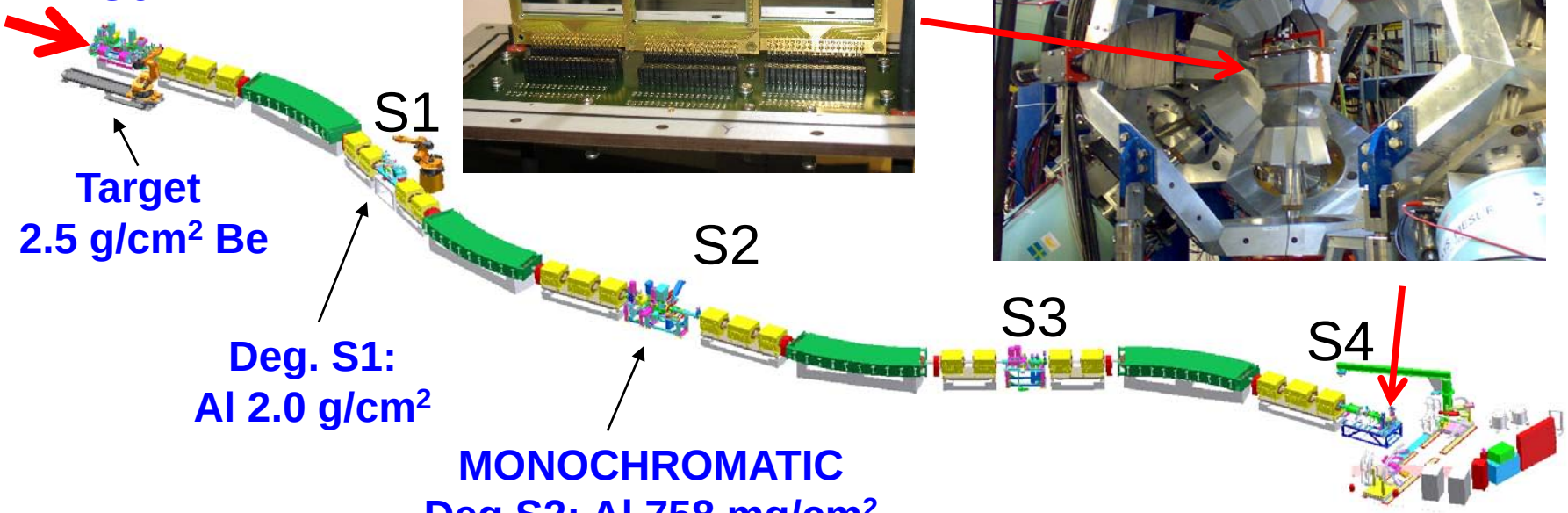
# Experimental setup

## FRS-Rising at GSI: stopped beam campaign

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

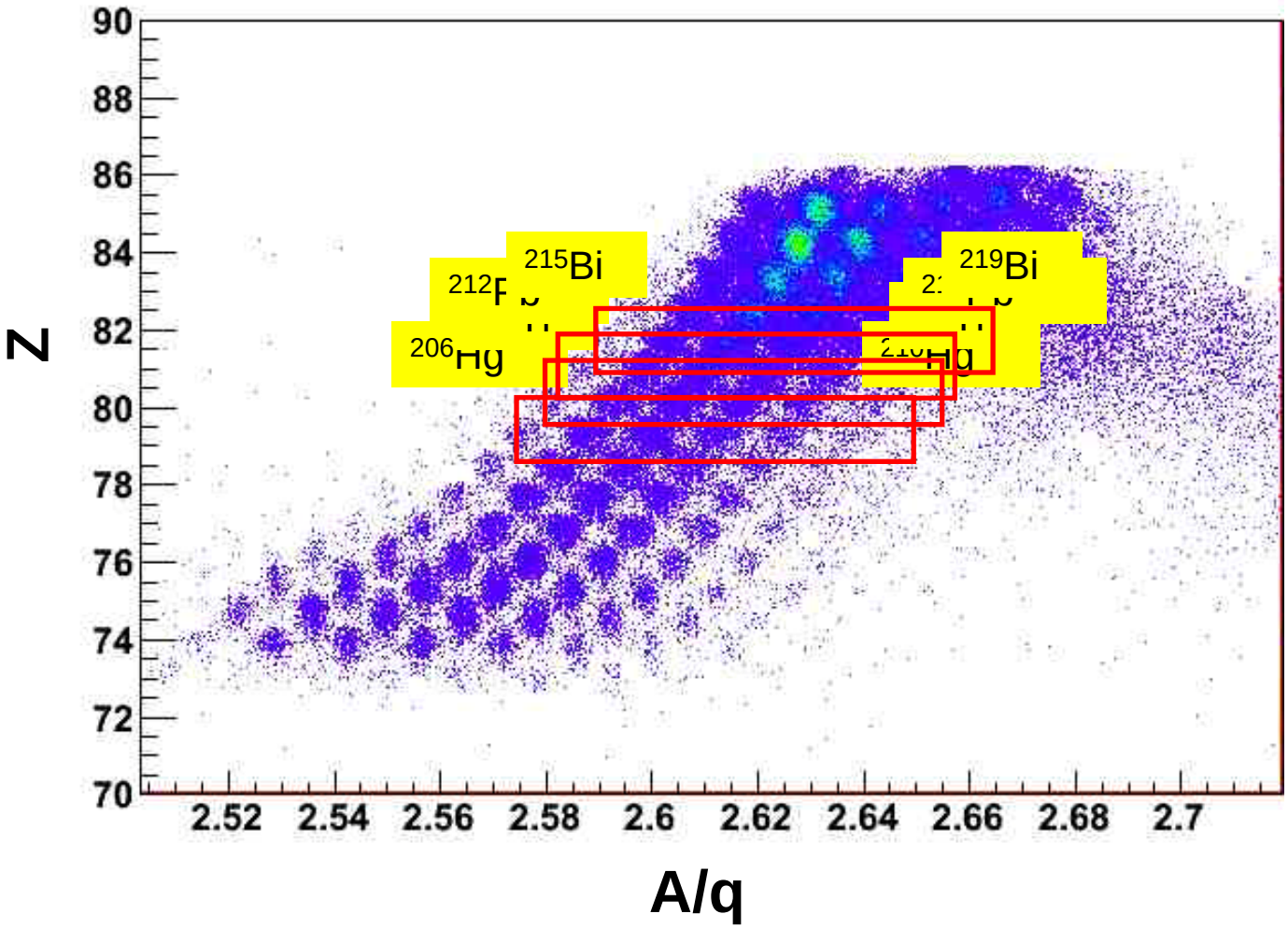
**15 CLUSTERs x 7 crystals**
**$\varepsilon_\gamma$ = 11% at 1.3MeV**



