Universität zu Köln

Institut für Kernphysik
Zülpicher Strasse 77
50937 Cologne, Germany

Exploring heavy nuclei using lifetime measurements of excited states

Christoph Fransen
Institut für Kernphysik, Universität zu Köln, Cologne, Germany

ESNT Workshop Saclay, November 2015

Outline

1. Introduction

2. The plunger technique

3. Other lifetime techniques used by our group:
   a. Fast timing
   b. Doppler-shift attenuation method

4. Shape coexistence in neutron deficient Hg isotopes

5. Critical point symmtries in the A=180 mass region

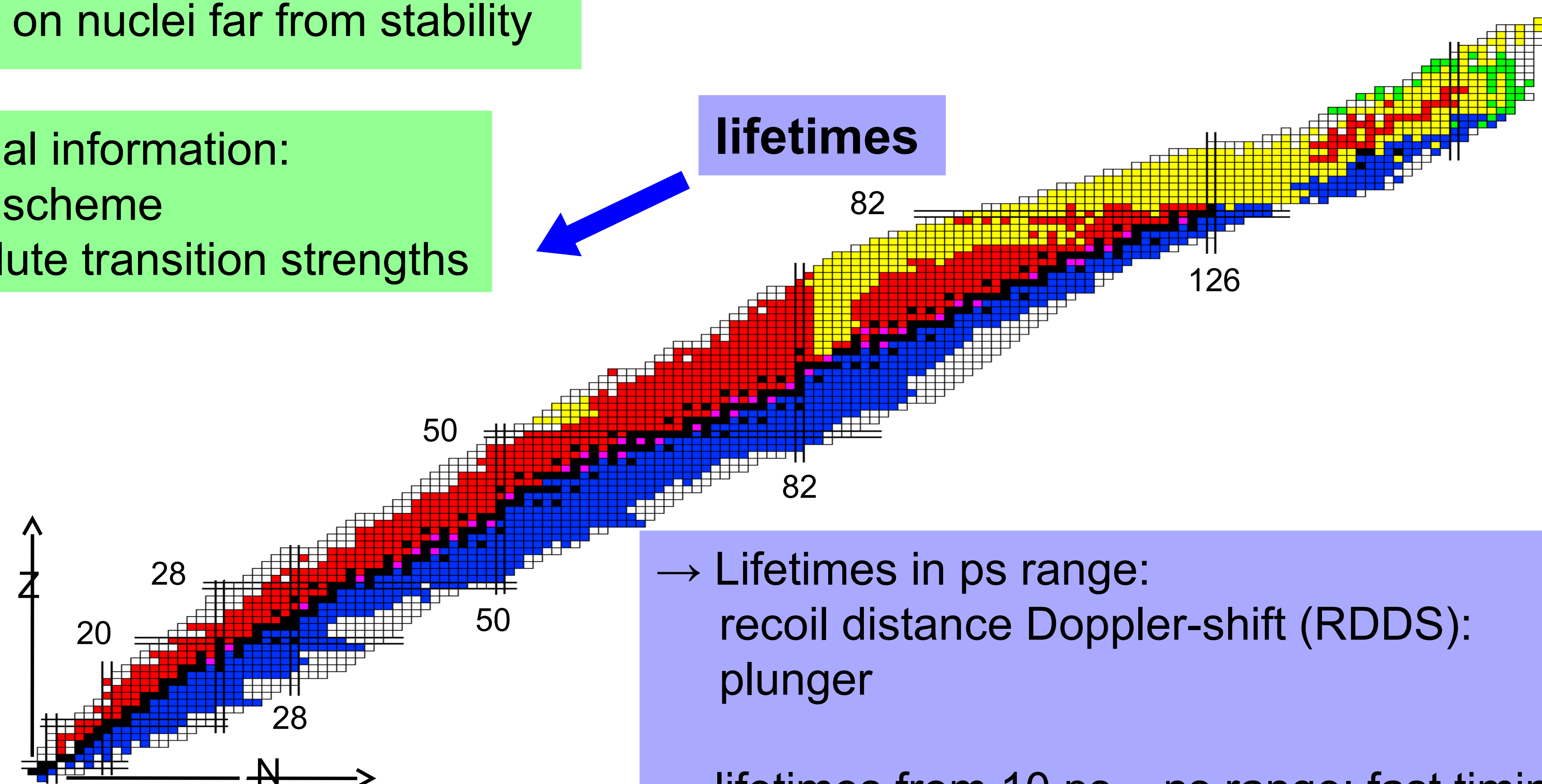
6. Search for isovector excitations in the vicinity of ^{208}Pb

Introduction

Present nuclear physics:
focus on nuclei far from stability

Crucial information:
level scheme
absolute transition strengths

lifetimes

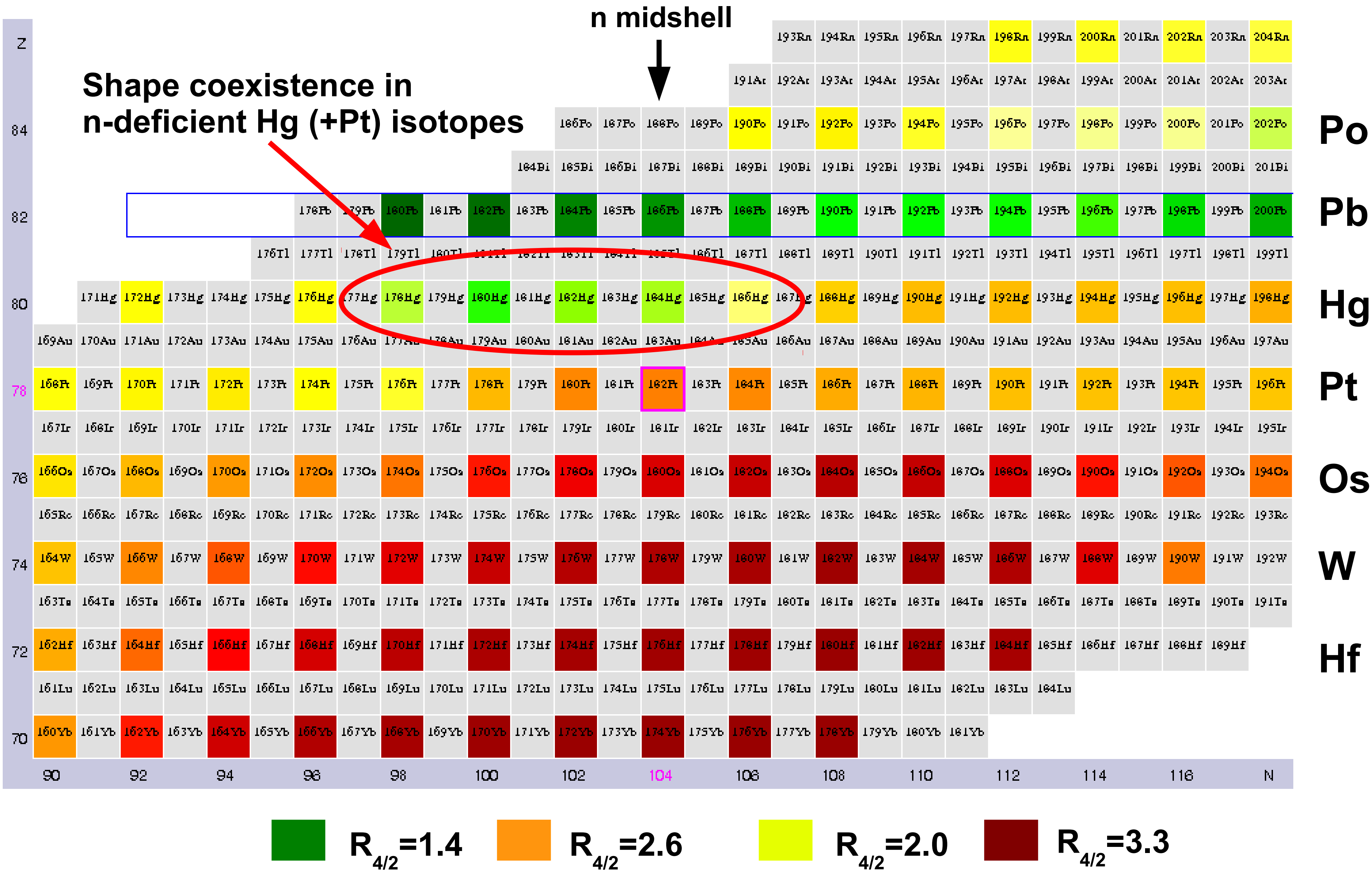


→ Lifetimes in ps range:
recoil distance Doppler-shift (RDDS):
plunger

→ lifetimes from 10 ps – ns range: fast timing

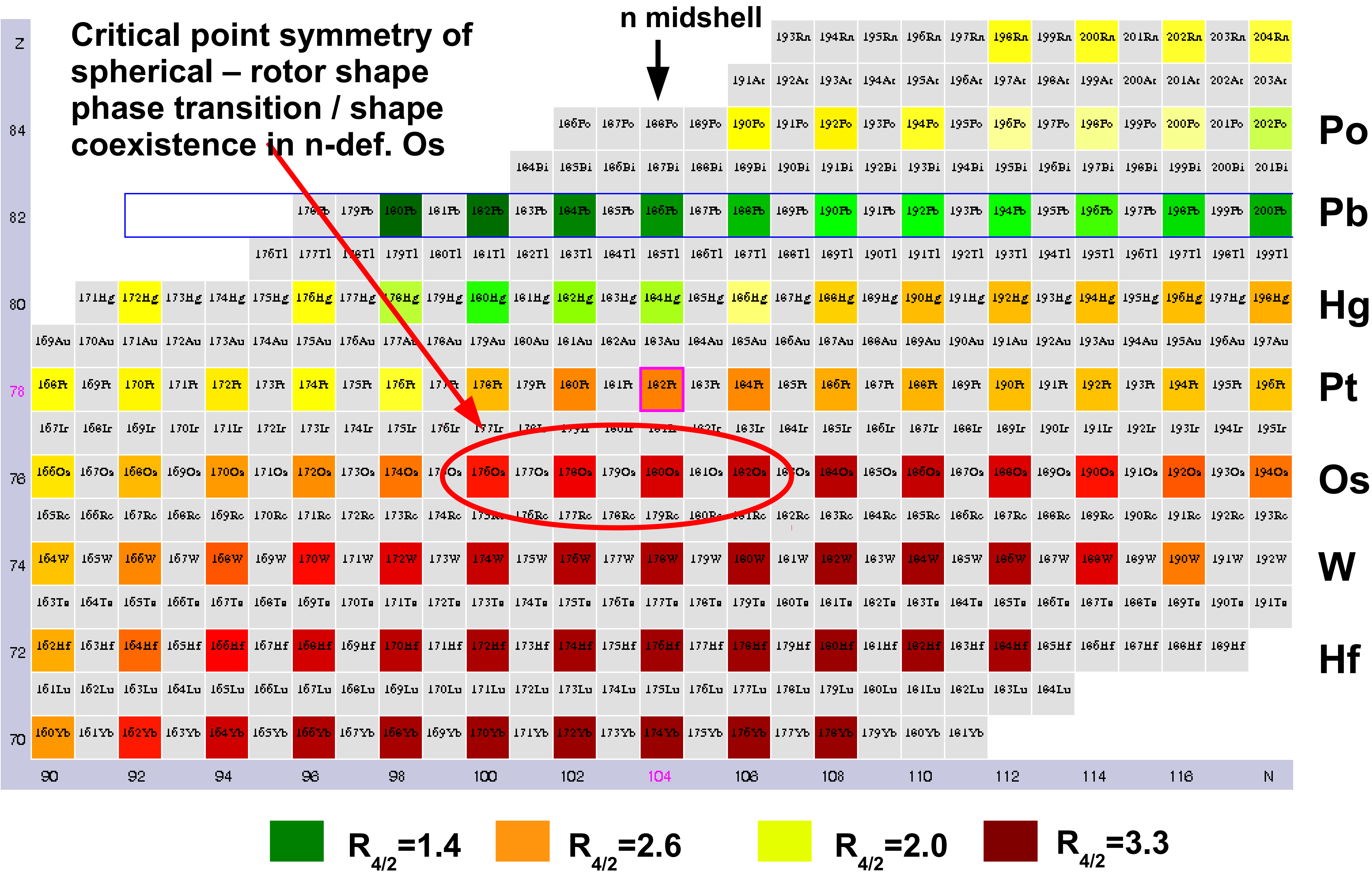
→ lifetimes in fs range:
Doppler-shift attenuation method (DSAM)

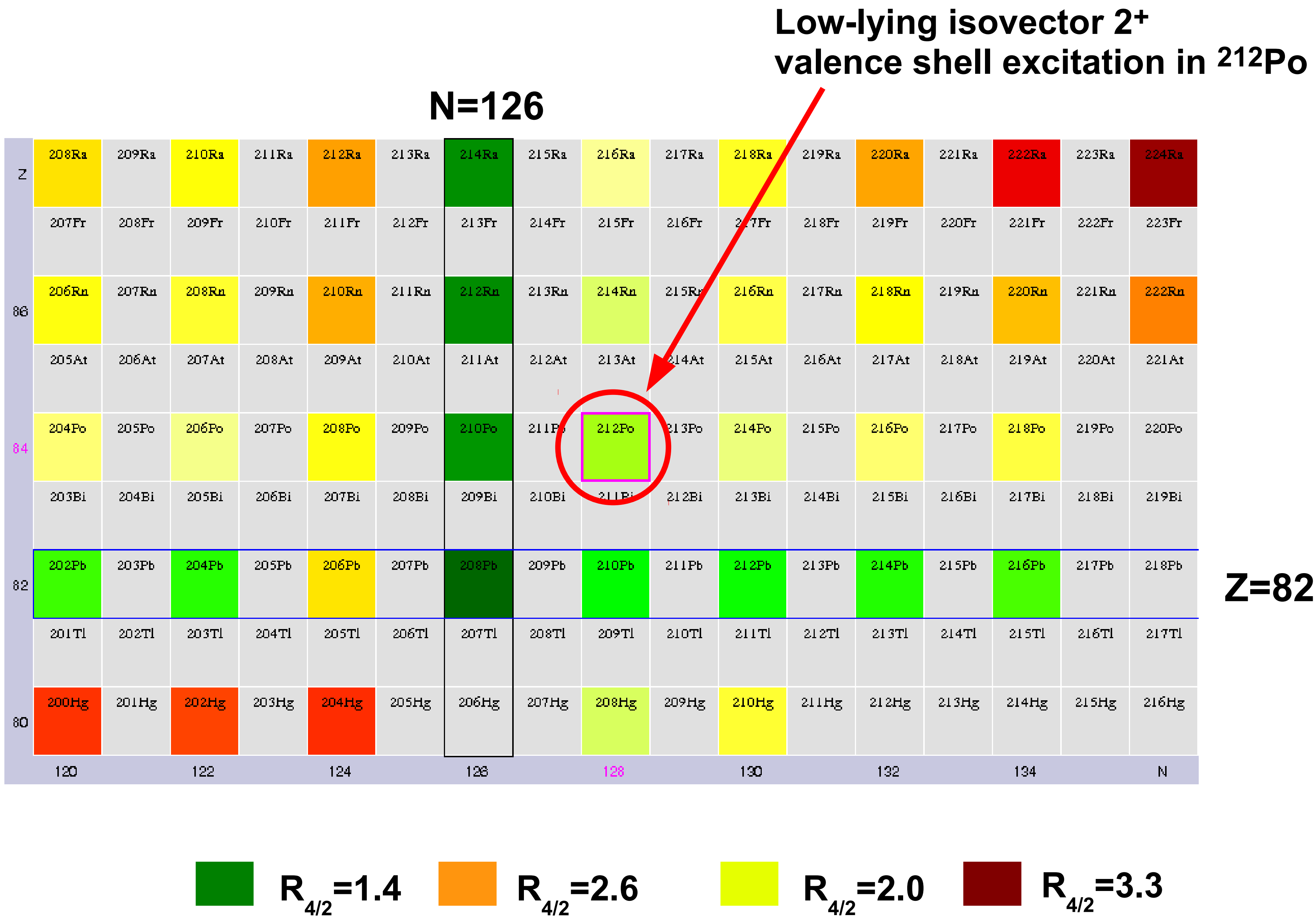
Introduction



Introduction

Critical point symmetry of spherical – rotor shape phase transition / shape coexistence in n-def. Os




Low-lying isovector 2+ valence shell excitation in 212Po
N=126
Z=82
Z
86
84
82
80
208Ra 209Ra 210Ra 211Ra 212Ra 213Ra 214Ra 215Ra 216Ra 217Ra 218Ra 219Ra 220Ra 221Ra 222Ra 223Ra 224Ra
207Fr 208Fr 209Fr 210Fr 211Fr 212Fr 213Fr 214Fr 215Fr 216Fr 218Fr 219Fr 220Fr 221Fr 222Fr 223Fr
206Rn 207Rn 208Rn 209Rn 210Rn 211Rn 212Rn 213Rn 214Rn 216Rn 217Rn 218Rn 219Rn 220Rn 221Rn 222Rn
205At 206At 207At 208At 209At 210At 211At 212At 213At 215At 216At 217At 218At 219At 220At 221At
204Po 205Po 206Po 207Po 208Po 209Po 210Po 212Po 214Po 215Po 216Po 217Po 218Po 219Po 220Po
203Bi 204Bi 205Bi 206Bi 207Bi 208Bi 209Bi 210Bi 212Bi 213Bi 214Bi 215Bi 216Bi 217Bi 218Bi 219Bi
202Pb 203Pb 204Pb 205Pb 206Pb 207Pb 208Pb 209Pb 210Pb 211Pb 212Pb 213Pb 214Pb 215Pb 216Pb 217Pb 218Pb
201Tl 202Tl 203Tl 204Tl 205Tl 206Tl 207Tl 208Tl 209Tl 210Tl 211Tl 212Tl 213Tl 214Tl 215Tl 216Tl 217Tl
200Hg 201Hg 202Hg 203Hg 204Hg 205Hg 206Hg 207Hg 208Hg 209Hg 210Hg 211Hg 212Hg 213Hg 214Hg 215Hg 216Hg
120 122 124 126 128 130 132 134 N
R4/2=1.4
R4/2=2.6
R4/2=2.0
R4/2=3.3