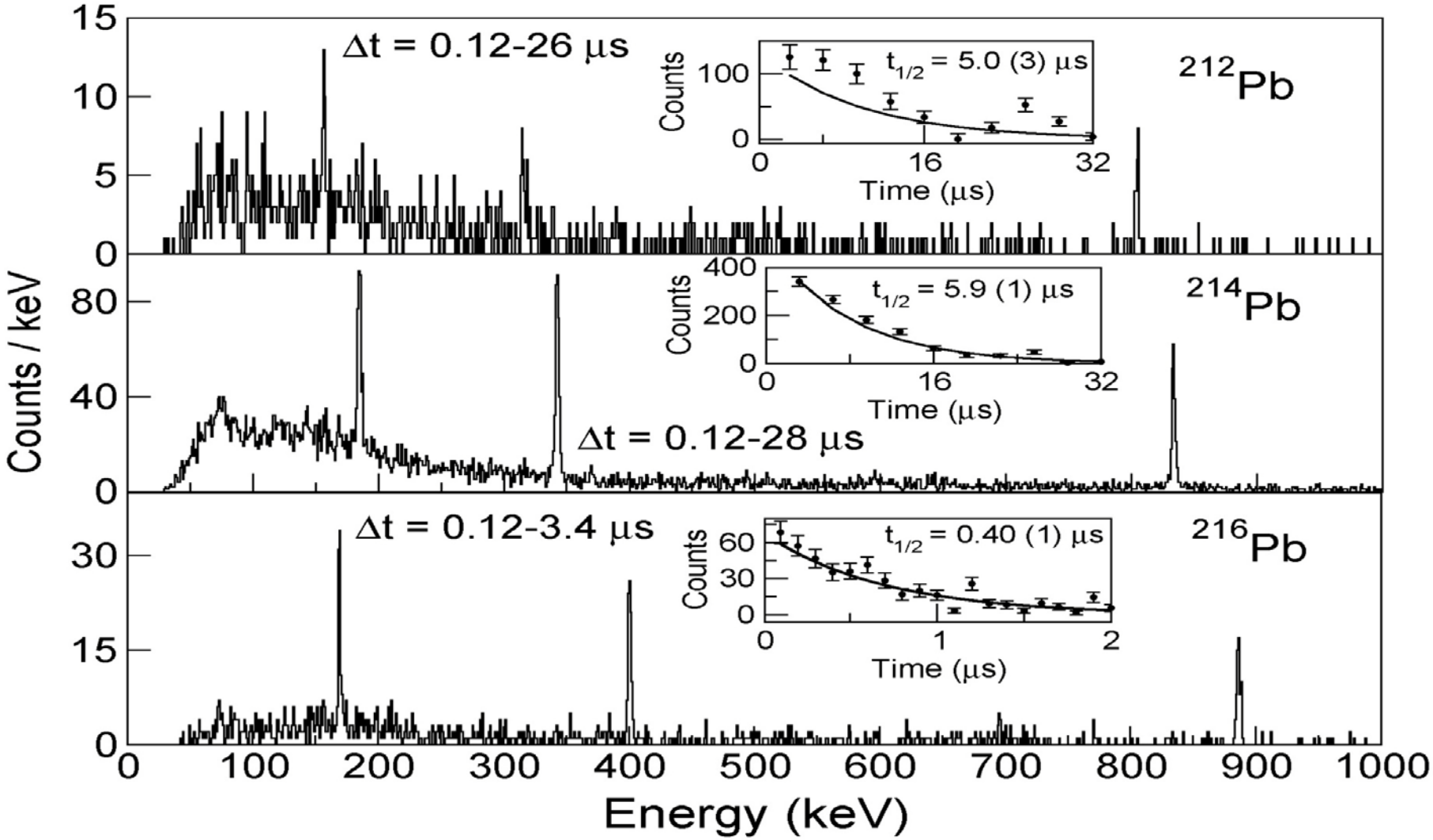


# Nuclei populated in the fragmentation

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



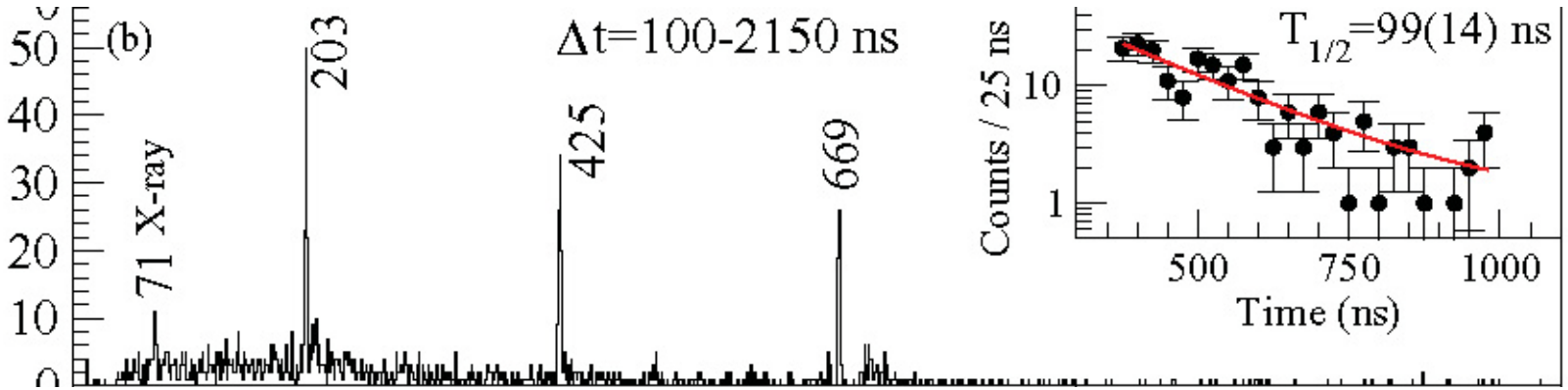
# $^{212,214,216}$Pb: $8^+$ isomer



# $^{210}$Hg isomer

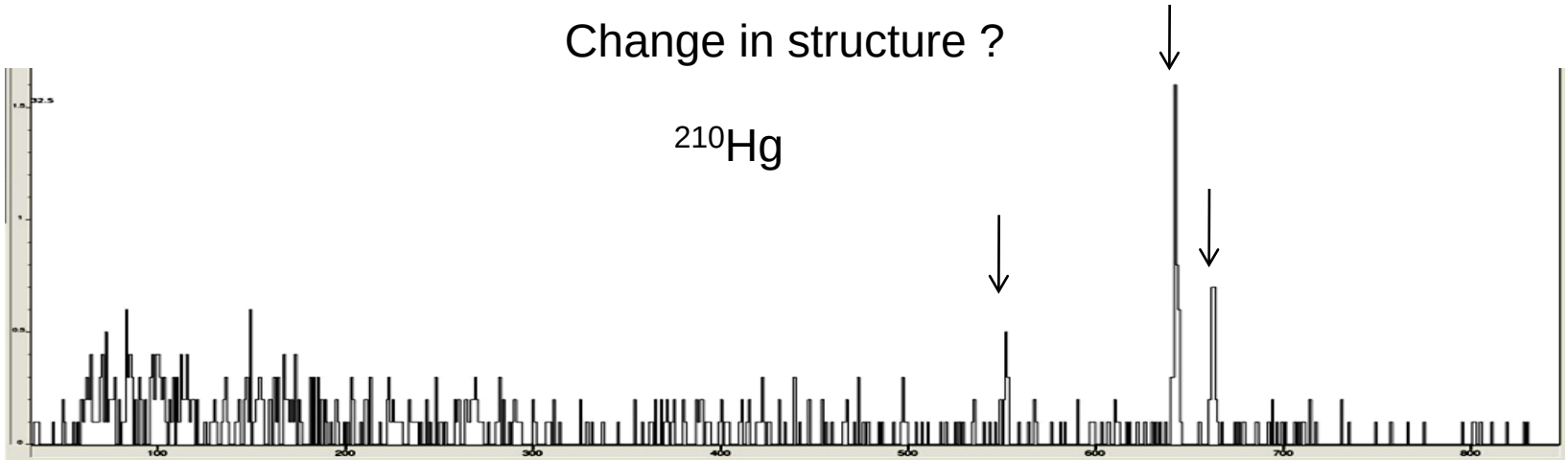
$^{208}$Hg

**PRC 80, 061302(R)**




Change in structure ?