Outline

1. Introduction

2. The plunger technique

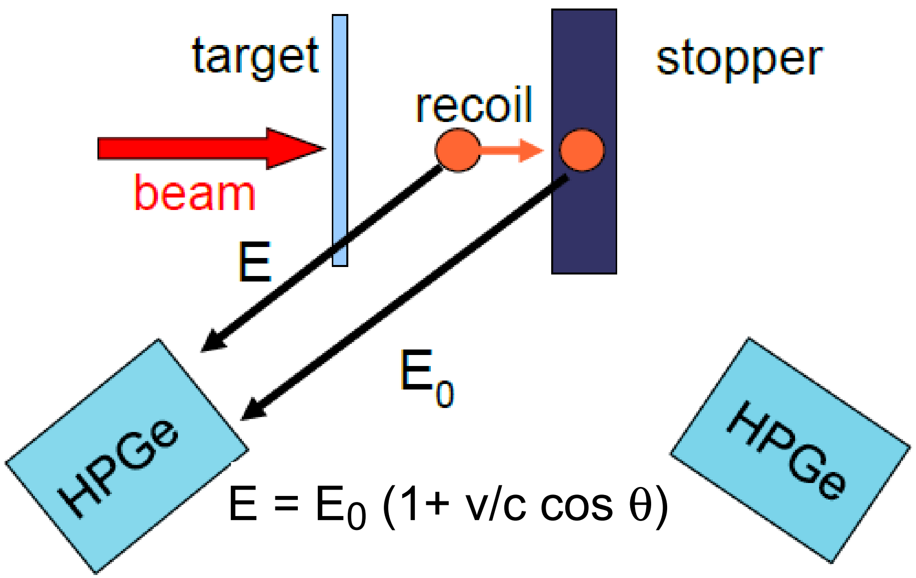
3. Other lifetime techniques used by our group:
   a. Fast timing
   b. Doppler-shift attenuation method

4. Shape coexistence in neutron deficient Hg isotopes

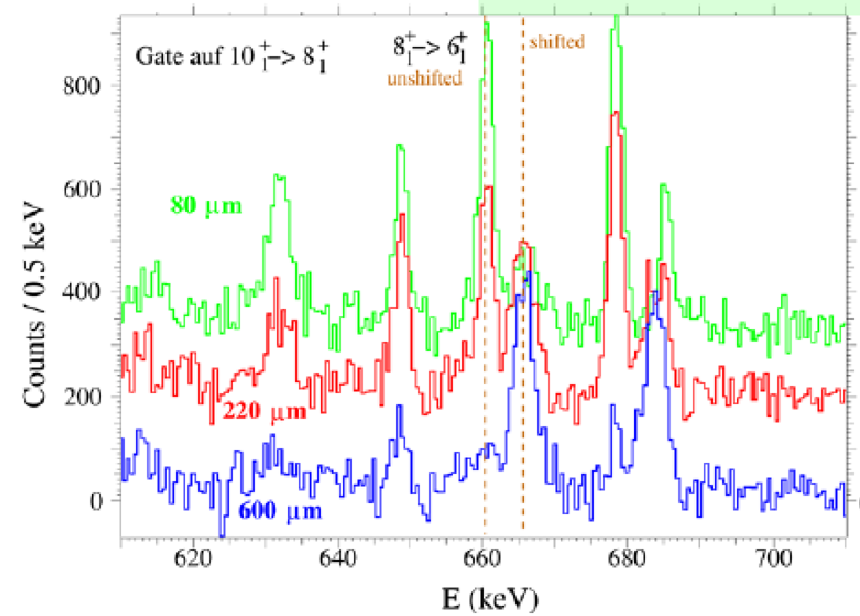
5. Critical point symmtries in the A=180 mass region

6. Search for isovector excitations in the vicinity of ^{208}Pb

The plunger technique



$^{92}Mo(^{10}B,3np)^{98}Pd$



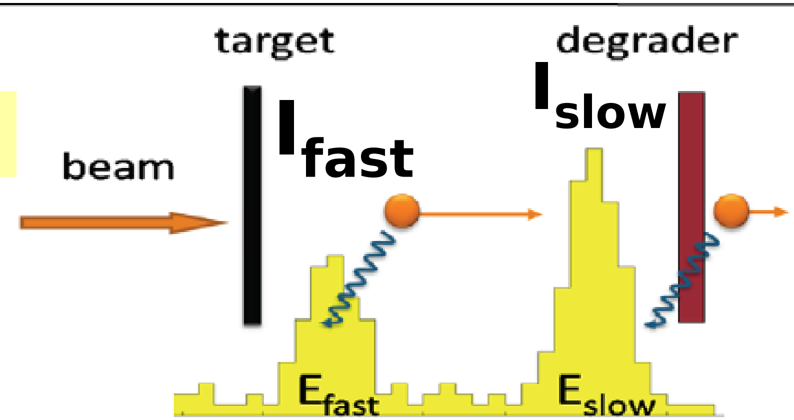
$$\tau(t_k) = \frac{I^{us}(t_k)}{\frac{d}{dt} I^{sh}(t_k)}$$

I^{us} = Intensity of the unshiftet γ-ray line

I^{sh} = Intensity of the Doppler-shifted component

Differential Plunger

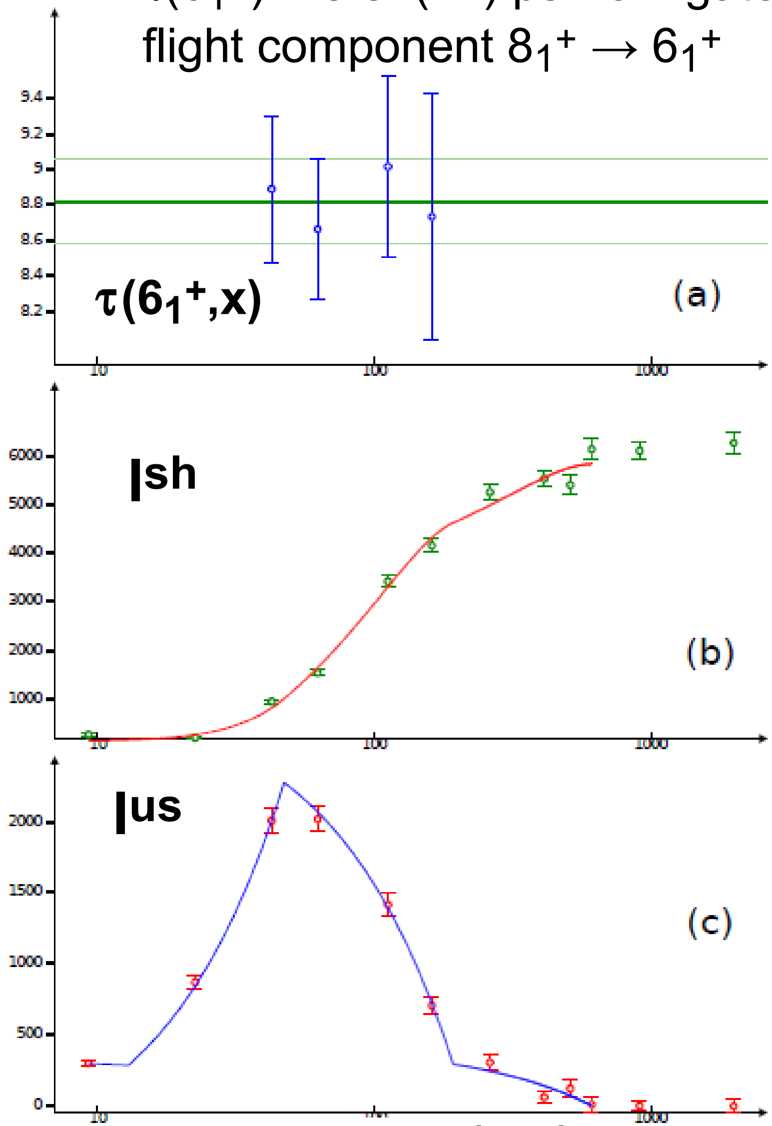
Use degrader instead of stopper to allow identification of recoils



Particle ident.:
LYCCA
S800 (MSU)

The plunger technique

$\gamma\gamma$ coincidence exp. on ^{184}Hg:
$\tau(6_1^+) = 8.82(24)$ ps from gate on flight component $8_1^+ \rightarrow 6_1^+$



Plot ratio $I^{us} / (I^{us} + I^{sh})$ versus target – stopper distance

Every distance in sensitive range gives a lifetime value.

Differential Decay Curve Method (DDCM)
Allows to easily discover systematic errors

$$\tau(t_k) = \frac{I^{\mathrm{us}}(t_k)}{\frac{d}{dt} I^{\mathrm{sh}}(t_k)}$$

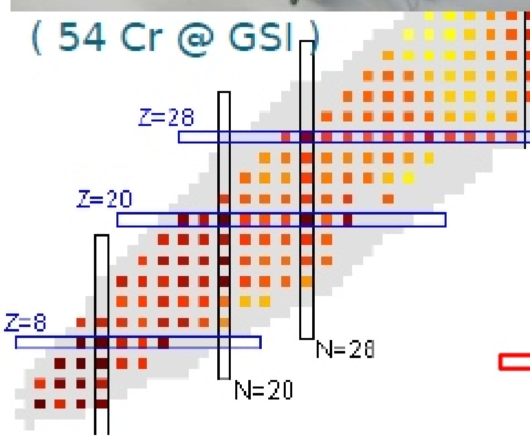
$$I^{\mathrm{us}} = \text{Intensity of the unshiftet } \gamma\text{-ray line}$$

$$I^{\mathrm{sh}} = \text{Intensity of the Doppler-shifted component}$$

Different plunger devices...

relativistic Coulex
~ 200 MeV/u

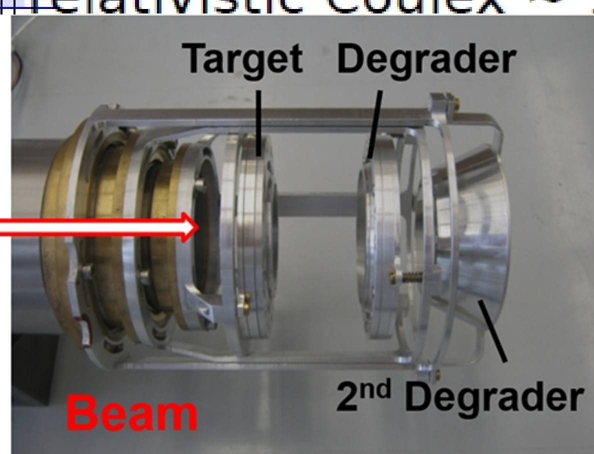
(54 Cr @ GSI)



Fusion-evaporation
Safe Coulex inverse kinematics

178Pt @ iThemba
180Pt @ JYFL
178Hg @ JYFL
184,186,188Hg @ ANL
n-def. Os @ Cologne
… and several more

Knock-out and
relativistic Coulex ~ 100 MeV/u



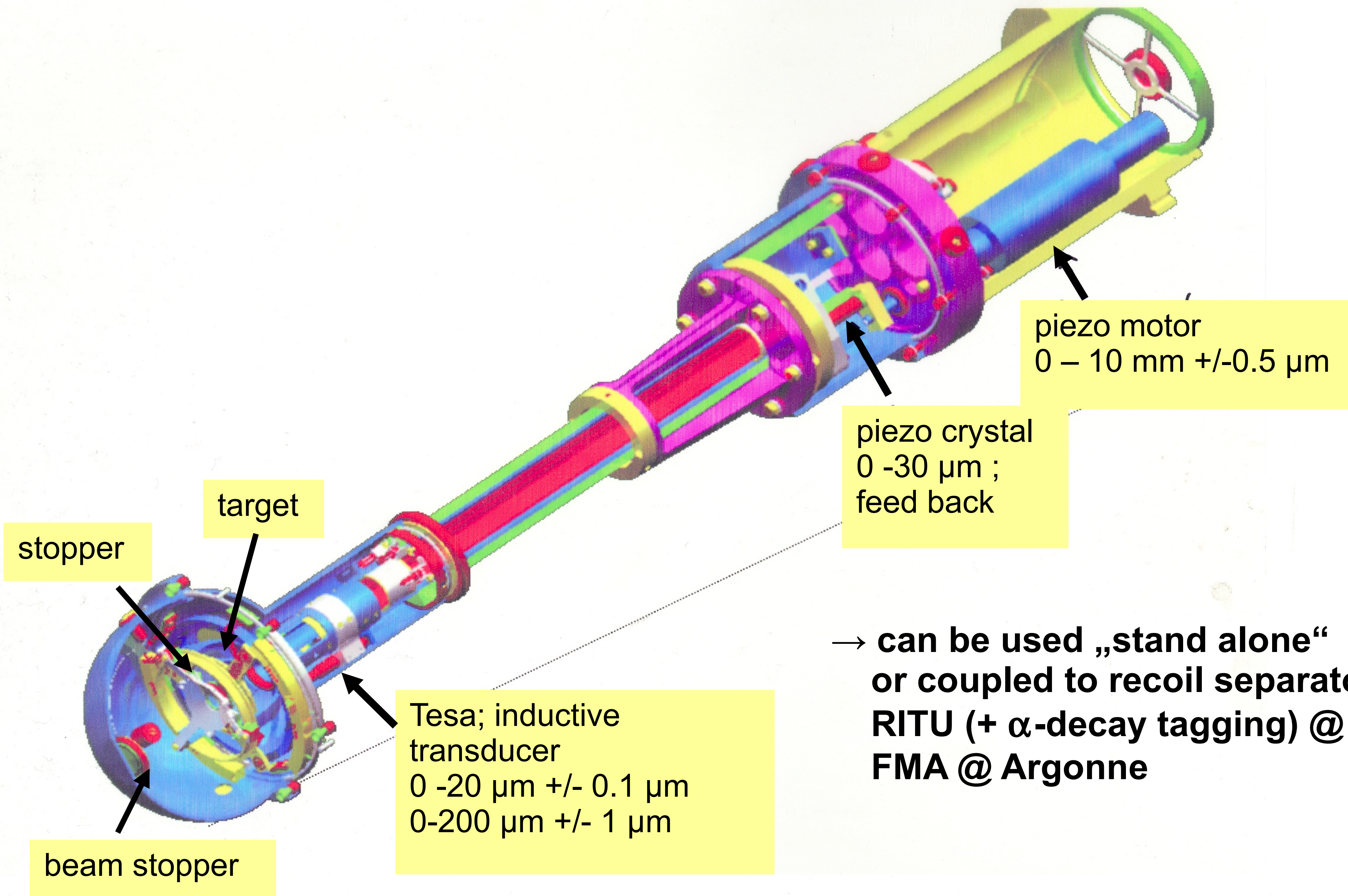
58,60,62 Cr
@ NSCL

TRIPLEX plunger
H. Iwasaki, NSCL

Deep-inelastic scattering

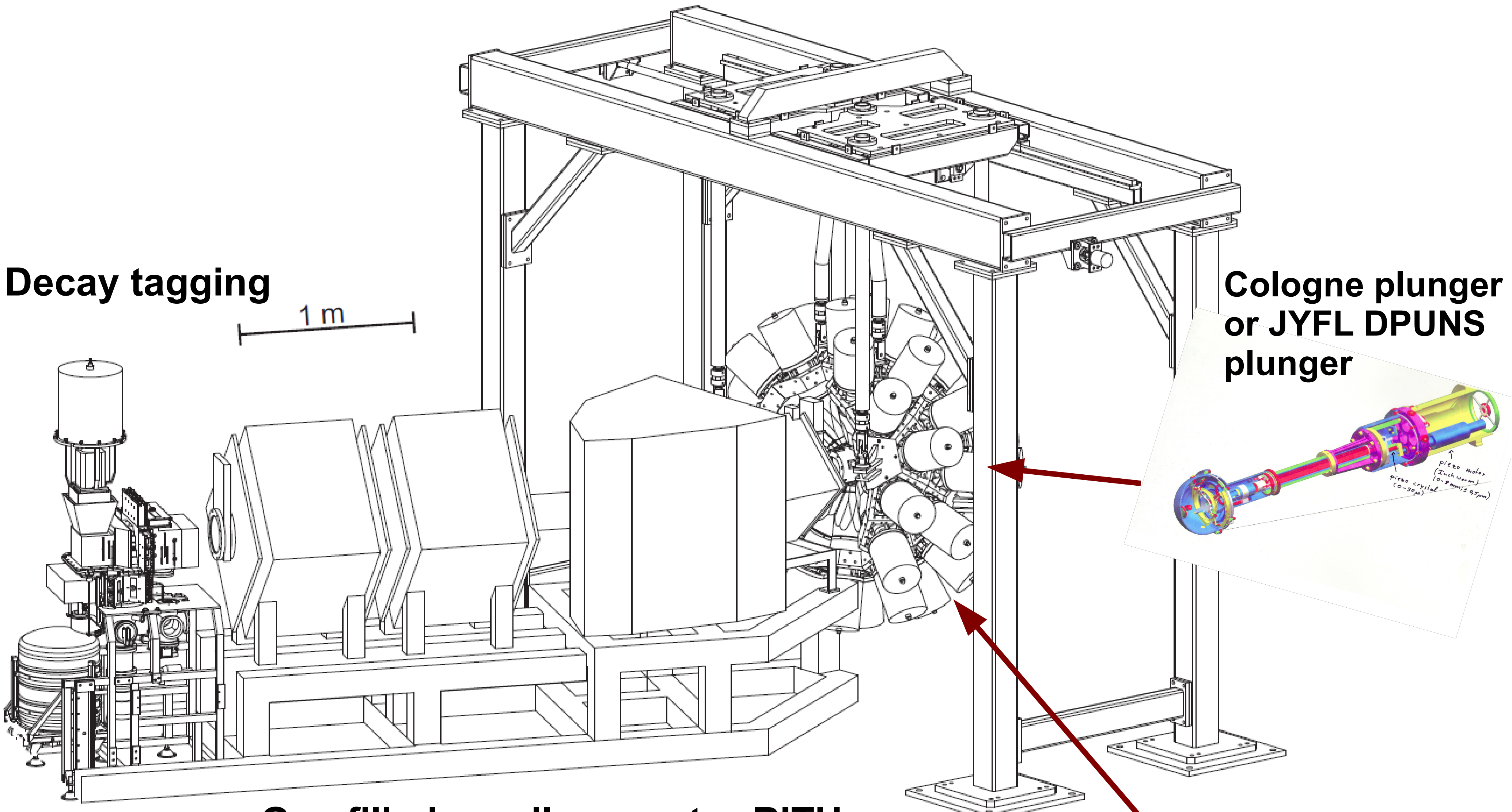
63, 65Co, 62,64 Fe @ GANIL
A=200 mass region @ GANIL

The Cologne „standard“ plunger: Fusion-evaporation, low-energy coulex, ...