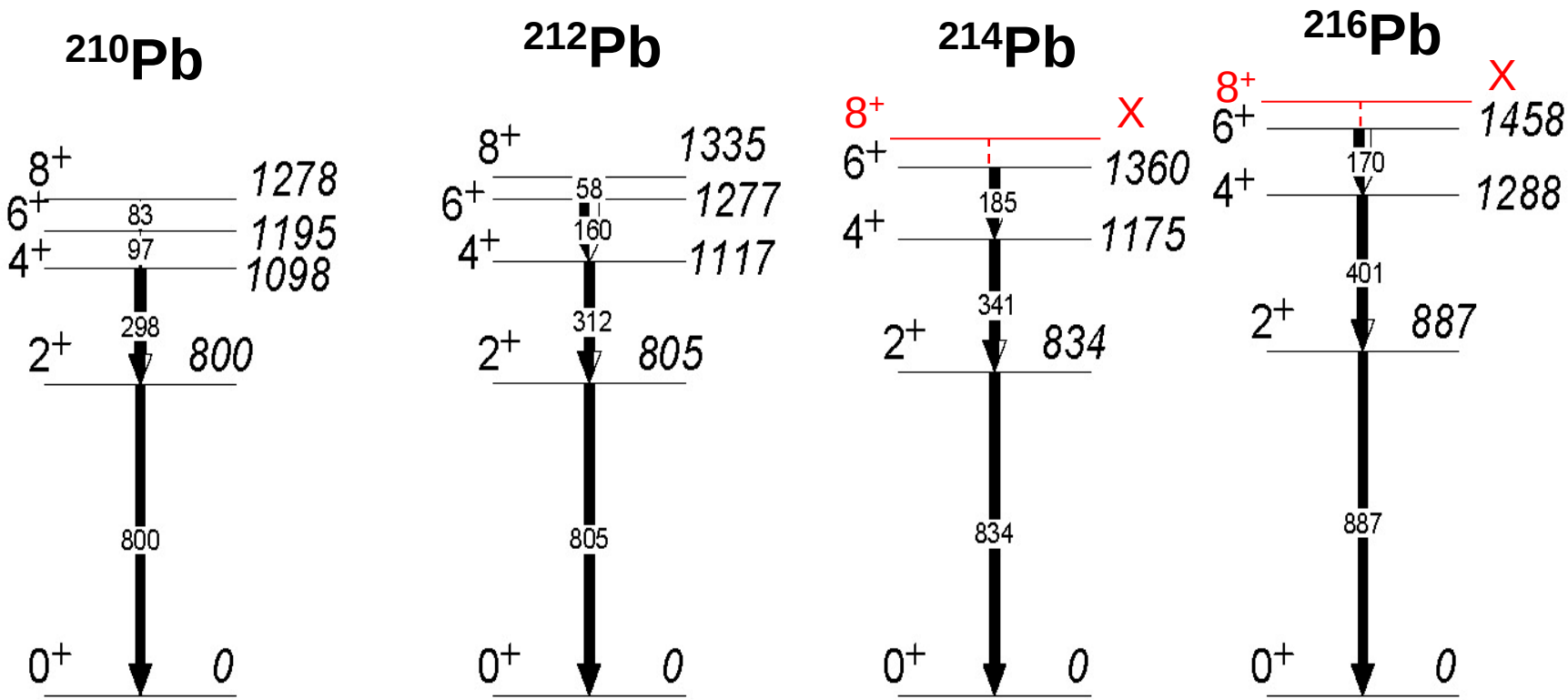
$^{210}$Hg



**Energy (keV)**

# Experimental level schemes

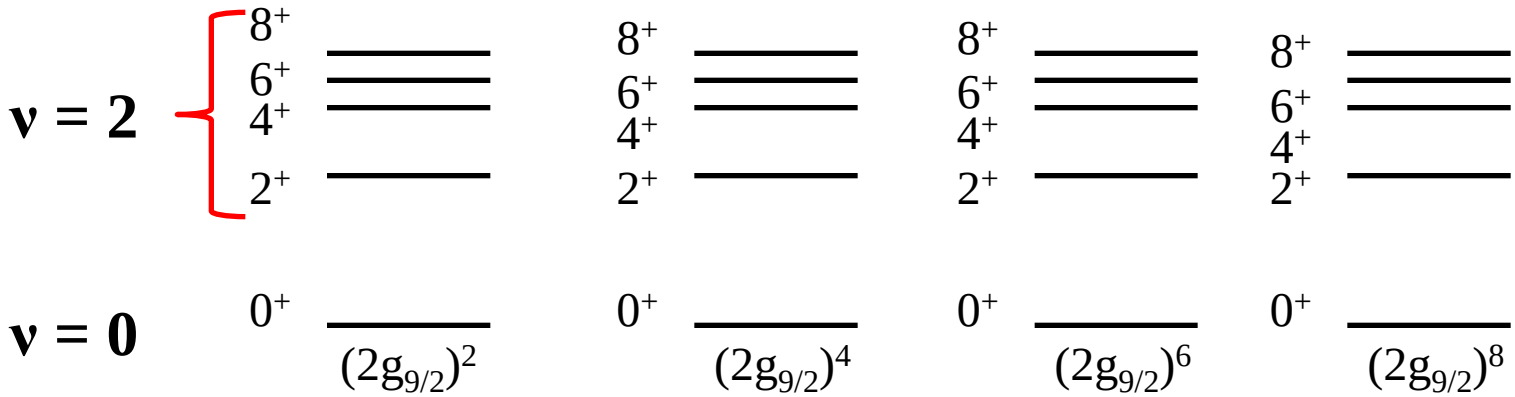
The $8^+$ isomer is a seniority isomer, involving neutrons in the $2g_{9/2}$



# The seniority scheme

Nucleons in a valence $j^n$ configuration behave according to a seniority scheme: the states can be labelled by their seniority v

**SENIORITY SCHEME**

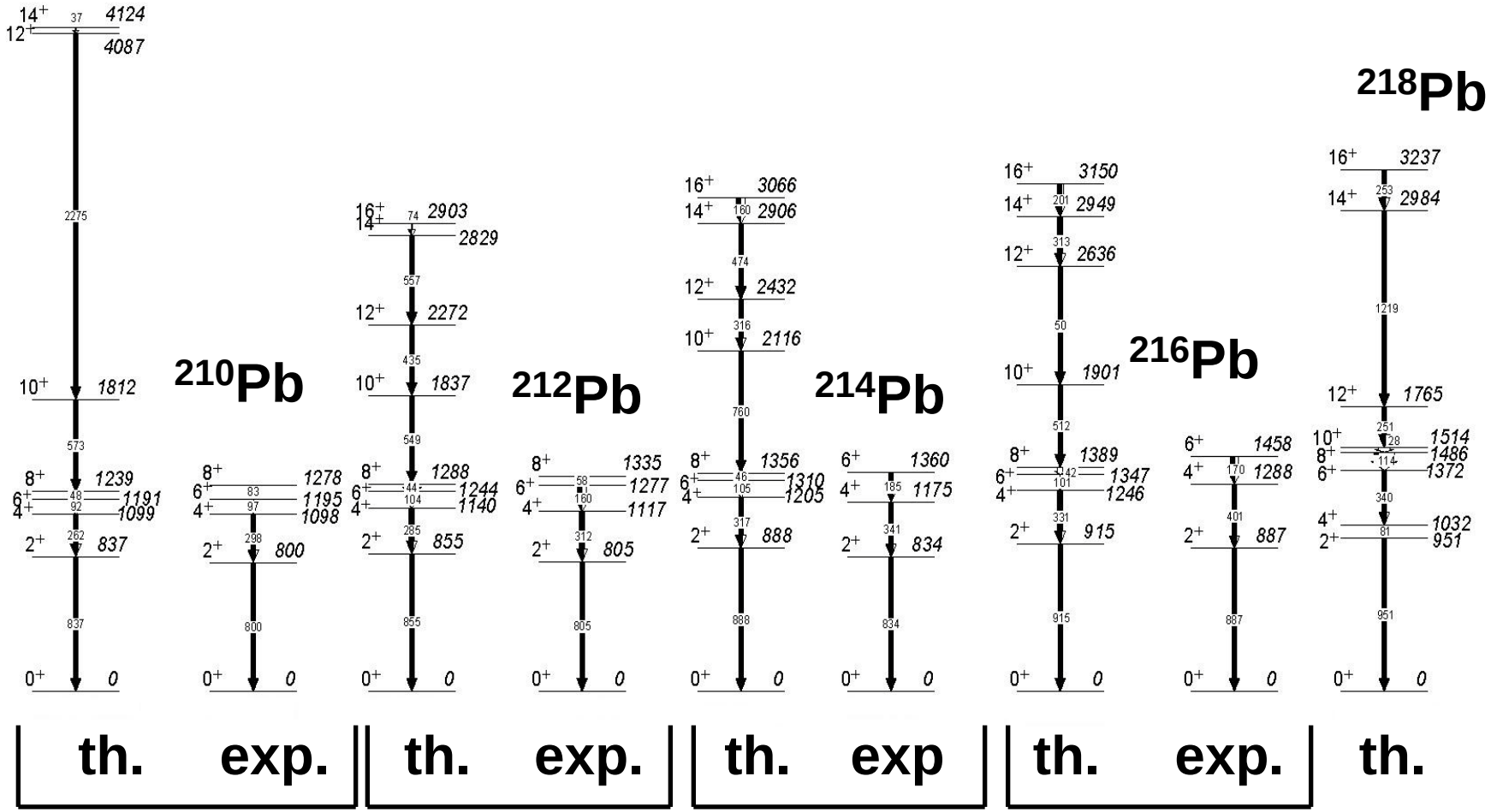



For even-even nuclei, the $0^+$ ground state has seniority v = 0, while the $2^+$, $4^+$, $6^+$, $8^+$ states have v = 2

In a pure seniority scheme, the relative level energies do not depend on the number of particles in the shell j

# Shell Model calculations Kuo-Herling

Calculations with Antoine and Nathan codes and K-H interaction



# Wave functions from Kuo-Herling

The neutron $2g_{9/2}$ shell has a dominant role for the $8^+$ isomeric state.
$1i_{11/2}$ , $1j_{15/2}$ and $3d_{5/2}$ also play a role

$8^+$ state wave functions: occupational numbers show quite pure wave functions

| | $^{210}$Pb n = 2 | $^{212}$Pb n = 4 | $^{214}$Pb n = 6 | $^{216}$Pb n = 8 | $^{218}$Pb n = 10 |
|---|---|---|---|---|---|
| $2g_{9/2}$ | 1.99 | 3.39 | 4.78 | 6.21 | 6.96 |
| $1i_{11/2}$ | 0.005 | 0.33 | 0.68 | 1.04 | 2.16 |
| $1j_{15/2}$ | 0.002 | 0.16 | 0.32 | 0.43 | 0.59 |
| $3d_{5/2}$ | 0.0008 | 0.04 | 0.08 | 0.11 | 0.14 |

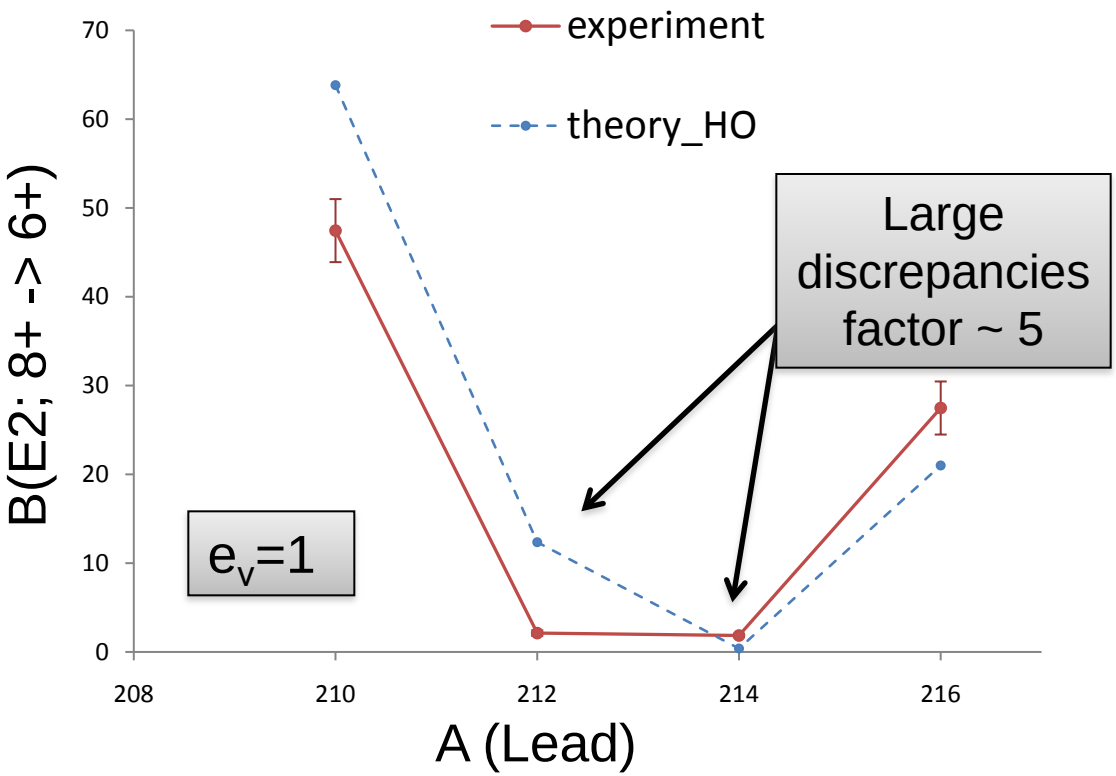
Occupational numbers

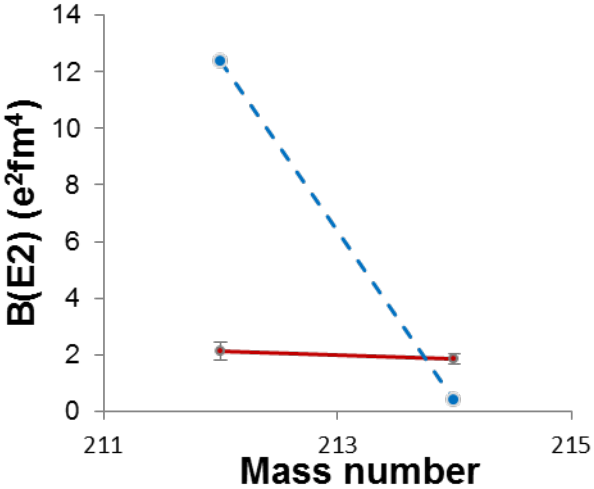
The ground state wave functions are in general more fragmented, with the $1i_{11/2}$ shell around 25 - 30 %

# Reduced transition prob. B(E2)

B(E2) calculated considering internal conversion coefficients, and a 20-80 keV energy interval for unknown transitions.

| $^{210}Pb$ | $^{212}Pb$ | $^{214}Pb$ | $^{216}Pb$ |
|---|---|---|---|
| **$T_{1/2}$ = 0.20 (2) μs** | **$T_{1/2}$ = 5.0 (3) μs** | **$T_{1/2}$ = 5.9 (1) μs** | **$T_{1/2}$ = 0.40 (1) μs** |



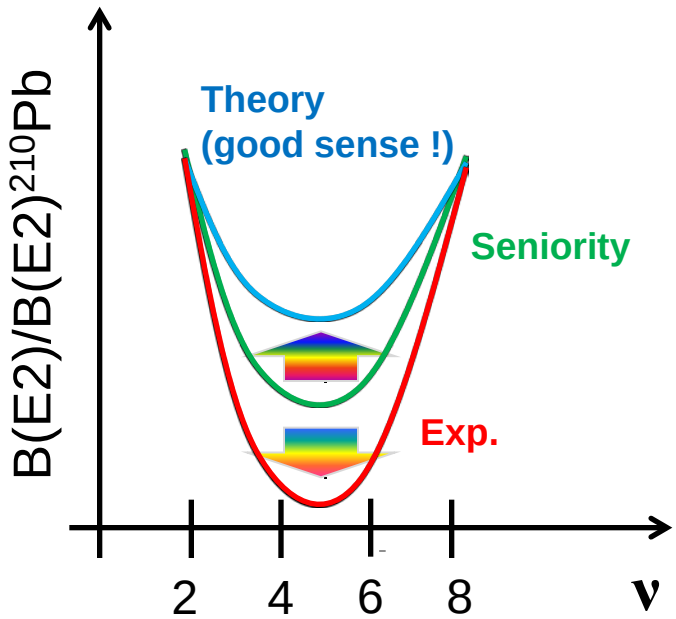



# Seniority scheme conserved

| | $^{210}$Pb | $^{212}$Pb | $^{214}$Pb | $^{216}$Pb |
|---|---|---|---|---|
| B(E2) $e^2fm^4$ Experiment | 47(4) | 2.1(3) | 1.66-2.4 | 24.7-30.5 |
| B(E2) $e^2fm^4$ Theory | 64 | 12.4 | 0.4 | 25.7 |