→ can be used „stand alone“ or coupled to recoil separators:
RITU (+ α-decay tagging) @ Jyväskylä
FMA @ Argonne

The plunger at the recoil separator RITU



Outline

1. Introduction

2. The plunger technique

3. Other lifetime techniques used by our group:
   a. Fast timing
   b. Doppler-shift attenuation method

4. Shape coexistence in neutron deficient Hg isotopes

5. Critical point symmtries in the A=180 mass region

6. Search for isovector excitations in the vicinity of ^{208}Pb

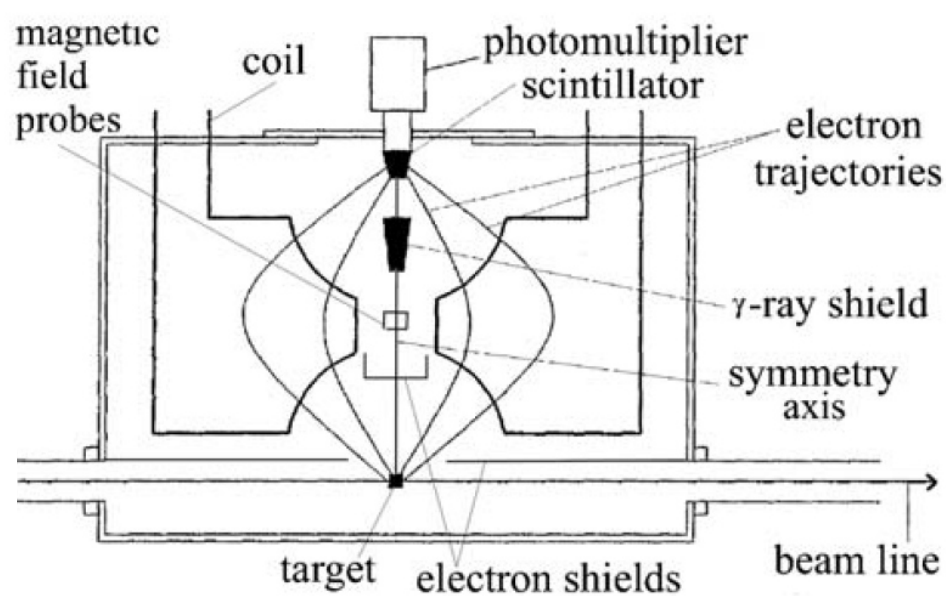
Fast timing

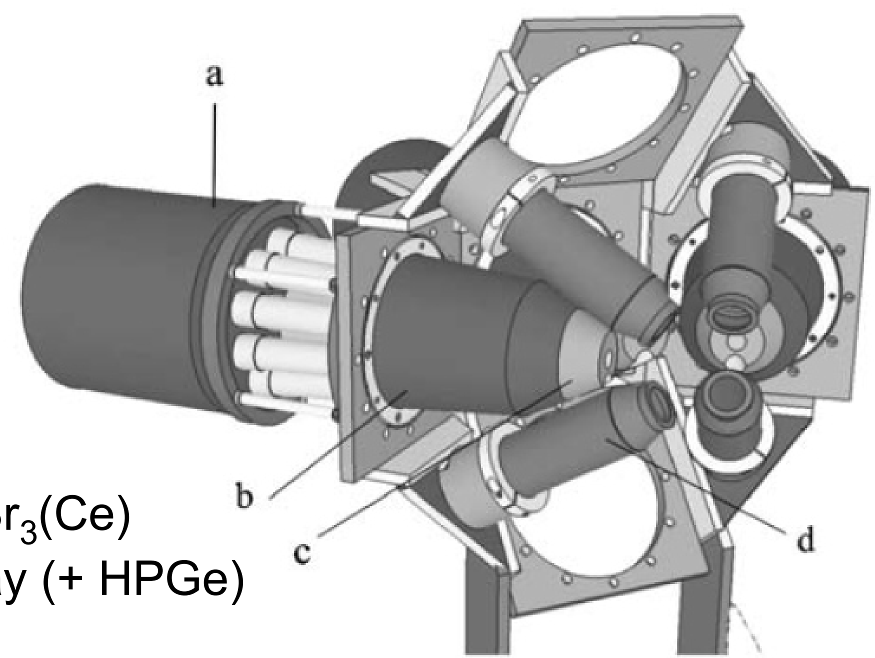
→ **level lifetimes from delayed coincidences between populating and depopulating transitions.**

→ **fast detectors: γ – γ coincidences between $LaBr_3(Ce)$ detectors: FWHM = 200 ps or conversion electron (ce) – γ coincidences for transitions with large conversion factors.**

→ **lifetime range: ~ns – 10 ps**

Orange e- spectrometer





$LaBr_3(Ce)$ array (+ HPGe)

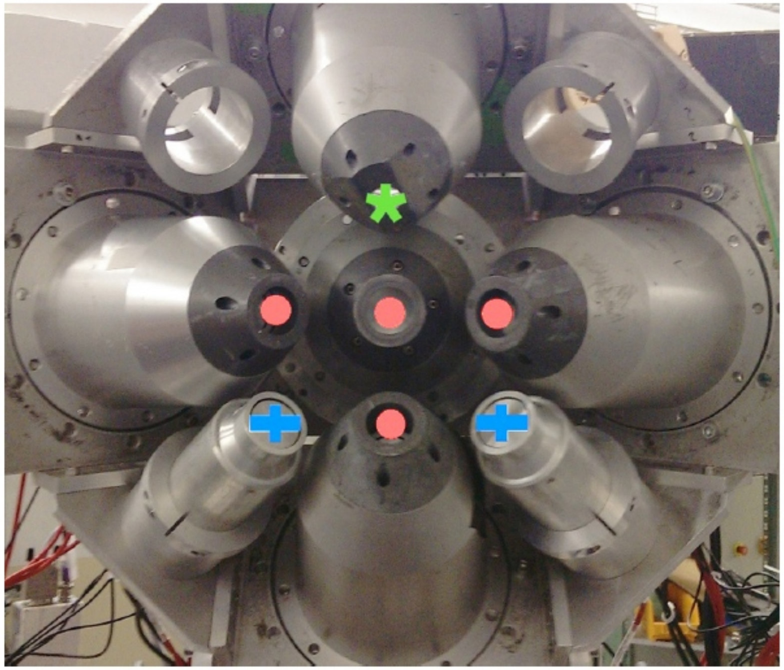
Setup at IKP Cologne for fast timing measurements using ce – γ coincidences

Fast timing

→ level lifetimes from delayed coincidences between populating and depopulating transitions.

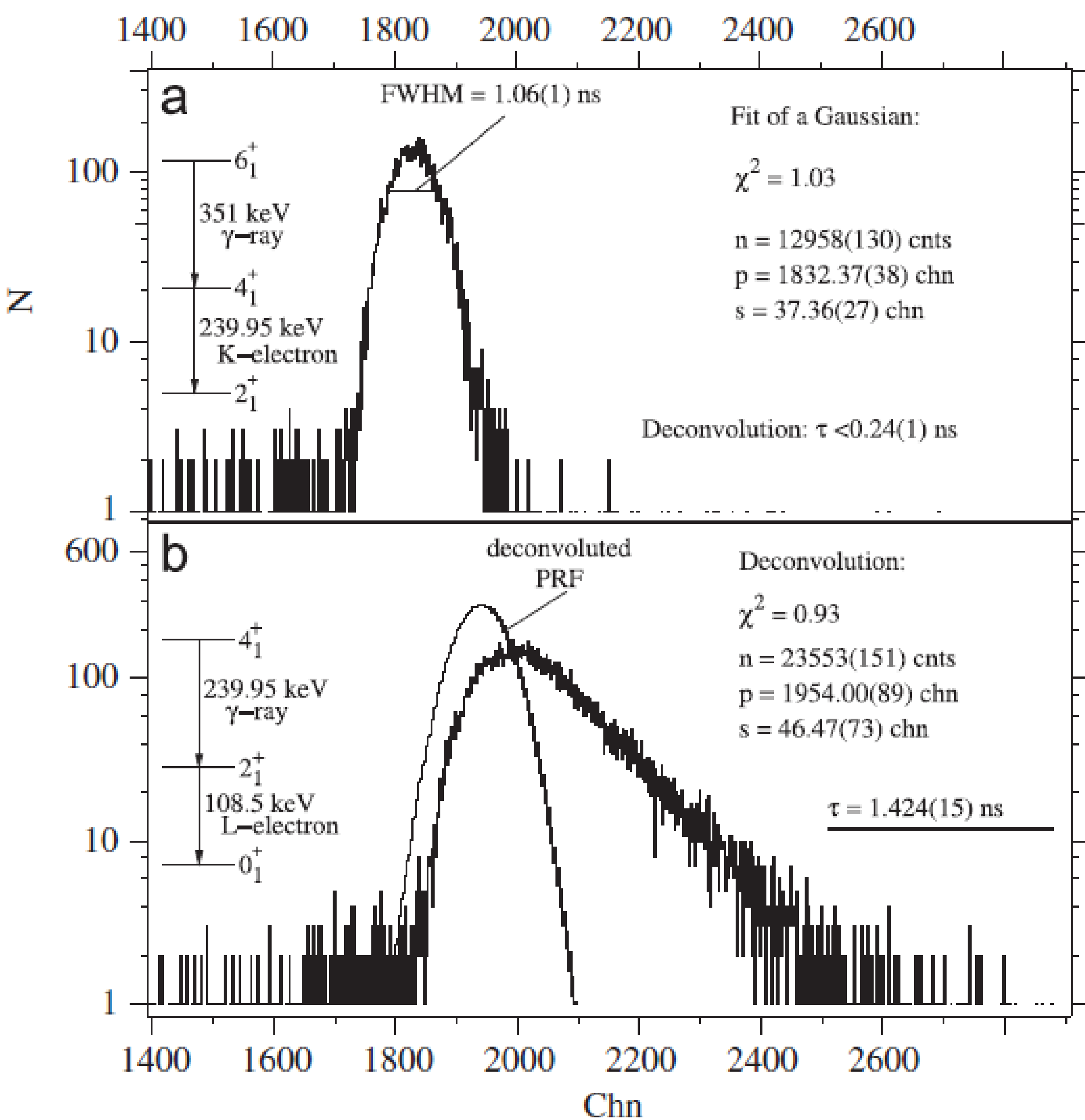
→ fast detectors: $\gamma - \gamma$ coincidences between $LaBr_3(Ce)$ detectors: FWHM = 200 ps
or conversion electron (ce) – γ coincidences
for transitions with large conversion factors.

→ lifetime range: ~ns – 10 ps



Setup at IKP Cologne
for fast timing measurements
using $\gamma - \gamma$ coincidences between
$LaBr_3(Ce)$ detectors with anti-Compton shields „●" and unshielded „✚"

Example: $\tau(2_1^+)$ in ^{176}W from e^- – γ time distribution

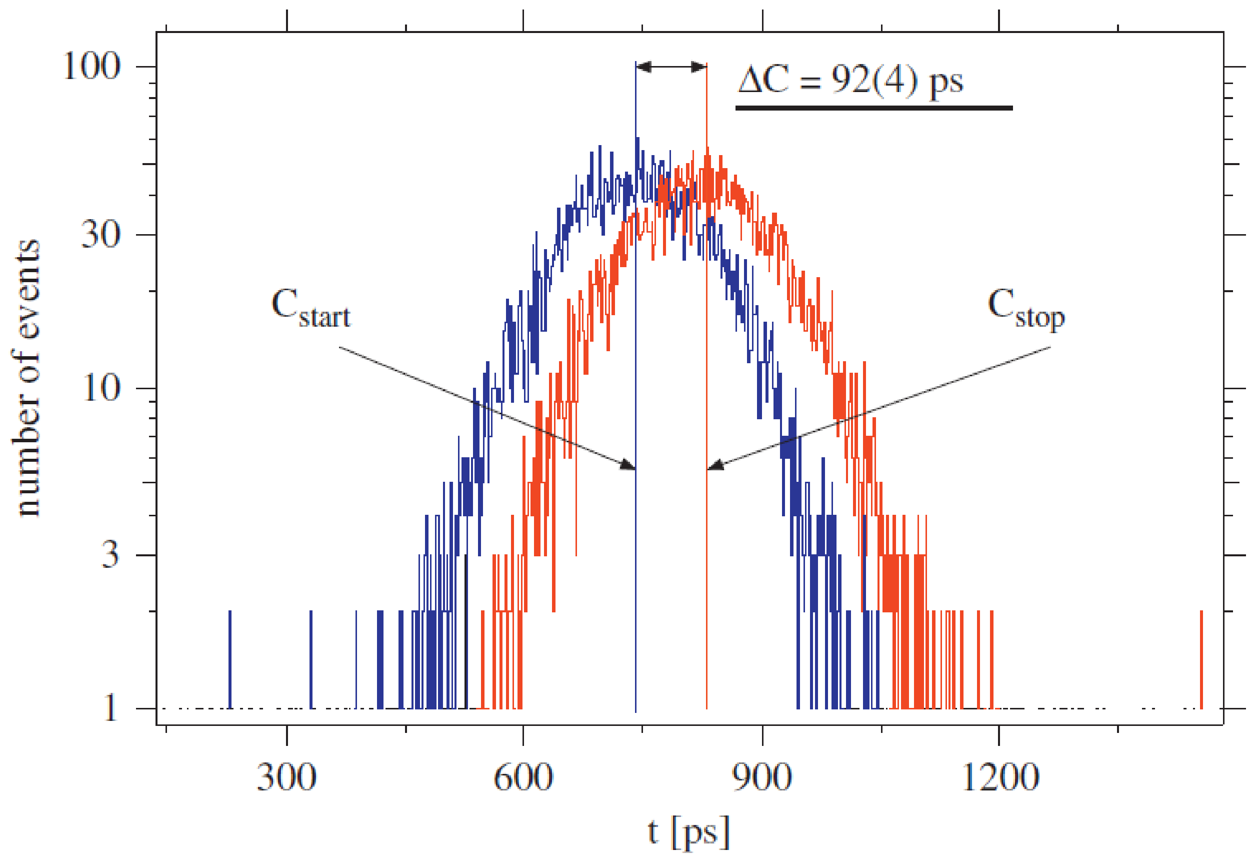


→ **deconvolute prompt response function and time response function of level of interest.**

→ **calibr.: 12.1 ps/chn**

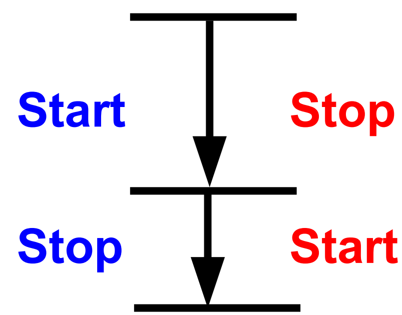
J.M. Regis et al., NIM A 606, 466 (09)

Picosecond sensitive fast timing:
Mirror symmetric centroid difference method



Two $LaBr_3(Ce)$ detectors:

$$\Delta C(\Delta E_\gamma)_{decay} = PRD(\Delta E_\gamma)_{decay} + 2\tau$$



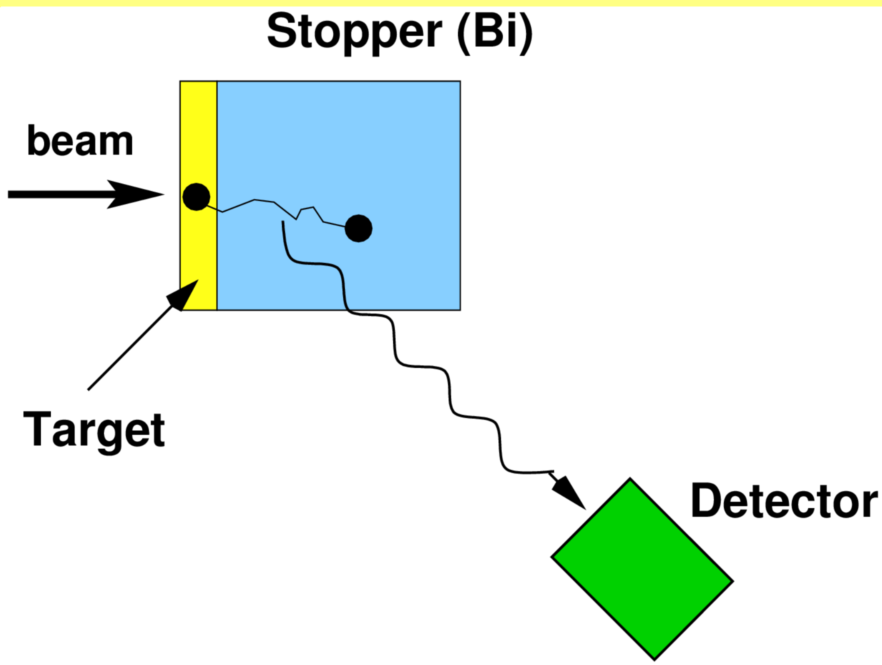
Fast timing array with N equal detectors:
Individual time-walk characteristics treated stochastic:

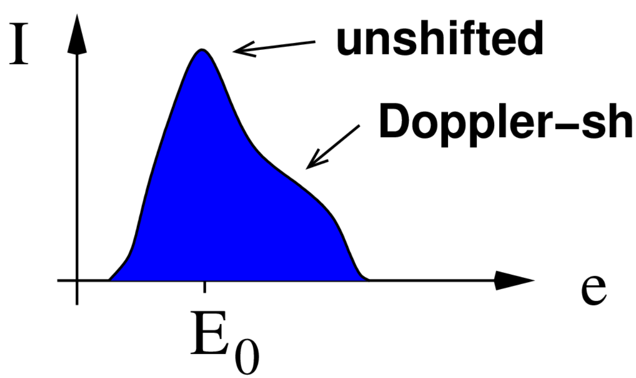
$$\overline{\Delta C}(E_\gamma) = \overline{\mathrm{PRD}}(E_\gamma) + 2\tau$$

→ **Generalized Centroid Difference Method**

J.M. Regis et al., NIM A 726, 191 (13)

Determination of lifetimes in the sub-ps range: The Doppler-shift attenuation method (DSAM)





$$L'(\tau, v) = \int_0^\infty N(v,t) r(t,\tau) dt$$

$$L'(\tau, v) \rightarrow L'(\tau, E)$$

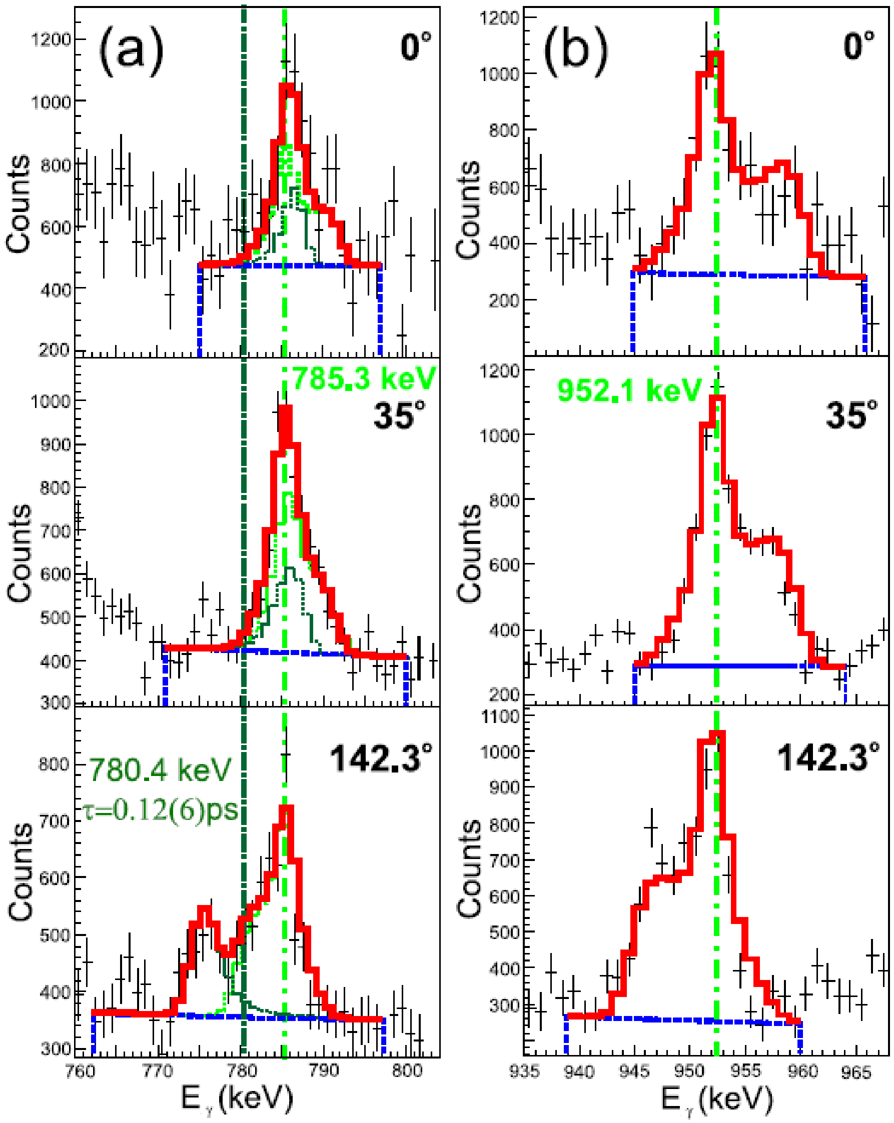
$$L(\tau, E) = \int_{E_{min}}^{E_{max}} L'(\tau, e) f(e,\sigma) de$$

$$f(e,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} \cdot e^{-\frac{(e-E_0)^2}{2\sigma^2}}$$

→ **Simulate slowing down (Monte Carlo/GEANT4)**
→ **use (semi-empiric) electronic stopping powers and nuclear stopping**
→ **include angular straggling due to nuclear collisions.**

P. Petkov: DSAM analysis using DDCM

Determination of lifetimes in the sub-ps range: The Doppler-shift attenuation method (DSAM)



$2_2^+ \rightarrow 2_1^+$ $2_3^+ \rightarrow 2_1^+$

952.1 keV
τ=0.80(3) ps

Example:
Determination of lifetimes of the 2_2^+ and 2_3^+ states in ^{212}Po

(G. Rainovski, D. Kocheva)
$^{208}Pb(^{12}C,^{8}Be)^{212}Po$
@ Cologne FN Tandem

Outline

1. Introduction

2. The plunger technique

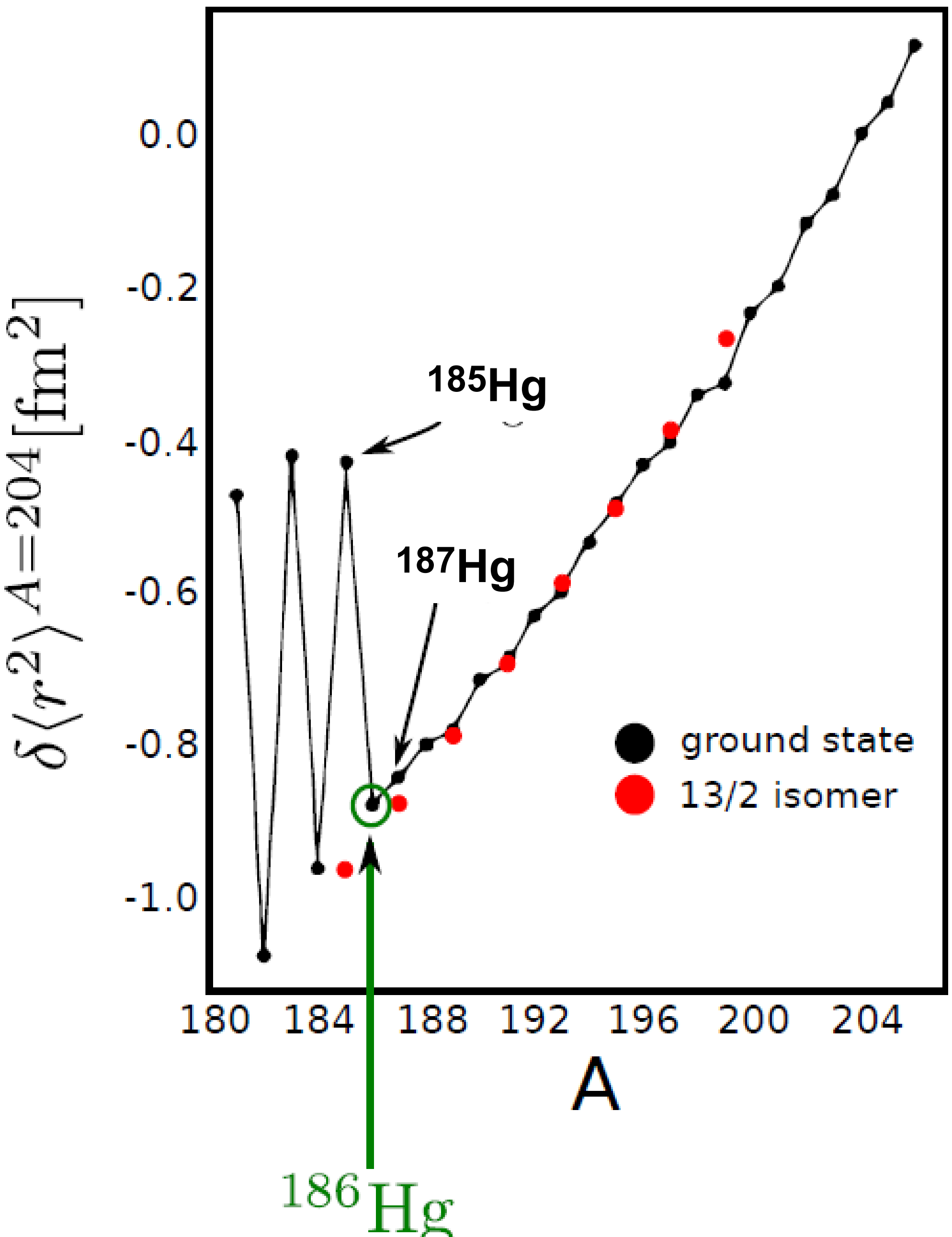
3. Other lifetime techniques used by our group:
   a. Fast timing
   b. Doppler-shift attenuation method

4. Shape coexistence in neutron deficient Hg isotopes

5. Critical point symmtries in the A=180 mass region

6. Search for isovector excitations in the vicinity of ^{208}Pb

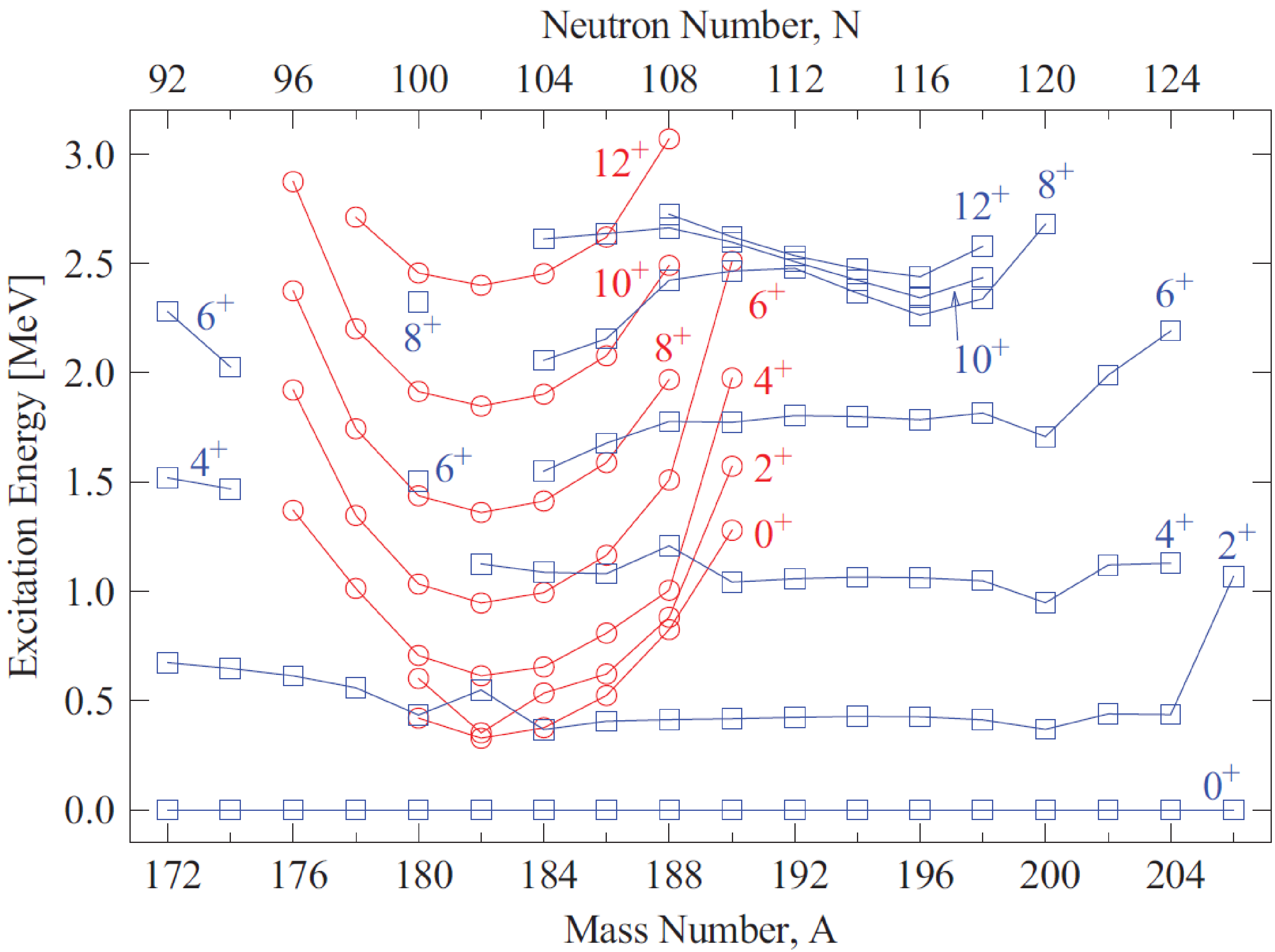
Shape coexistence in light Hg isotopes



S. Frauendorf, S.V. Pashkevich, PLB 55, 365 (1975):

Sharp change in mean-square radius ^{187}Hg → ^{185}Hg: evidence for transition weakly oblate → prolate deformed

Shape coexistence in light Hg isotopes: excitation energies



From L. Gaffney et al., PRC 89, 024307 (14)

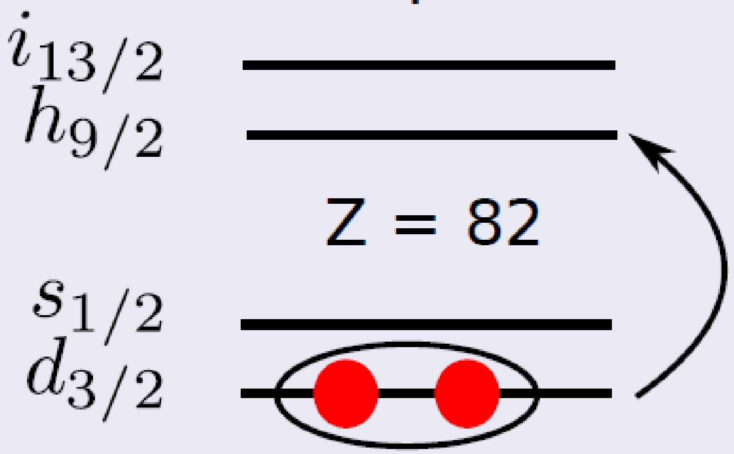
Shape coexistence in light Hg isotopes

Several theoretical approaches

- $\pi(0p-2h)$ and $\pi(2p-4h)$, e.g., W. Nazarewicz et al Phys. Lett. B., 305 (1993) 195-201
- J.L. Wood et al Phys. Rep. 215 (1992) 101-201
- IBM, R. Fossion et. al., Phys. Rev. C 67, 024306 (2003)
- Self-consistent Mean Field + particle number restauration: T. Duguet et al, Phys. Lett B 559 (2003) 201; M. Bender et. al., J. Phys. G: Nucl. Part. Phys. 31 (2005) S1611-S1616
- Rel. Mean Field + BCS, e.g. S. Yoshida, Phys. Rev. C 55 (1997) 3, Vretenar et al.

Shell-model picture

Shell-model picture



Second collective excitation: rotational band on 2p-4h excitation

Shape coexistence in light Hg isotopes

Several theoretical approaches

- $\pi(0p-2h)$ and $\pi(2p-4h)$, e.g., W. Nazarewicz et al Phys. Lett. B., 305 (1993) 195-201
- J.L. Wood et al Phys. Rep. 215 (1992) 101-201
- IBM, R. Fossion et. al., Phys. Rev. C 67, 024306 (2003)
- Self-consistent Mean Field + particle number restauration: T. Duguet et al, Phys. Lett B 559 (2003) 201; M. Bender et. al., J. Phys. G: Nucl. Part. Phys. 31 (2005) S1611-S1616
- Rel. Mean Field + BCS, e.g. S. Yoshida, Phys. Rev. C 55 (1997) 3, Vretenar et al.