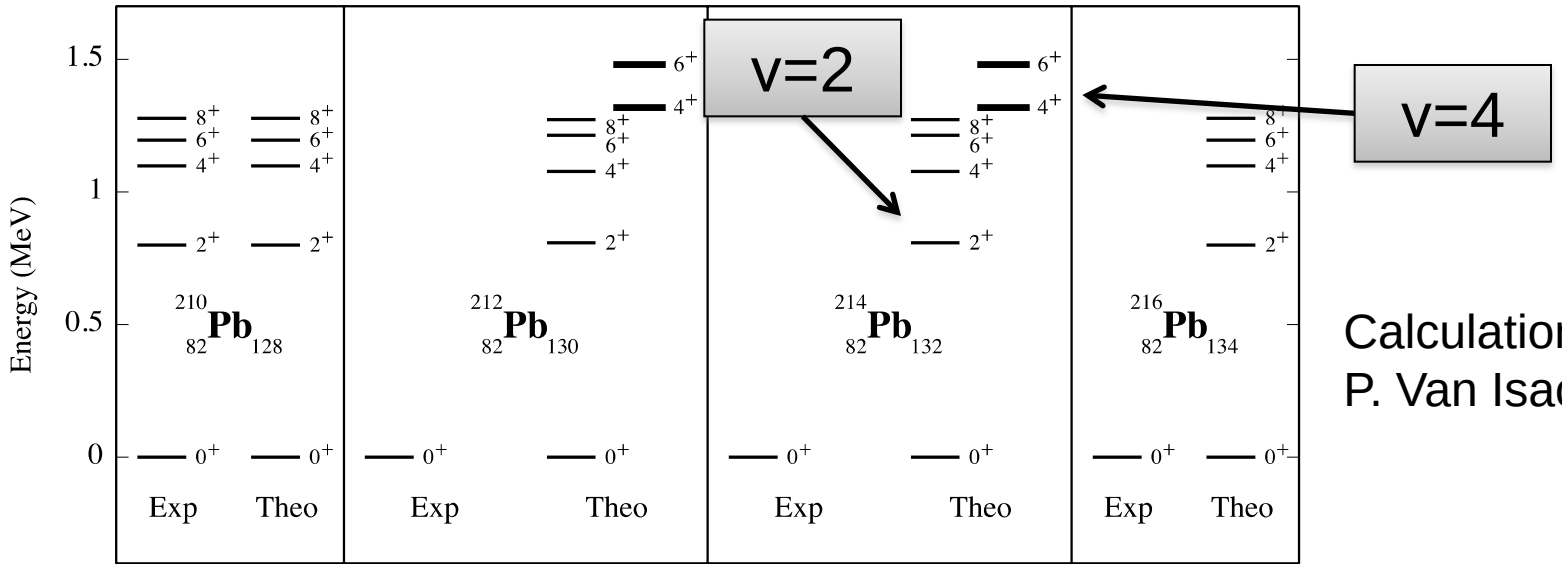
**Pure seniority scheme for $g_{9/2}$: 9 : 1 : 1 : 9**

PLB 606, 34 (2005)




- The results are roughly independent of the interaction used: K-H, CD-Bonn, Delta, Gaussian (apart for $^{214}$Pb)
- One possibility is the mixing of states (6+), or p-h excitations across the shell closure
- Problems with $g_{9/2}$ seniority isomers also for the first $g_{9/2}$ (Ni, Cd)

# Seniority mixing?




Calculations by P. Van Isacker

- Mixing between one v=2 and two v=4 states in $^{212,214}$Pb. The quadrupole matrix element to v=4 states is more than five times the one to v=2, and opposite in sign
- Even a small mixing (few %) would be enough to correct the B(E2) value for $^{212}$Pb
- One possibility is the mixing of states (6+) with seniority 4: need to modify the interaction (pairing, 3-body…)

# Core excitations below N=126, Z=82

Standard realistic/phenomenogical interactions such as the K-H are renormalized to take into account excitations from the core, but NOT all can be included (quadrupole is a three-body operator!)

Another possibility is the inclusion of 2p-2h excitations from the N=126 core. Calculations in BCS, but unable yet to reproduce results with shell-model codes

| | | |
|---|---|---|
| $^{210}$Pb | $(vg9/2)^4$ same sign of $(vg9/2)^2$,but smaller | Slightly smaller B(E2) |
| $^{212}$Pb | $(vg9/2)^6$ opposite sign of $(vg9/2)^4$, same magnitude | Smaller B(E2): close exp. value |
| $^{214}$Pb | $(vg9/2)^8$ same sign of $(vg9/2)^6$, but 3 time larger | Larger B(E2): too large ? |

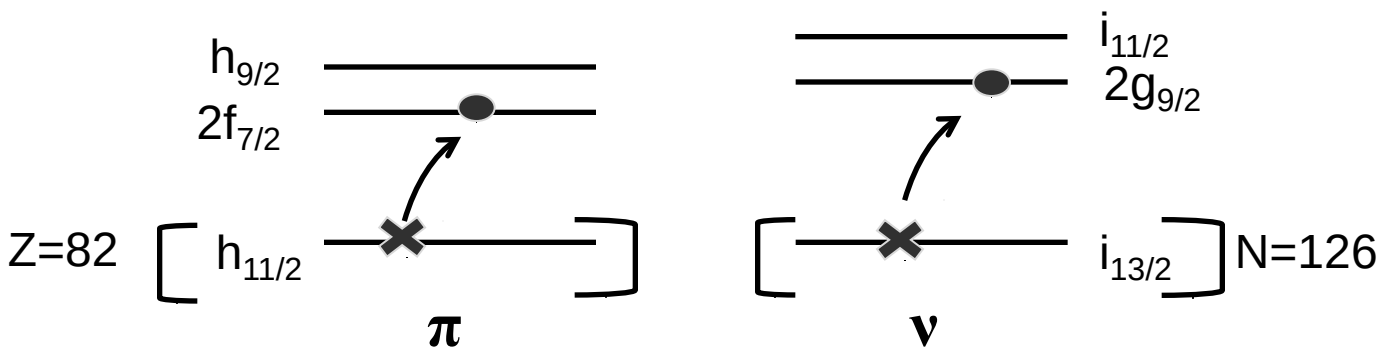
Developing a new interaction with A. Zuker and F. Nowacki to break up the N=126, Z=82 shell gap.

# Core excitations below N=126, Z=82: calculations

Computational problems:

- very large space, but hopefully only 2 holes significant.
- Nathan code necessary!

Interaction: we are building an interaction starting from a $V_{lowK}$ and then renormalizing quadrupole and pairing.




Very small breaking observed so far, but changes in B(E2): in agreement with strengths between quadrupole partners, quasi-SU(3) mechanism: PRC 52, 1741 (1995)

# Conclusions

- 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. B(E2) values are a sensitive probe to understand in detail the features of the nuclear force → Seniority mixing; 3N forces, relevant valence space
- The mechanism leading to the violation of the expected seniority scheme may be more general, and relevant also for other parts of the nuclide chart (Sn?, Ni?, Cd?)