Interacting Boson Model

Interacting Boson Model: low-lying excitations, valence electrons paired to s,d bosons

For ^{186}Pb :

$$\hat{H} = \hat{H}_{reg} + \hat{H}_{2p2h} + \hat{H}_{4p4h} + \hat{V}_{mix}$$

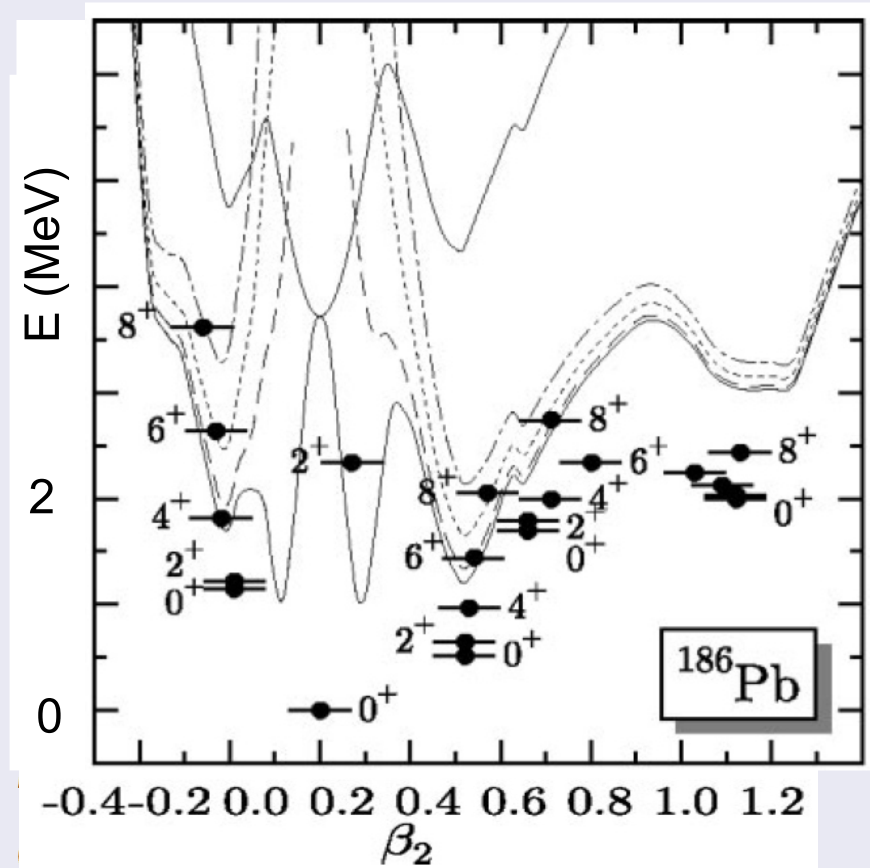
$$\begin{aligned} \hat{H}_{2p2h} &= \varepsilon_{2p2h}\hat{n}_d \\ &+ \kappa_{2p2h}\hat{Q}_{2p2h}\cdot\hat{Q}_{2p2h} + \Delta_{2p2h} \end{aligned}$$

Hamiltonians for individual excitations + mixing term

Shape coexistence in light Hg isotopes

Several theoretical approaches

- $\pi(0p-2h)$ and $\pi(2p-4h)$, e.g., W. Nazarewicz et al Phys. Lett. B., 305 (1993) 195-201
- J.L. Wood et al Phys. Rep. 215 (1992) 101-201
- IBM, R. Fossion et. al., Phys. Rev. C 67, 024306 (2003)
- Self-consistent Mean Field + particle number restauration: T. Duguet et al, Phys. Lett B 559 (2003) 201; M. Bender et. al., J. Phys. G: Nucl. Part. Phys. 31 (2005) S1611-S1616
- Rel. Mean Field + BCS, e.g. S. Yoshida, Phys. Rev. C 55 (1997) 3, Vretenar et al.

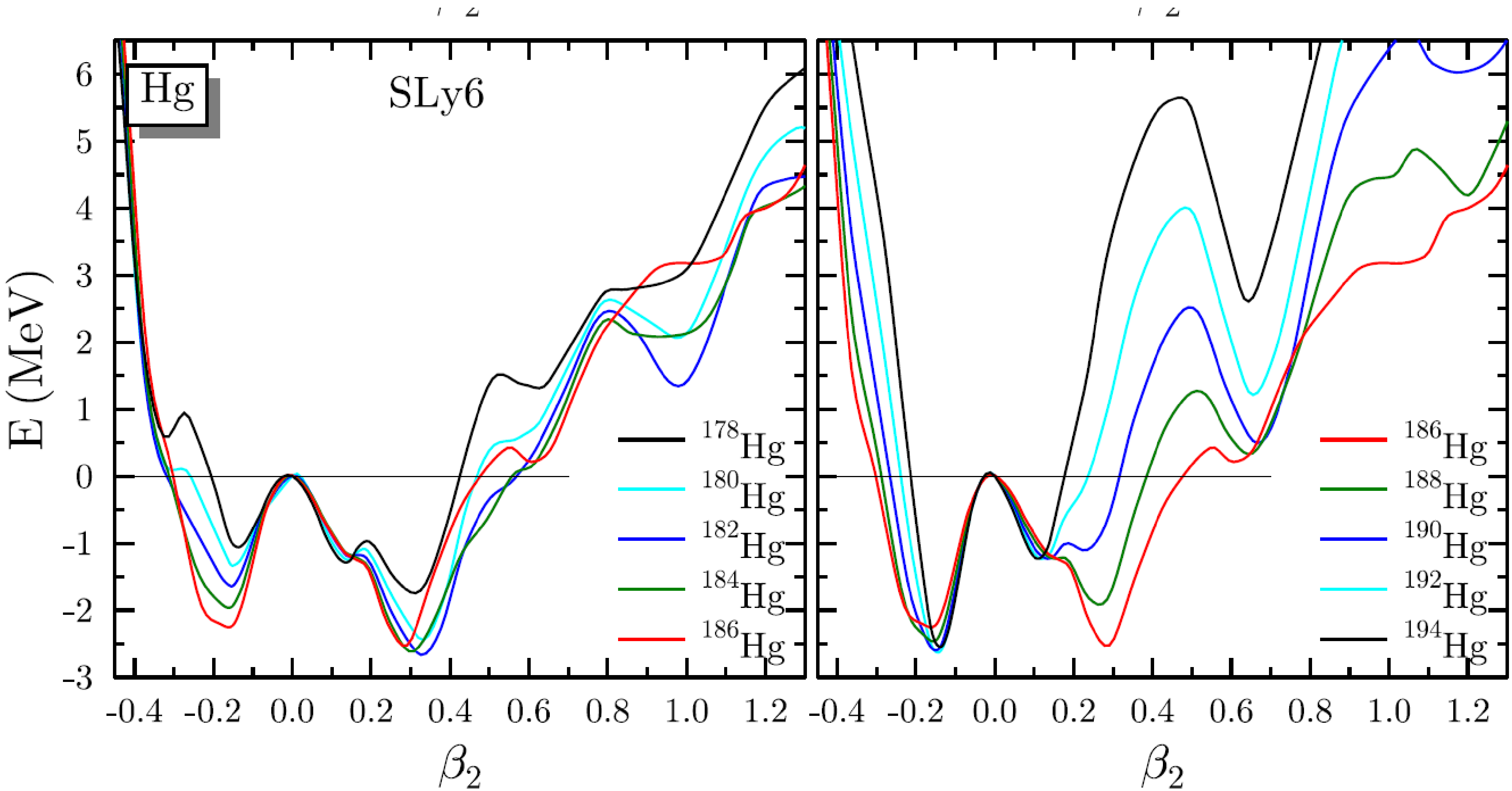


M. Bender et al., PRC 69, 064303 (04)

Configuration mixing of angular momentum and particle projected self-consistent mean field states, Skyrme interaction SLy6

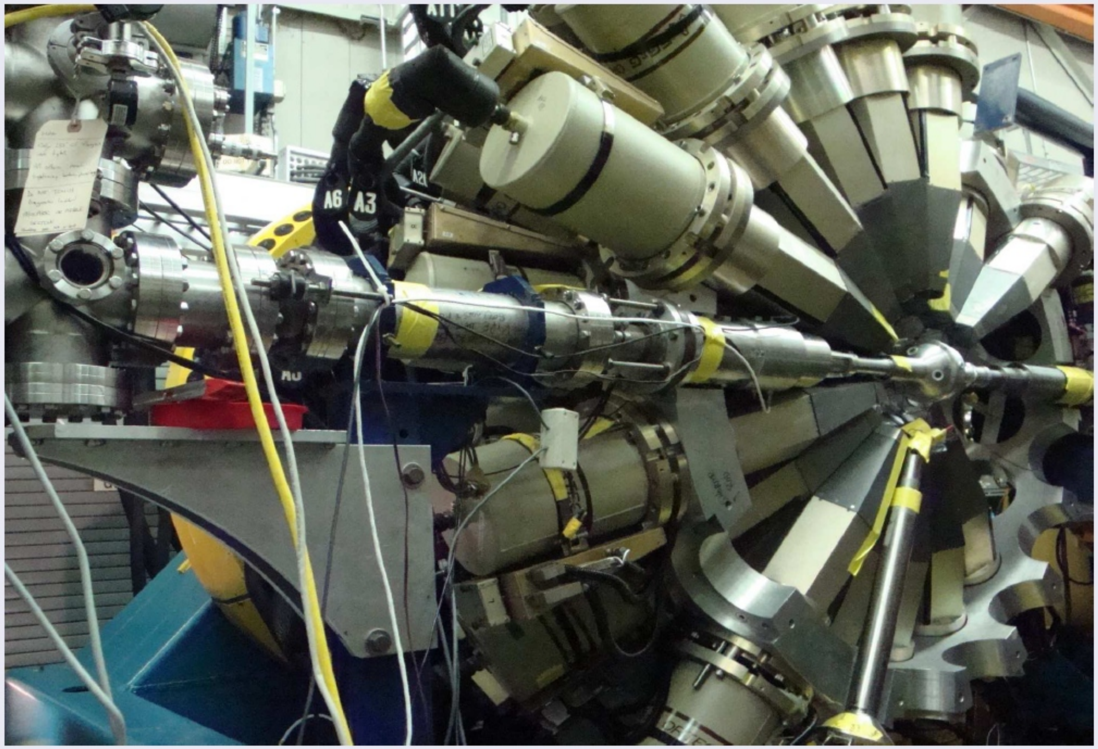
→ shape coex. in Pb isotopes

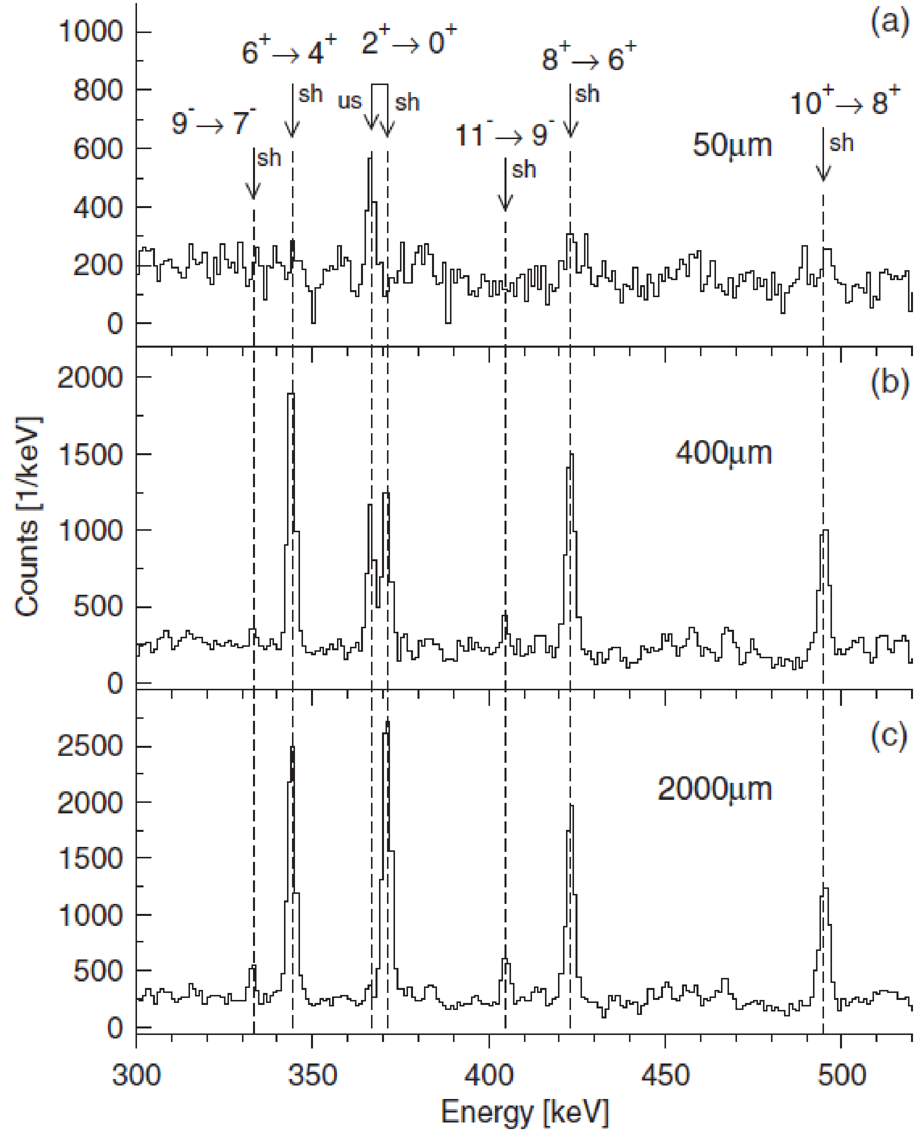
Systematic microscopic energy density calculations for Hg isotopes (SLy6, M. Bender, Bordeaux)



J.M. Yao, M. Bender, P.-H. Heenen, PRC 87, 034322 (12)

Plunger experiments on ^{184,186}Hg @ ANL





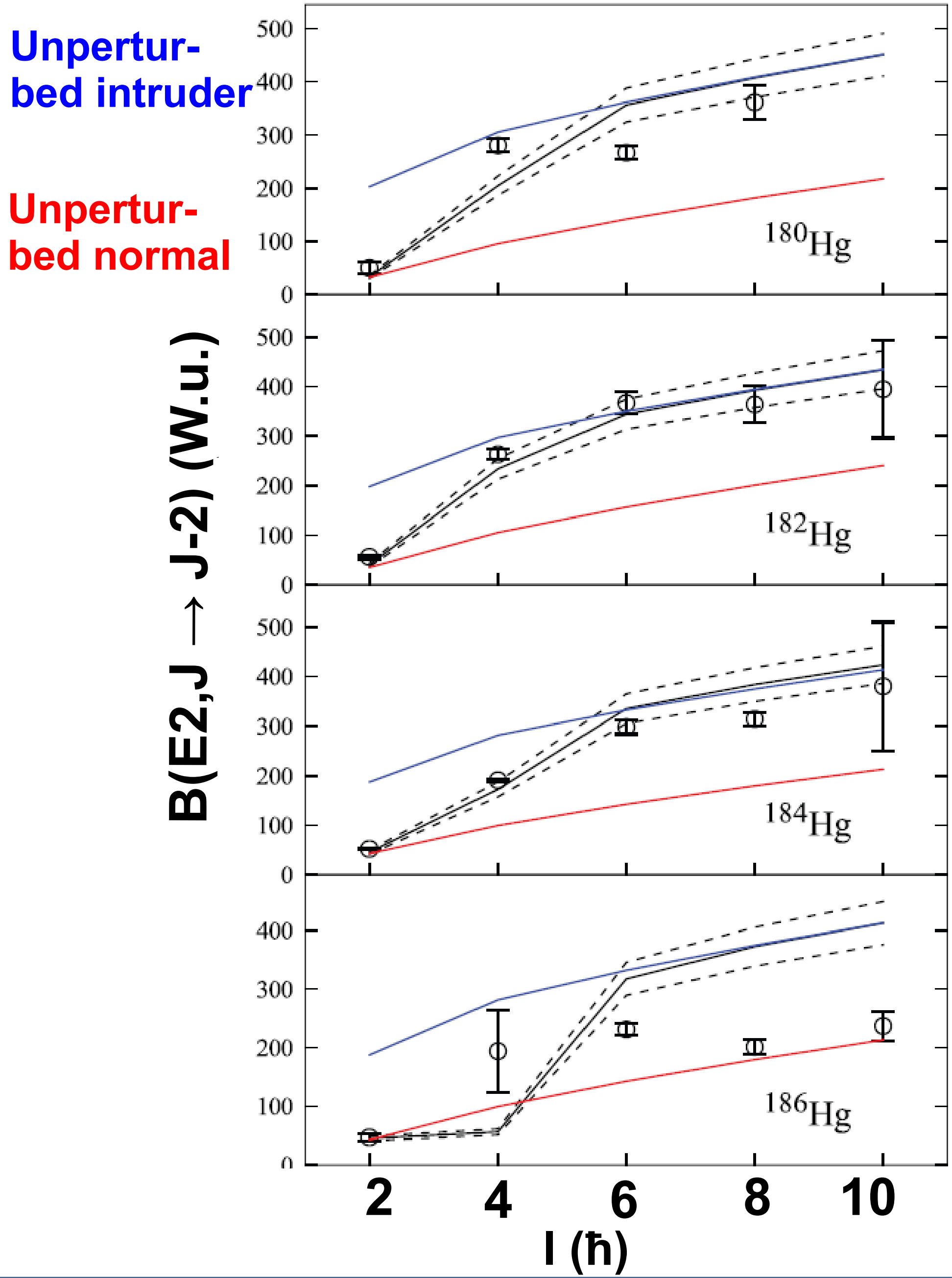
Cologne plunger @ GAMMASPHERE

^{148}Sm(^{40}Ar,4n)^{184}Hg, E(^{40}Ar) = 200 MeV
^{150}Sm(^{40}Ar,4n)^{186}Hg, E(^{40}Ar) = 195 MeV

L. Gaffney, M. Hackstein et al.,
Phys. Rev. C 89, 024307 (14)

^{184}Hg, gate on shifted component
$4_1^+ \to 2_1^+$

Shape coexistence in light Hg isotopes: band mixing in $^{180-186}$Hg



Phenomenological two-band mixing calculations:
→ assume spin-independent interaction between two rotational structures
→ wave function amplitudes of two config. from mixing strengths (Lane et al., NPA 589, 129 (95))

			amplitude
^{182}Hg	$V = 89.4$ keV	0	0.9606
		2	0.5382
	$E_0^n = 25.9$ keV	4	0.1781
		6	0.1003
	$E_0^i = 309.0$ keV	8	0.0697
		10	0.0534
^{184}Hg	$V = 84.7$ keV	0	0.9725
		2	0.7172
	$E_0^n = 20.4$ keV	4	0.2014
		6	0.1025
	$E_0^i = 353.4$ keV	8	0.0679
		10	0.0506
^{186}Hg	$V = 66.3$ keV	0	0.9915
		2	0.9506
	$E_0^n = 8.9$ keV	4	0.2604
		6	0.0978
	$E_0^i = 505.4$ keV	8	0.0587

Shape coexistence in light Hg isotopes

0_1^+ normal oblate configuration

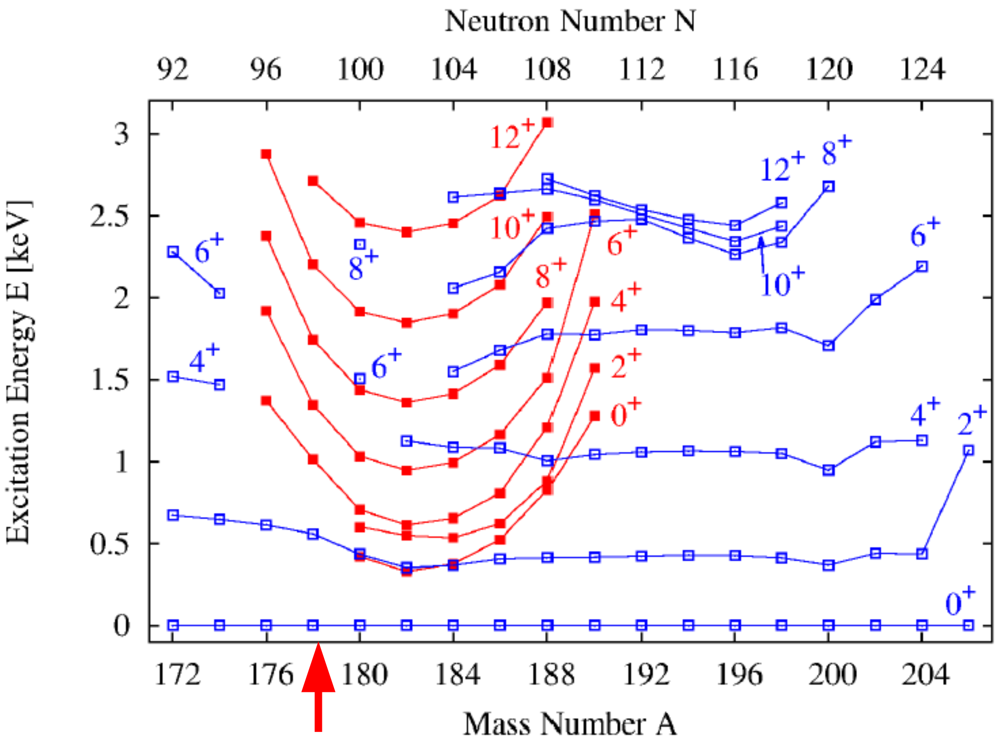
2_1^+ strongly mixed in ^{182}Hg: 50% of each configuration
^{186}Hg: nearly pure normal configuration

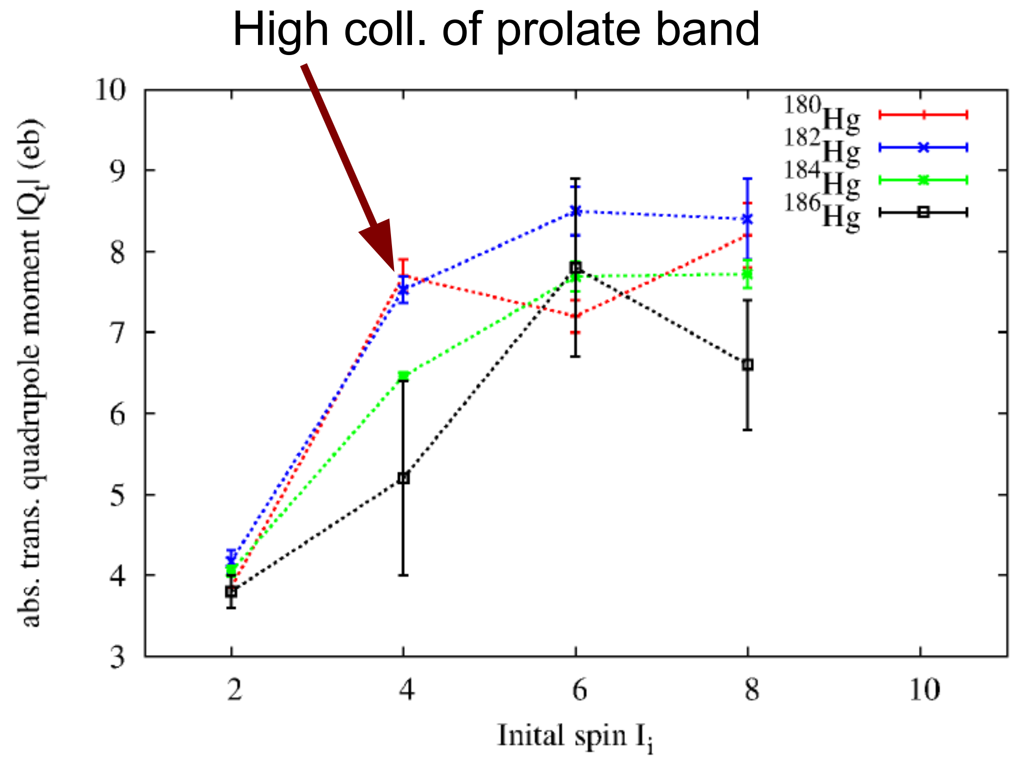
4_1^+ etc.: mainly prolate intruder configuration

L. Gaffney, M. Hackstein et al., PRC 89, 024307 (14)
Also confirmed in N. Bree et al., PRL 112, 162701 (14):
IBM based model, beyond mean field, two-state mixing

→ consistent with beyond mean field calculations
J.M. Yao, M. Bender, P.-H. Heenen, PRC 87, 034322 (12)

New experiments of our group: 1. Shape coexistence in ^{178}Hg



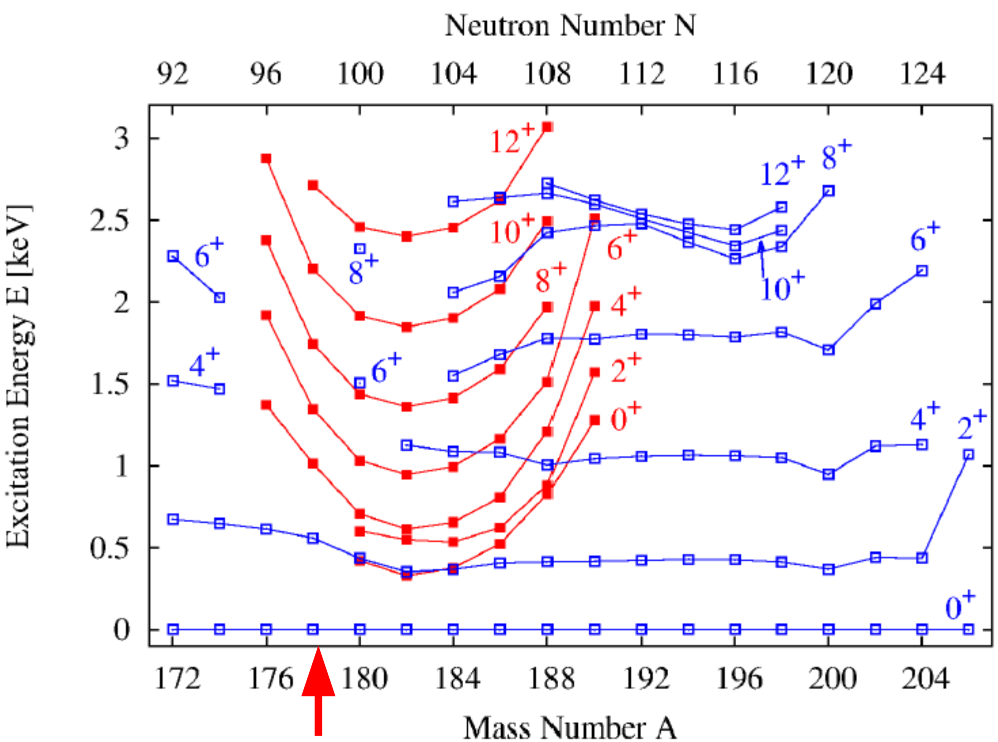


^{180,182}Hg: yrast E2 transition strengths from plunger exp. at JYFL using alpha-decay tagging (T. Grahn et al., PRC 80, 014324 (09))

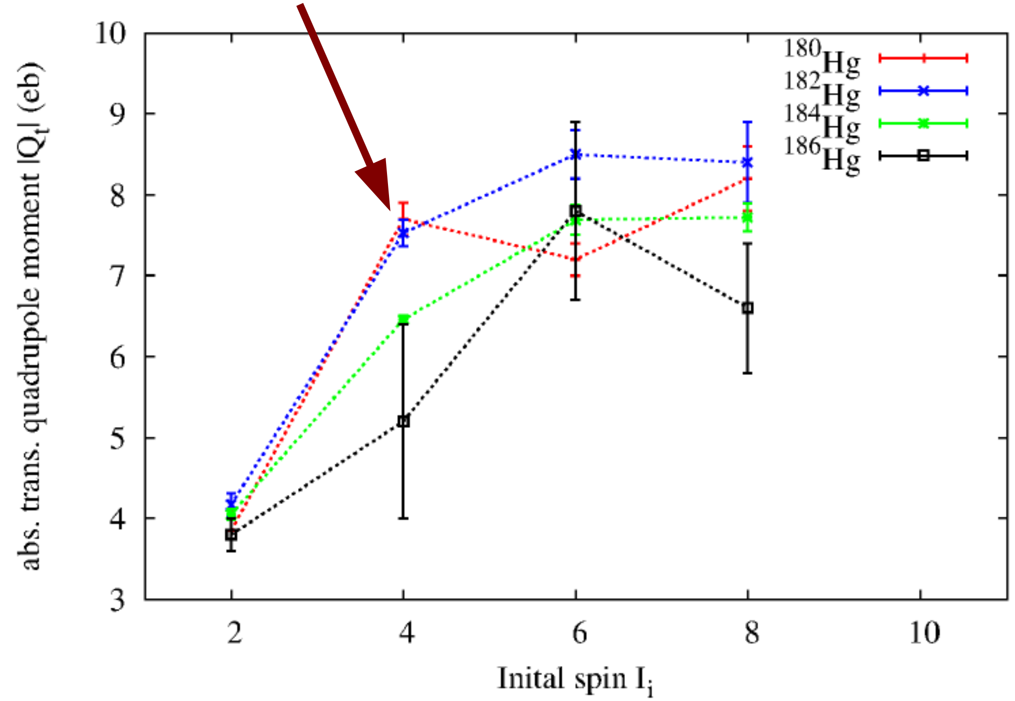
→ 2_1^+ exhibit strong admixture of coexisting prolate and oblate structures

→ drop of Q_t of $2_1^+ \rightarrow 0_1^+$ as compared to $4_1^+ \rightarrow 2_1^+$ by factor of 2: weaker deformed oblate character of ground states.

New experiments of our group:
1. Shape coexistence in ^{178}Hg



High coll. of prolate band

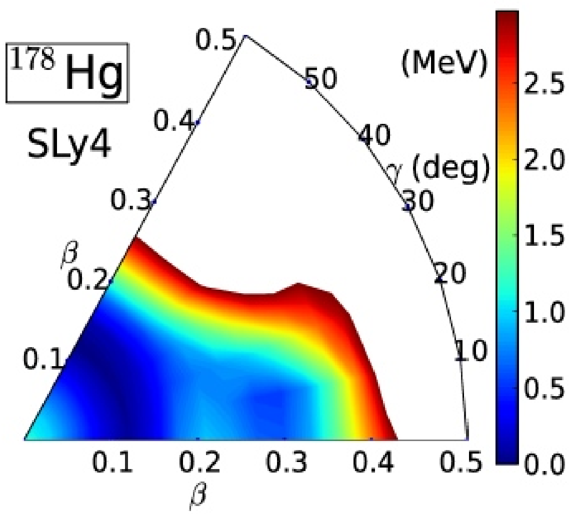


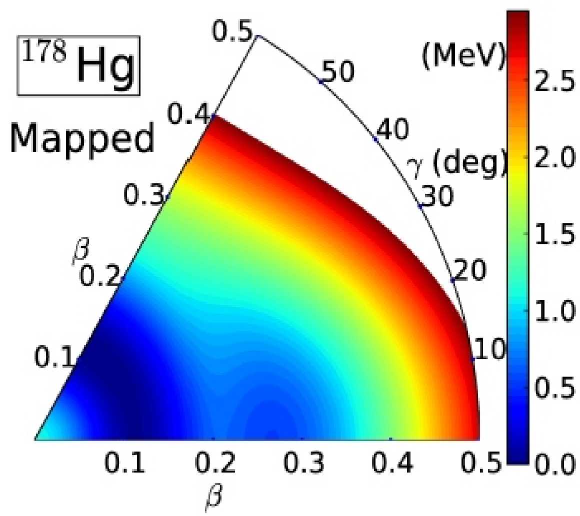
^{178}Hg: no data on E2 transition strengths:

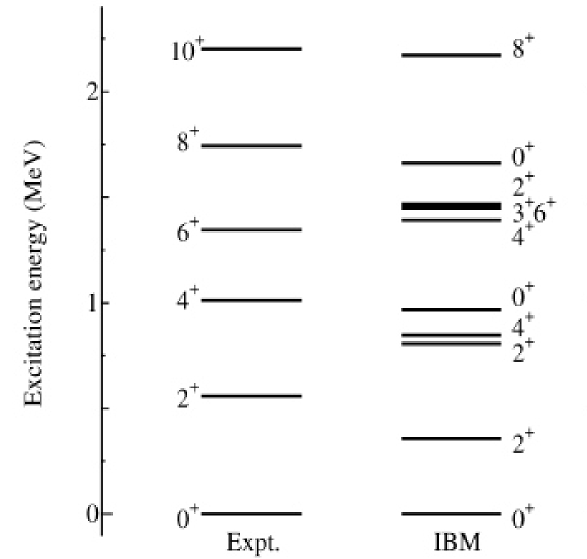
1. does parabolic trend continue?
2. understand increase of $E(2_1^+)$
3. assumption: transition towards near-spherical ground state
   M. Sandzelius et al., PRC 79, 064315 (09)

New experiments of our group: 1. Shape coexistence in ^{178}Hg

Theoretical approach (K. Nomura):
mapping PES of mean-field model onto PES of IBM
→ successful for shape coexistence in n-deficient Pb isotopes
→ applied for ^{178}Hg:





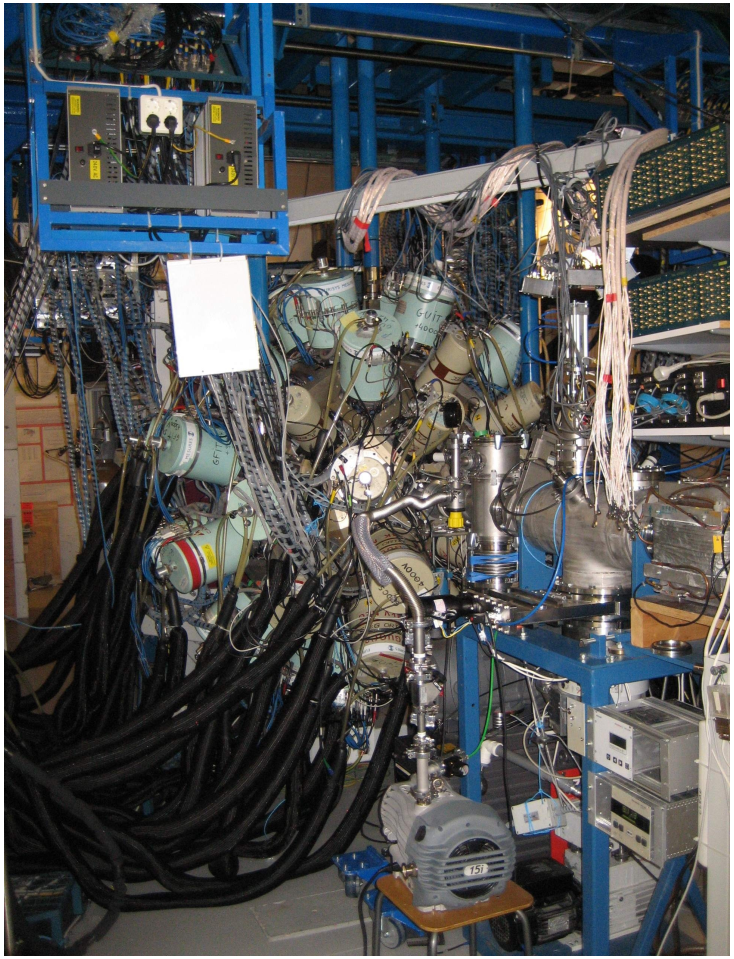


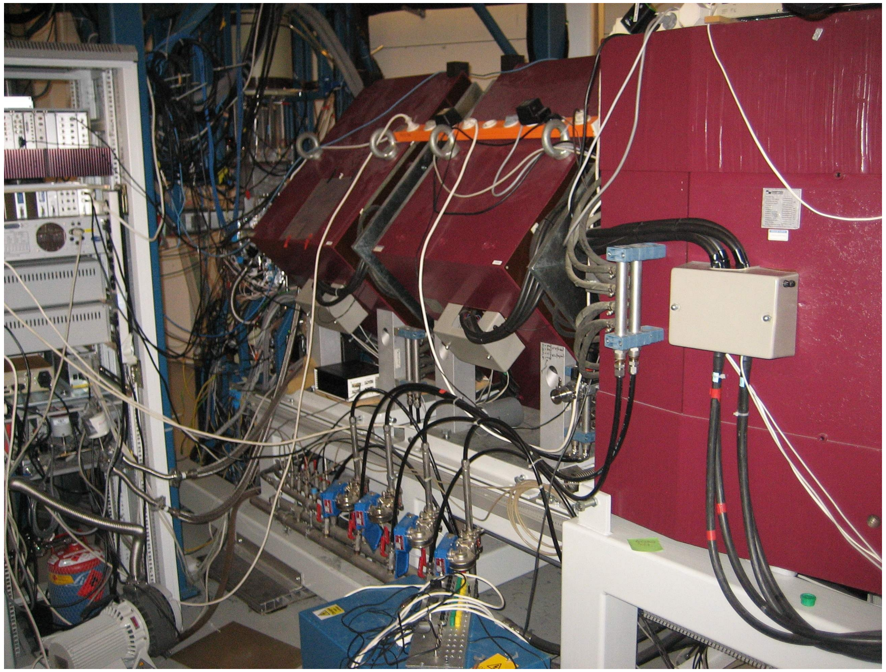
→ 0_2^+ (2p,2h) configuration, prolate def.
→ lowest yrast states: normal oblate / gamma-soft configuration

Measure yrast E2 transition strengths!