# Collaboration

**A. Gottardo, J.J. Valiente-Dobon, G. Benzoni, R. Nicolini,**
**E. Maglione, A. Zuker, M. Hjort-Jensen, A. Poves, F. Nowacki**
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.*

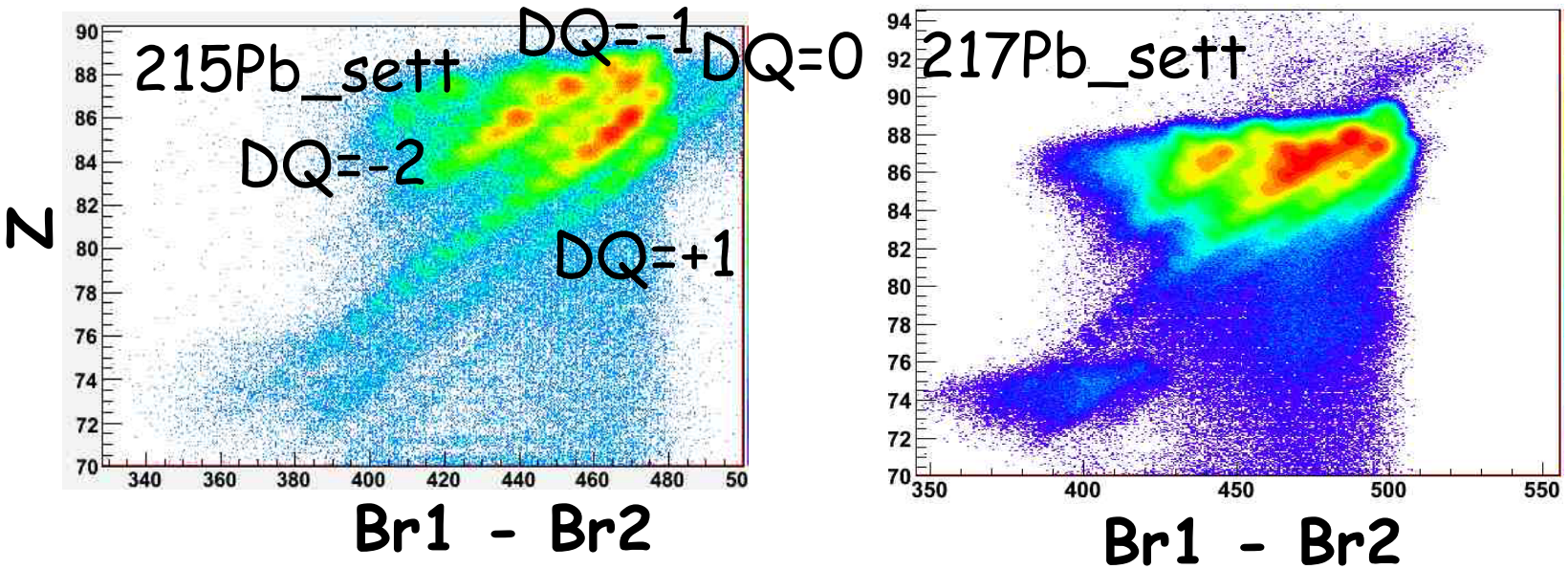
# Charge state selection

Formation of many charge states owing to interactions with materials

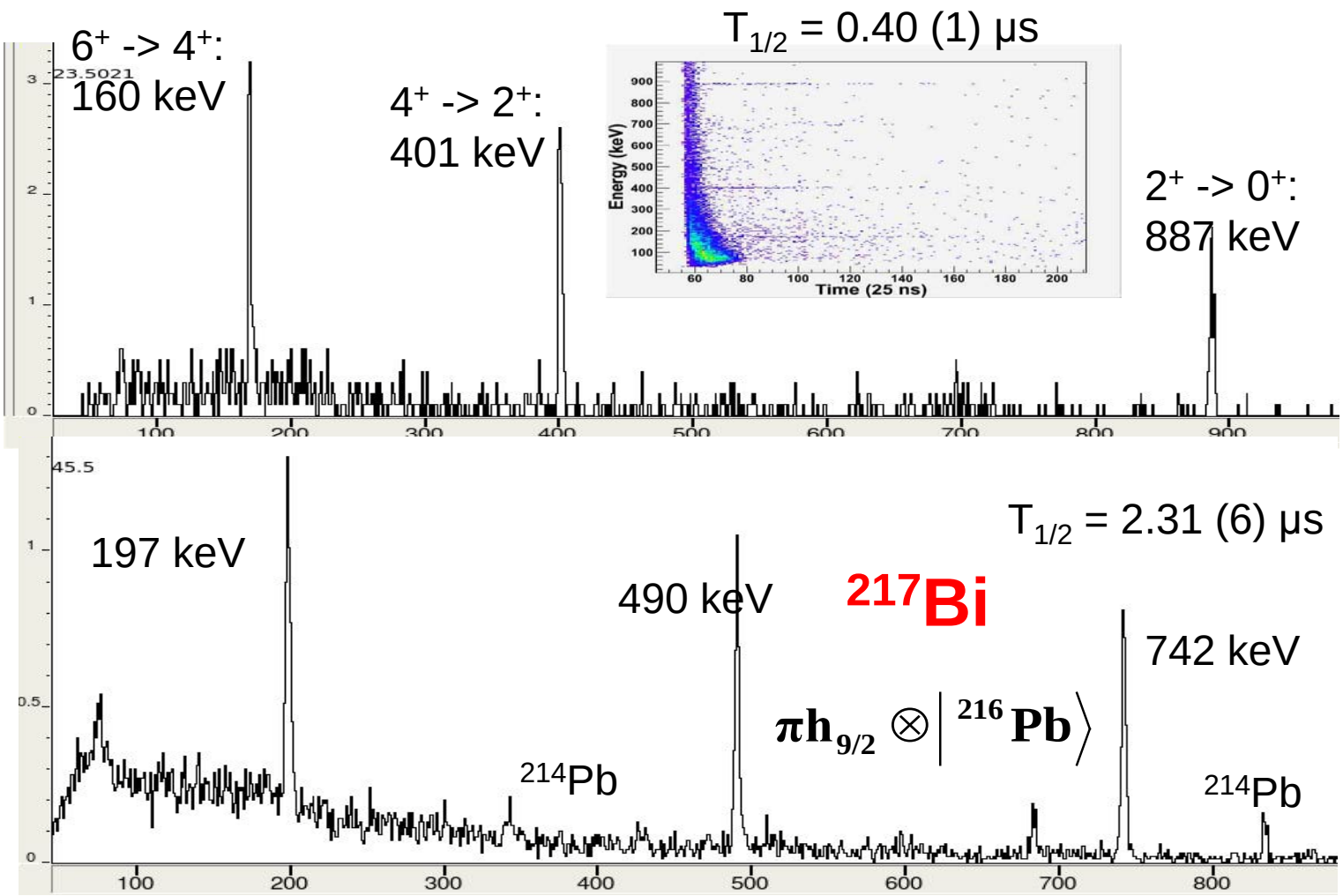
➔Isotope identification is more complicated

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

$(Br)_{Ta\text{-}S2} - (Br)_{S2\text{-}S4}$



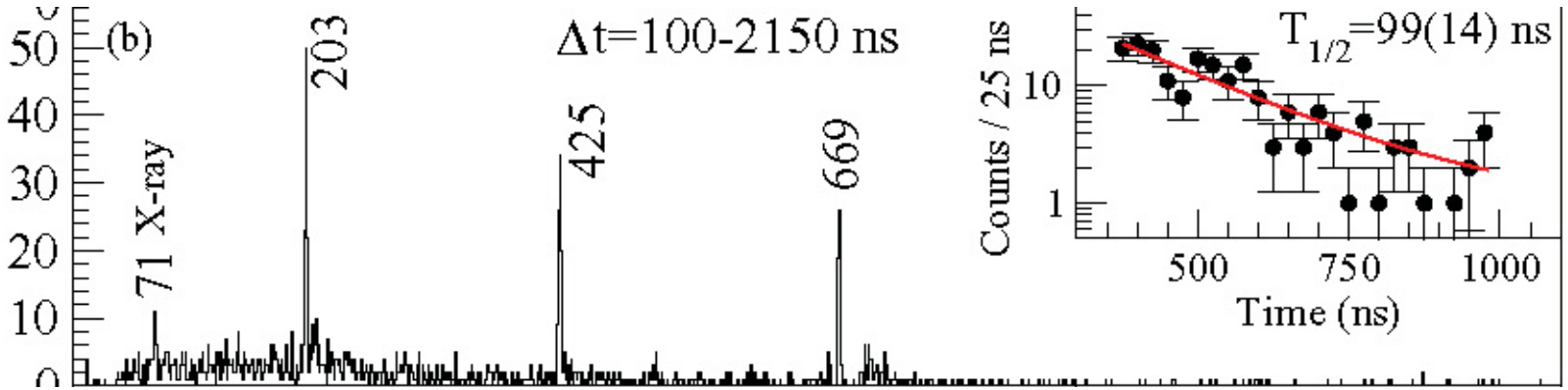
# $^{212,214,216}$Pb: $8^+$ isomer



# $^{210}$Hg isomer

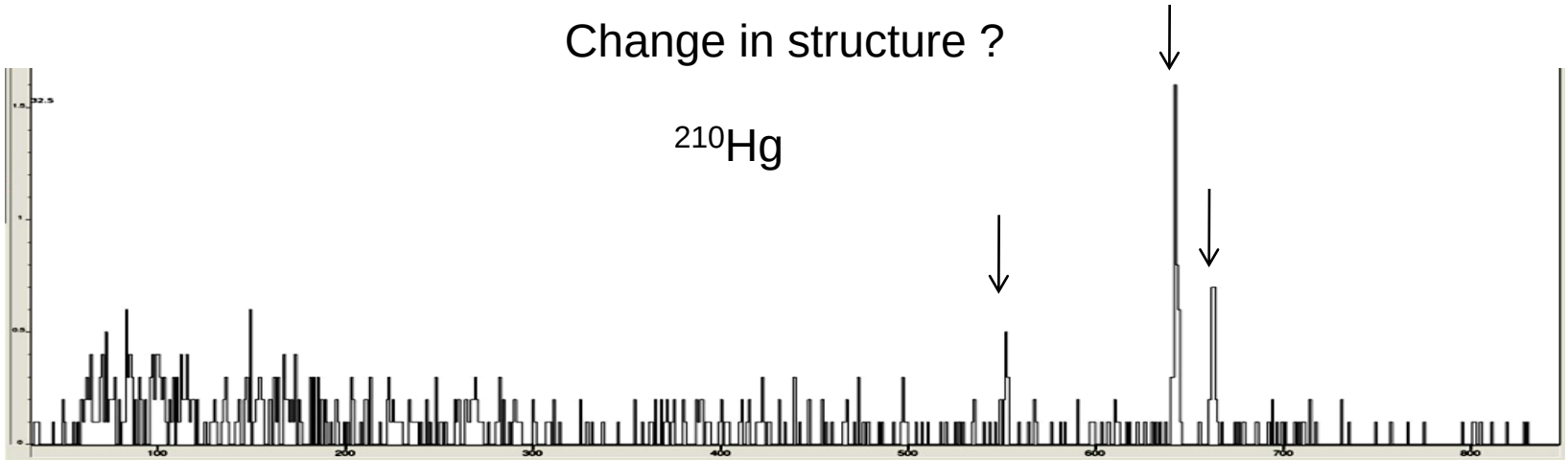
$^{208}$Hg

**PRC 80, 061302(R)**




Change in structure ?

$^{210}$Hg

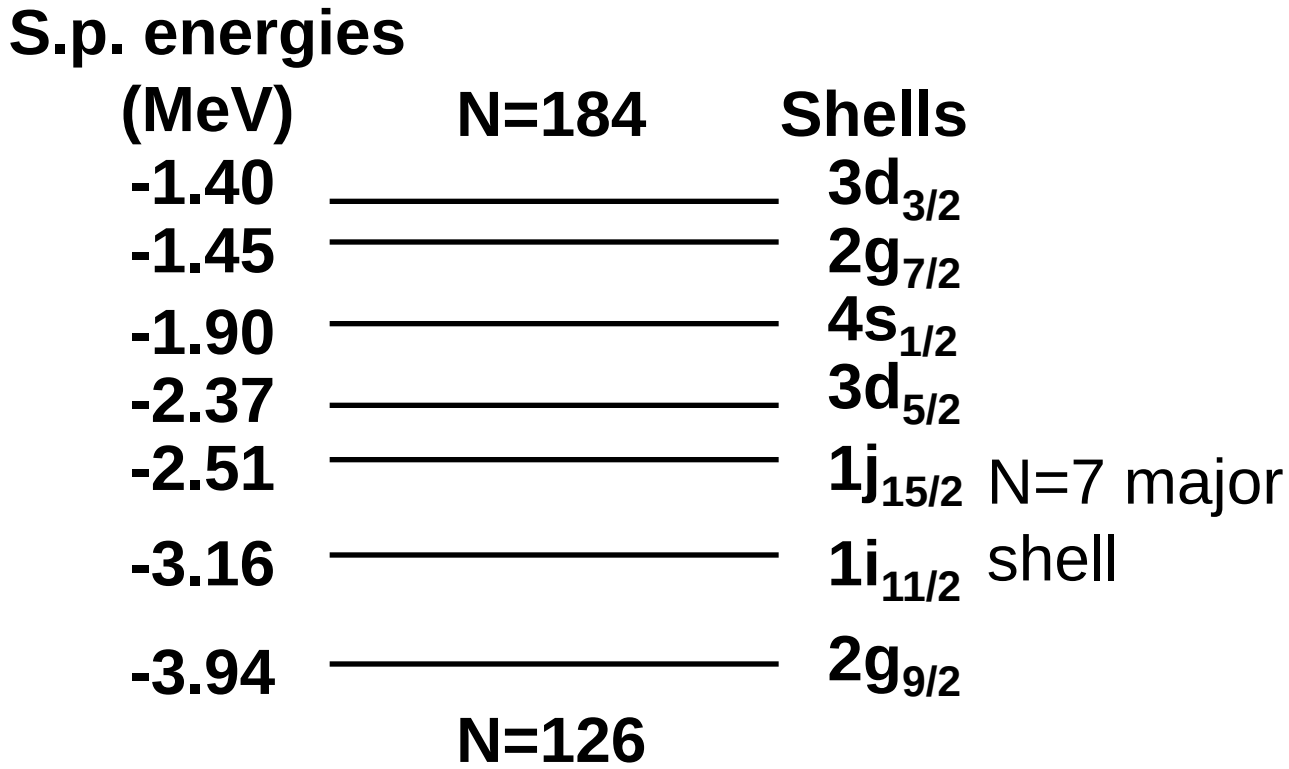


**Energy (keV)**

# Kuo-Herling interaction: Valence space

$^{208}$Pb is a doubly-magic nucleus (Z=82, N=126).

For neutron-rich Lead isotopes, the N=6 major shell is involved




PRC 43, 602 (1992)

Nuclear shell theory Amos-de-Shalit I. Talmi

In una singola j-shell la seniorità si mescola solo se si mescolano le seniorità 1 e 3. Tuttavia nelle j-shell minori di 9/2 è impossibile avere due stati con lo stesso momento angolare e seniorità 1 e 3, per cui non ci può essere mescolamento fra queste due seniorità e quindi fra nessuna seniorità sotto j=9/2.