New experiments of our group:
1. Shape coexistence in ^{178}Hg

Experiment 07/2014 at JYFL: JUROGAM + DPUNS Plunger + RITU + α-decay tagging
^{103}Rh(^{78}Kr,p2n)^{178}Hg @ 351.5 MeV
Implantation rate GREAT ^{178}Hg: 0.35 /s
σ(^{178}Hg) = 50 μbarn (Argonne)





RITU + GREAT

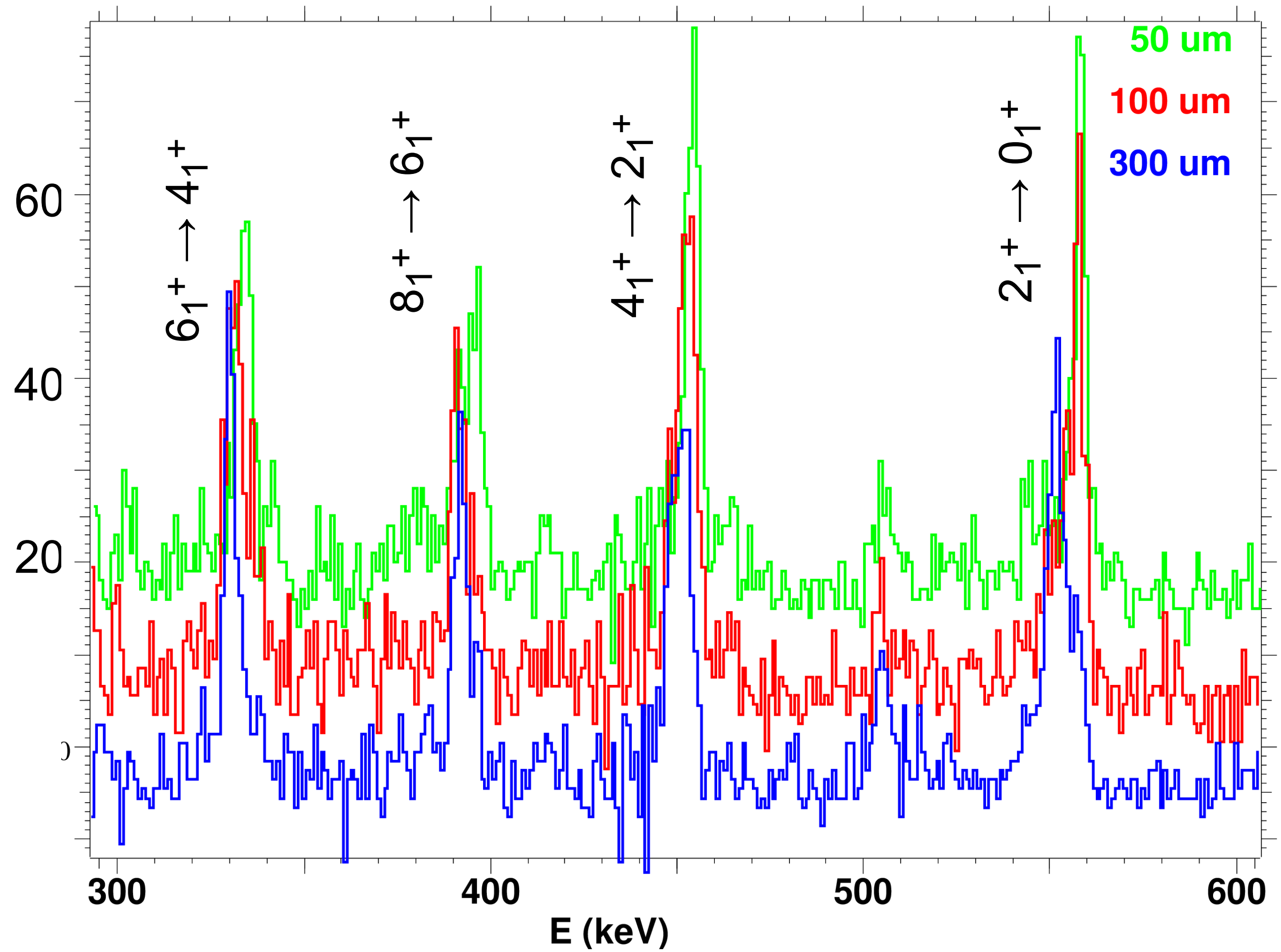
JUROGAM II + DPUNS Plunger

New experiments of our group:
1. Shape coexistence in ^{178}Hg

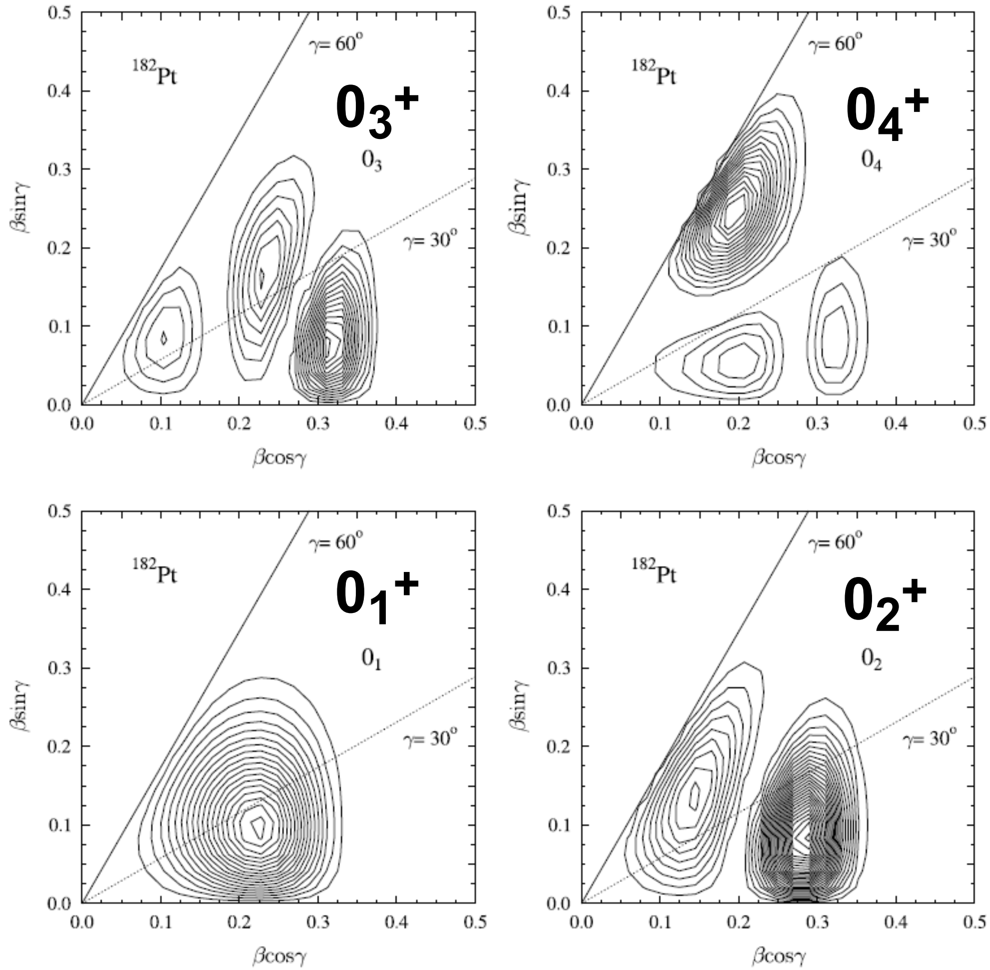
Experiment 07/2014 at JYFL: JUROGAM + DPUNS Plunger + RITU + α-decay tagging
^{103}Rh(^{78}Kr,p2n)^{178}Hg @ 351.5 MeV
Implantation rate GREAT ^{178}Hg: 0.35 /s

α-tagged spectrum ^{178}Hg

→ data analysis
under work...



New experiments of our group:
2. Shape coexistence in ^{180}Pt



GCM calculations for ^{182}Pt
K.A. Gladnishki, NPA 877, 19 (12)

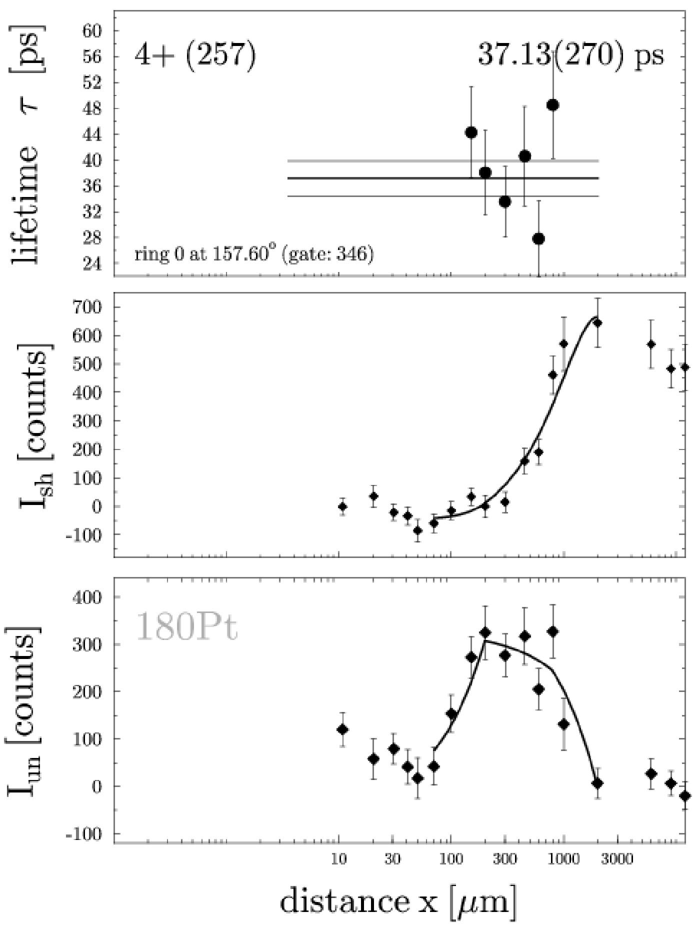
→ **Plunger experiment at JYFL:**
Cologne Plunger + JUROGAM II
^{98}Mo(^{86}Kr,4n)^{180}Pt @ 364 MeV
→ lifetimes of 4_1^+, 6_1^+, 8_1^+

→ **fast timing experiment at IKP Cologne**
HORUS spectrometer with 6 $LaBr_3$(Ce) detectors with BGO shields,
8 HPGe detectors
^{168}Yb(^{16}O,4n)^{180}Pt @ 88 MeV
->lifetimes of 2_1^+, 4_1^+

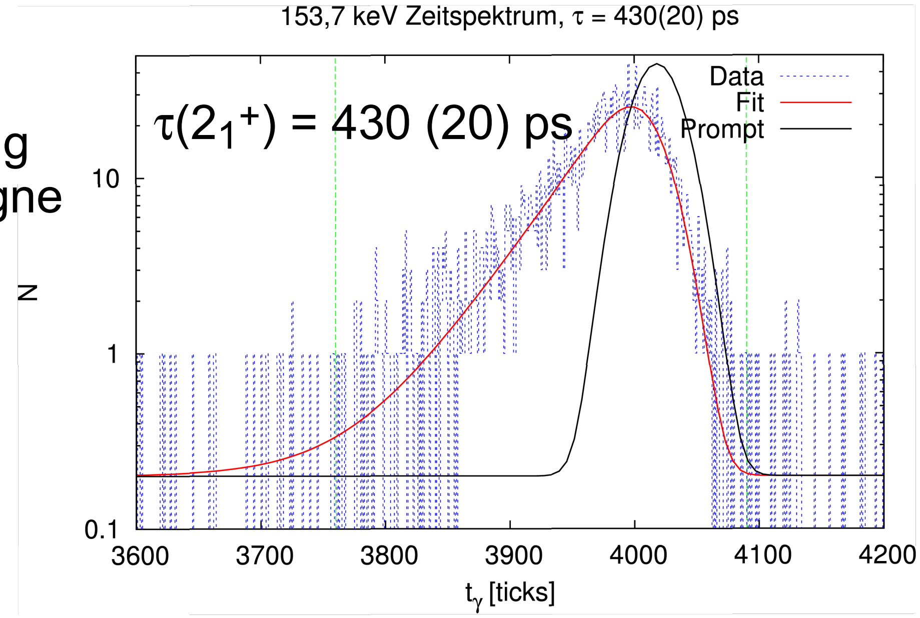
New experiments of our group:
2. Shape coexistence in ^{180}Pt

Preliminary results
C. Müller-Gatermann

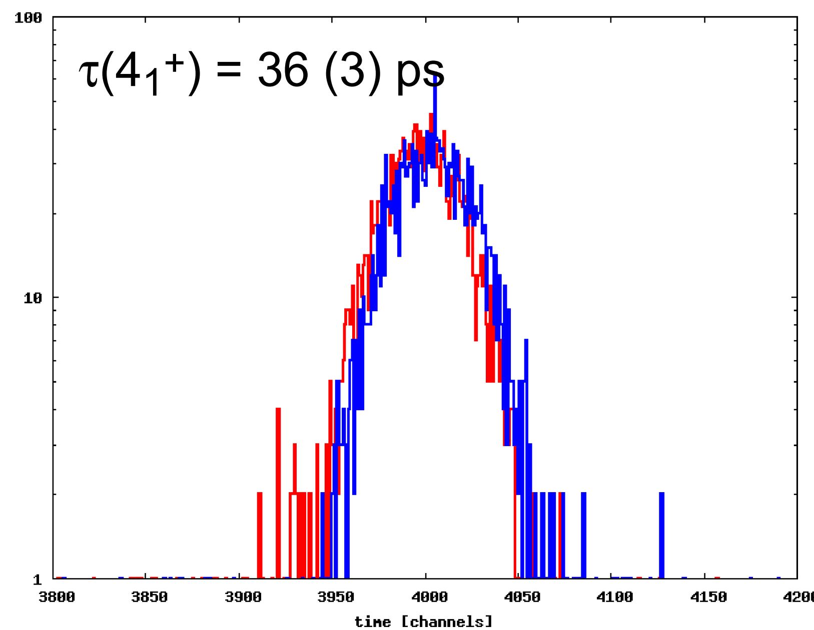
Plunger experiment JYFL
$\tau(4_1^+)$ = 37.1 (27) ps



Fast timing
IKP Cologne



GCD
method



Outline

1. Introduction

2. The plunger technique

3. Other lifetime techniques used by our group:
   a. Fast timing
   b. Doppler-shift attenuation method

4. Shape coexistence in neutron deficient Hg isotopes

5. Critical point symmtries in the A=180 mass region

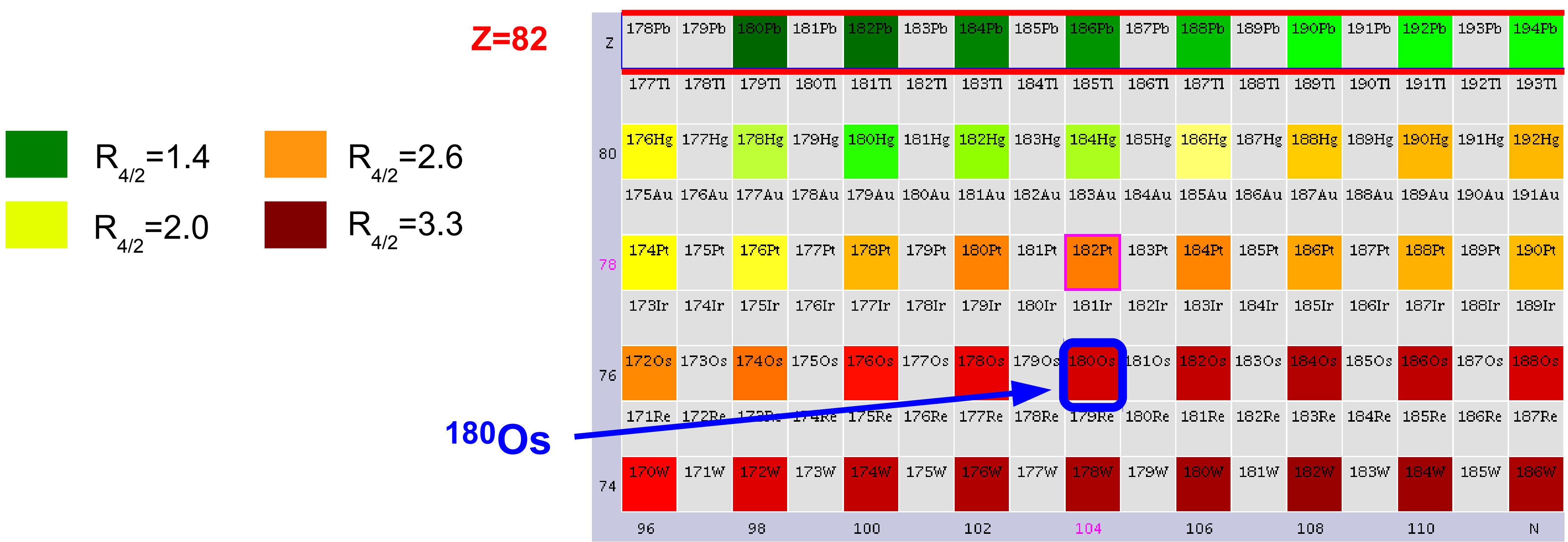
6. Search for isovector excitations in the vicinity of ^{208}Pb

Motivation: critical point symmetries in A=180 region?