# Reduced transition prob. B(E2)

| $8^+$ and $21/2^+$ isomers | $^{210}$Pb 2n | $^{211}$Pb 3n | $^{212}$Pb 4n | $^{213}$Pb 5n | $^{214}$Pb 6n | $^{216}$Pb 8n |
|---|---|---|---|---|---|---|
| B(E2) $e^2fm^4$ Experiment | 47(4) | 104(18) | 2.1(3) | 50-60 | 1.66-2.4 | 24.7-30.5 |
| B(E2) $e^2fm^4$ Theory K-H | 64 | 136 | 12.4 | 0.71 | 0.4 | 25.7 |
| B(E2) $e^2fm^4$ Theory CD-BONN | 65 | 139 | 12.71 | 2.54 | 0.17 | 19.15 |
| B(E2) $e^2fm^4$ Theory DELTA | 61.5 | 132 | 14.54 | 7.9 | 0.008 | 8.7 |

The results are roughly independent of the interaction used: K-H, CD-Bonn, Delta, Gaussian

# $^{211}$Pb

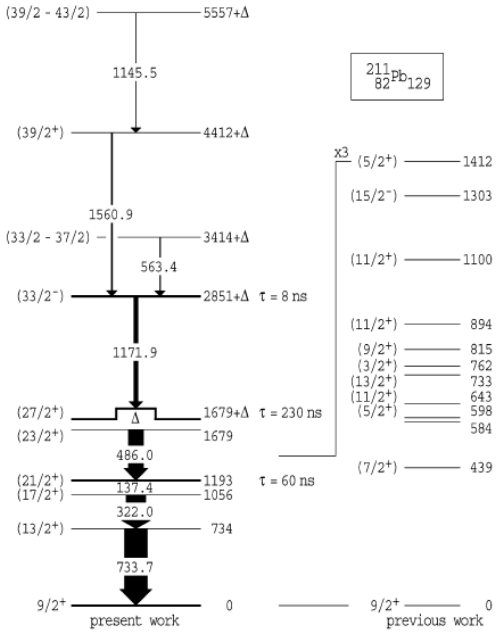



Table 2
Transition strengths and neutron effective charges in heavy lead nuclei

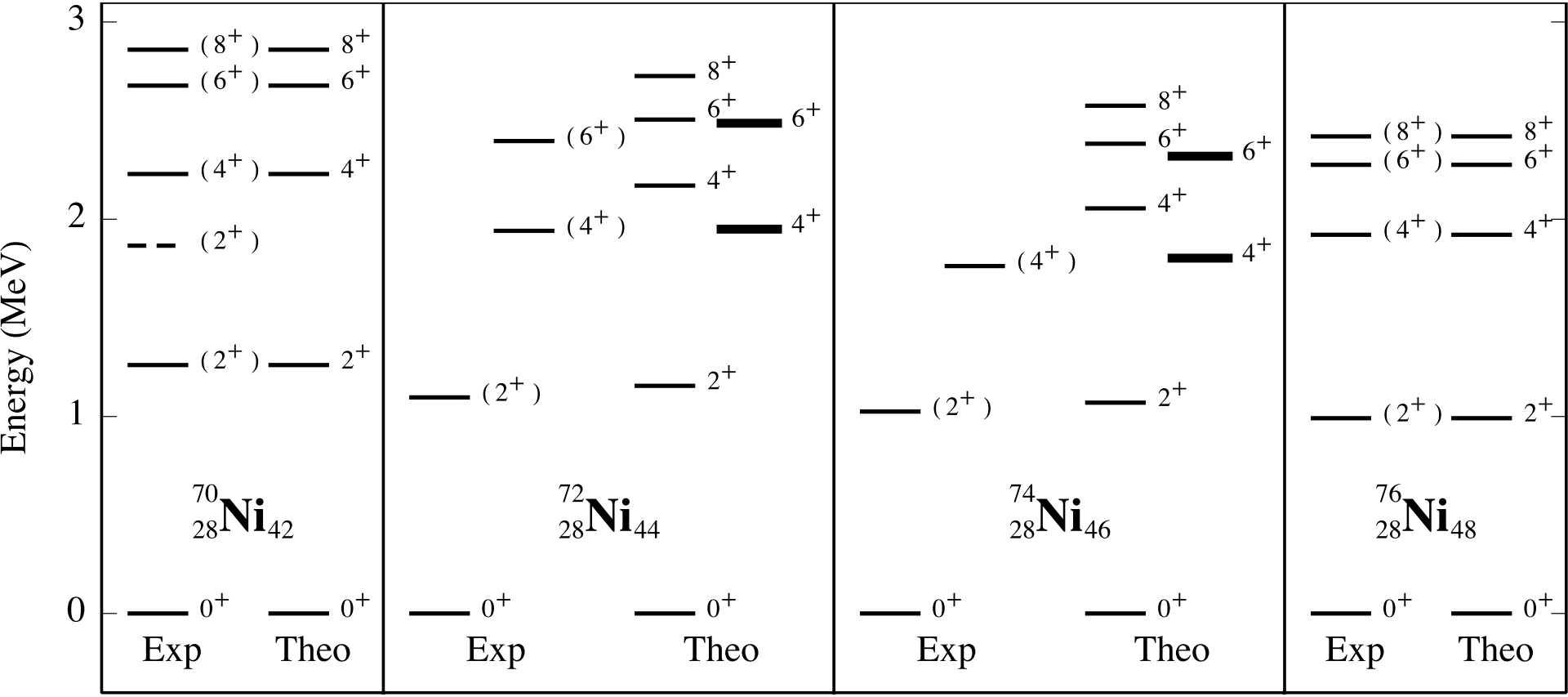
| Nucleus | Transition | Configurations | $B(E\lambda)_{expt}$ ($e^2$ fm$^{2\lambda}$) | $B(E\lambda)_{theory}$ ($e^2$ fm$^{2\lambda}$) | $e_{eff}$ |
|---|---|---|---|---|---|
| $^{210}$Pb | $8^+ \to 6^+$ | $g^2_{9/2}$ | 46(5) | 46(5) [1] | 0.96(4) [2] |
| $^{211}$Pb | $21/2^+ \to 17/2^+$ | $g^3_{9/2}$ | 104(18) | 91(10) [3] | 1.07(12) |
| $^{211}$Pb | $27/2^+ \to 23/2^+$ | $g^2_{9/2} i_{11/2}$ | $75^{+14}_{-19}$ [4] | 54(8) | 1.2(2) |
| $^{212}$Pb | $8^+ \to 6^+$ | $g^4_{9/2}$ | 2.1(5) | 5.1(6) [5] | 0.60(12) |
| $^{211}$Pb | $33/2^- \to 27/2^+$ | $g_{9/2} i_{11/2} j_{15/2} \to g^2_{9/2} i_{11/2}$ | $71(18) \times 10^3$ | $66(14) \times 10^3$ [6] | |
| $^{211}$Pb | $39/2^+ \to 33/2^-$ | $i_{11/2} j^2_{15/2} \to i_{11/2} j_{15/2} g_{9/2}$ | $\geqslant 15 \times 10^3$ [7] | $100(22) \times 10^3$ [8] | |

1 Reference value

PLB 606, 34(2005)

# Ni isotopes

No isomers expected in Ni since the 6+ state is very much mixed.



# 3N forces in the $^{208}$Pb region

VOLUME 90, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 31 JANUARY 2003

## Three-Body Monopole Corrections to Realistic Interactions

A. P. Zuker

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(Received 23 September 2002; published 30 January 2003)

It is shown that a very simple three-body monopole term can solve practically all the spectroscopic problems—in the $p$, $sd$, and $pf$ shells—that were hitherto assumed to need drastic revisions of the realistic potentials.

DOI: 10.1103/PhysRevLett.90.042502 PACS numbers: 21.60.Cs, 21.30.–x, 27.20.+n, 27.30.+t

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## Configuration interactions constrained by energy density functionals

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ABSTRACT

A new method for constructing a Hamiltonian for configuration interaction calculations with constraints to energies of spherical configurations obtained with energy-density-functional (EDF) methods is presented. This results in a unified model that reproduced the EDF binding-energy in the limit of single-Slater determinants, but can also be used for obtaining energy spectra and correlation energies with renormalized nucleon–nucleon interactions. The three-body and/or density-dependent terms that are necessary for good nuclear saturation properties are contained in the EDF. Applications to binding-energies and spectra of nuclei in the region above $^{208}$Pb are given.

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