→ ^{176,178}Os: candidates for nuclei at critical point of spherical – rotor shape phase transition
A. Dewald et al., J. Phys. G 31, S1427 (05)

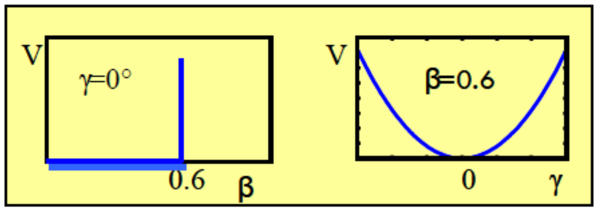
→ other approaches: - IBM
- GCM
→ Prediction of an oblate-prolate shape coexistence

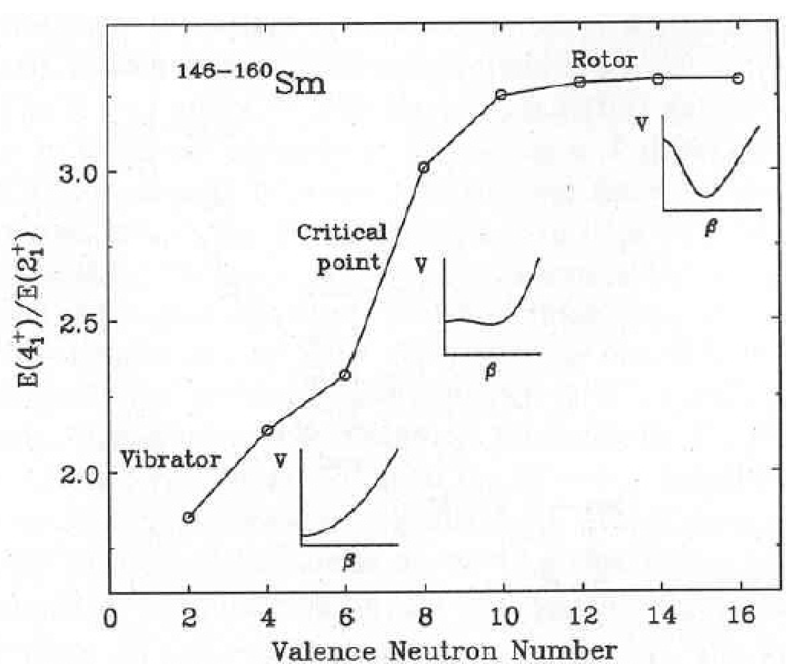
→ measure precisely yrast B(E2) values in ^{180}Os for the first time

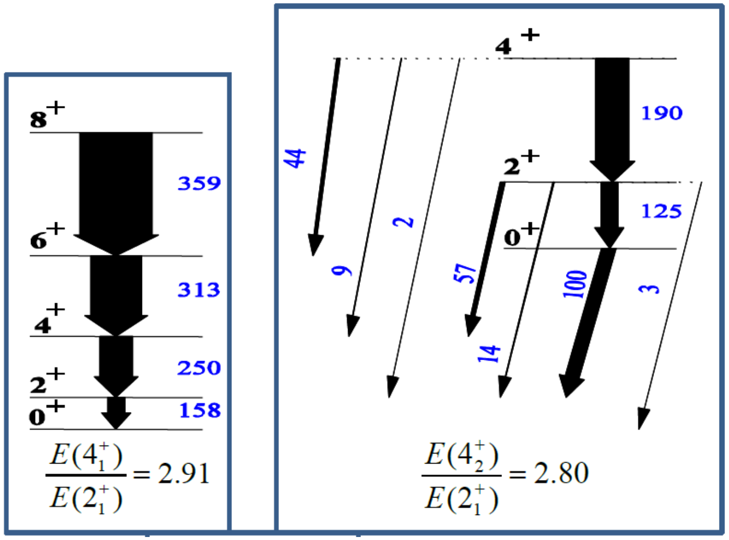


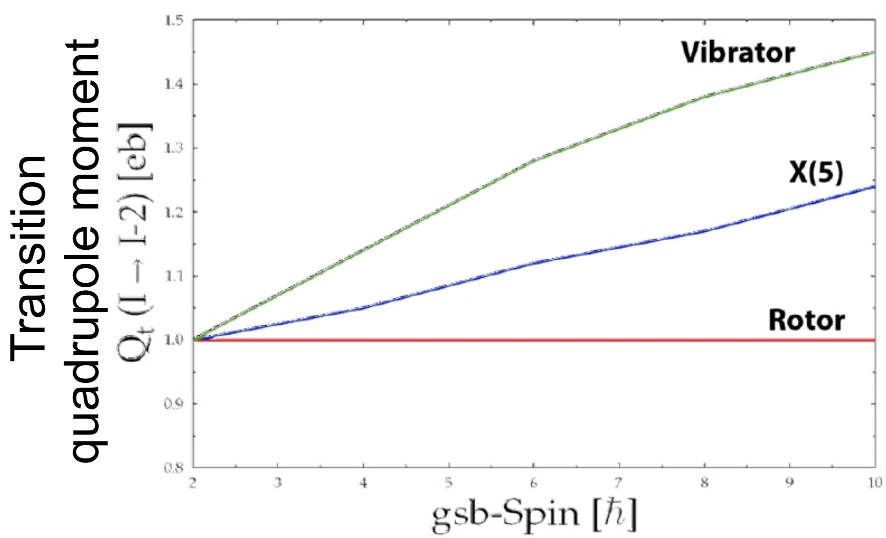
Motivation: X(5)

- F. Iachello, Phys. Rev. Lett. 87, 052502 (2001)
- X(5): critical point of the spherical – rotor shape phase transition
- Analytic solution of Bohr hamiltonian with square well potential for β
- Experimental signatures: **E2 strengths, level scheme**

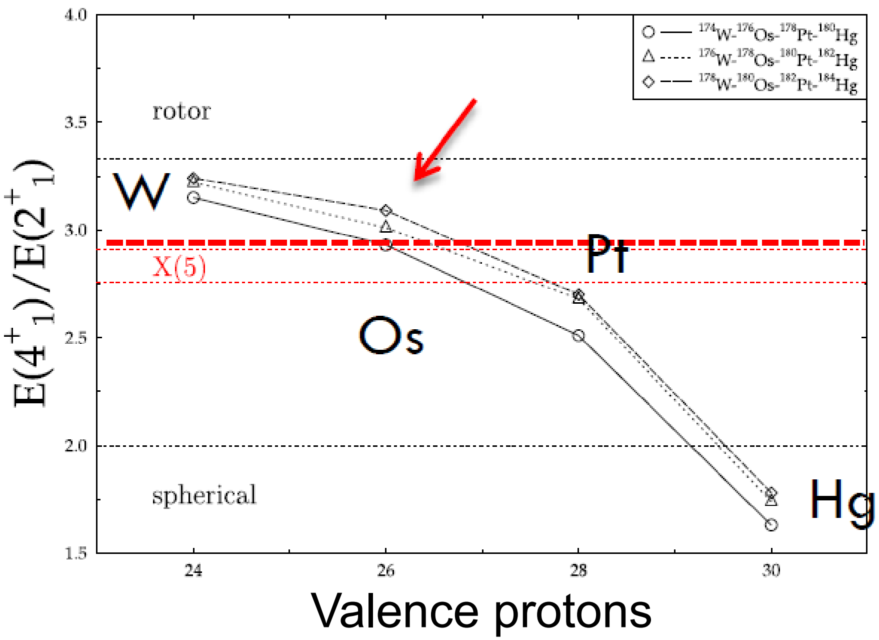


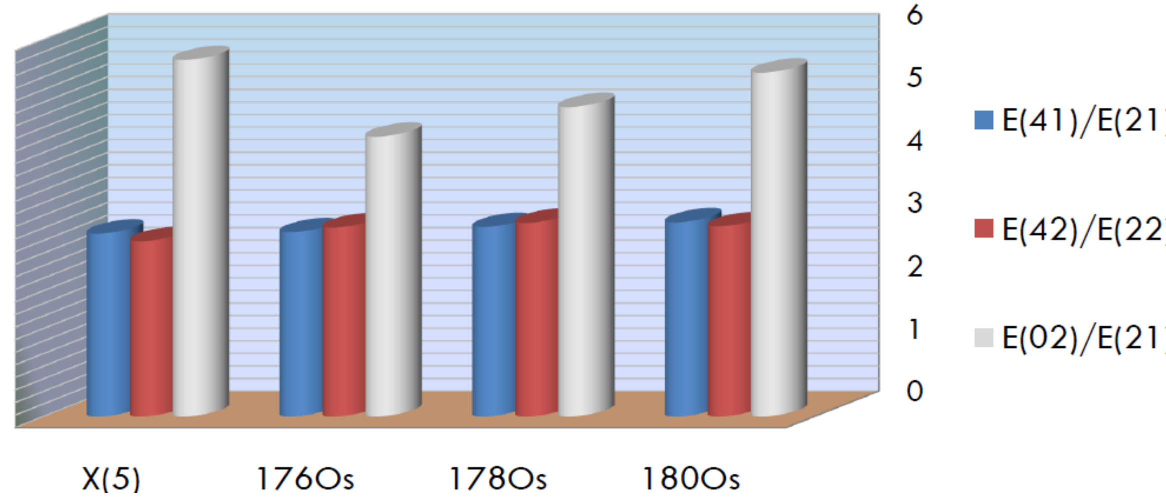




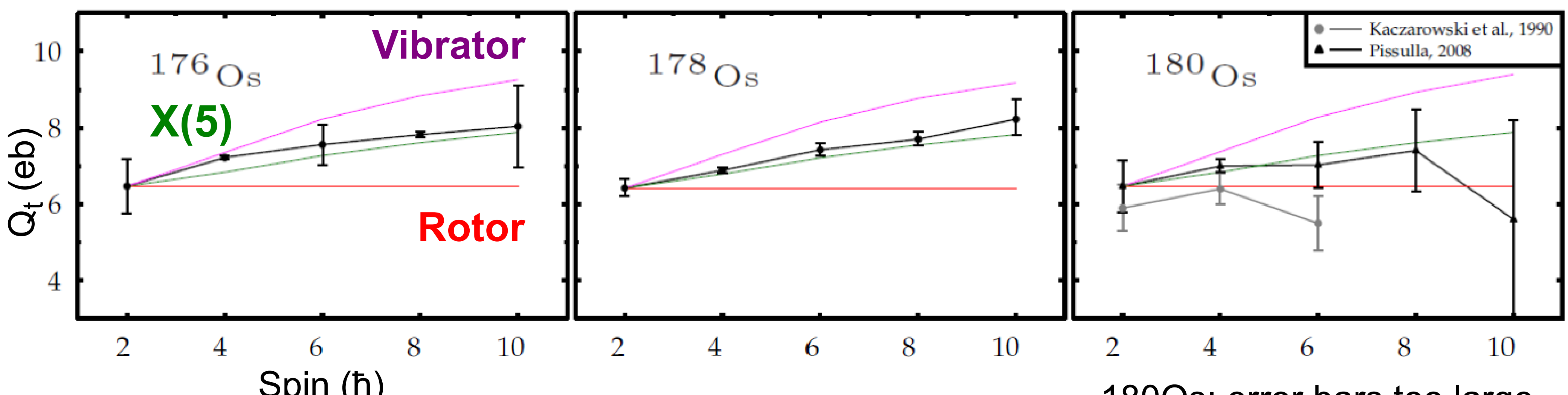


X(5) properties in A=180 region





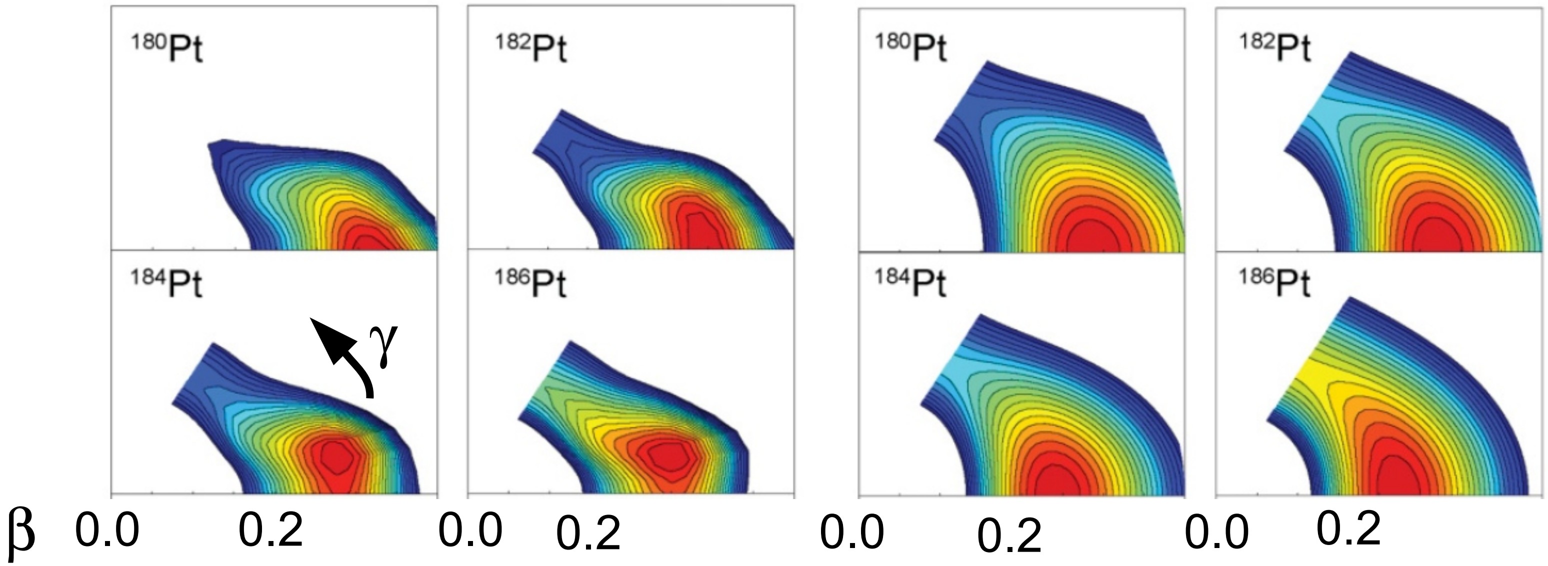
Transition quadrupol moments in yrast band:



→ 180Os: error bars too large.

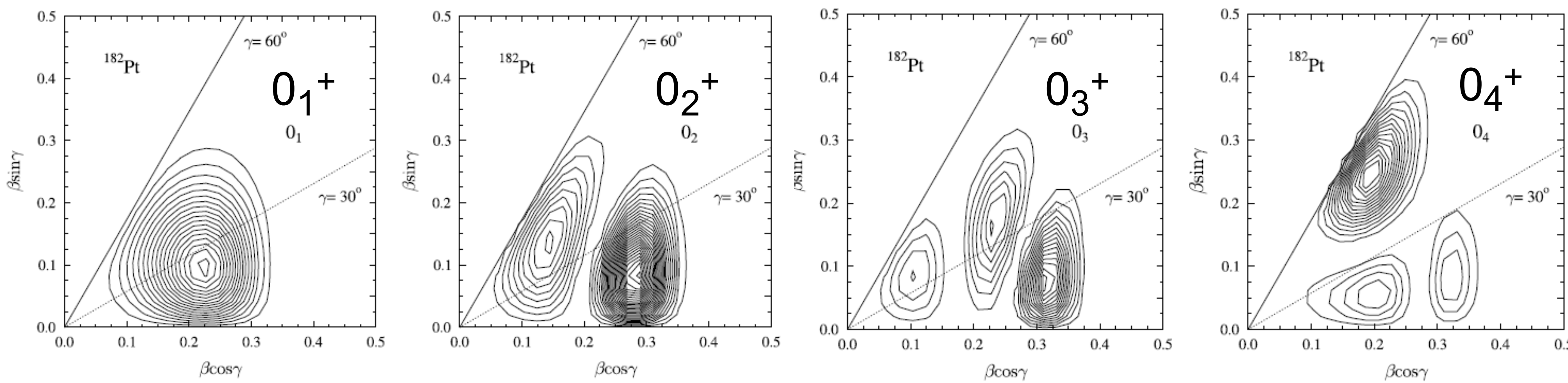
Oblate-prolate shape coexistence around ^{180}Os?

Potental Energy Surfaces (HFB) Potental Energy Surfaces (IBM)



$^{180-186}$Pt:
prolate minimum,
oblate saddle point
K. Nomura et al.,
PRC 83, 014309 (2011)

General collective model: PES for 0_1^+ - 0_4^+ states in ^{182}Pt: multi component structure
0_4^+ nearly oblate (K. Gladnishki et al., NPA 877, 19 (2012)) → ^{180}Os?



Experiment an ^{180}Os

Cologne plunger at GASP-II, INFN, Legnaro

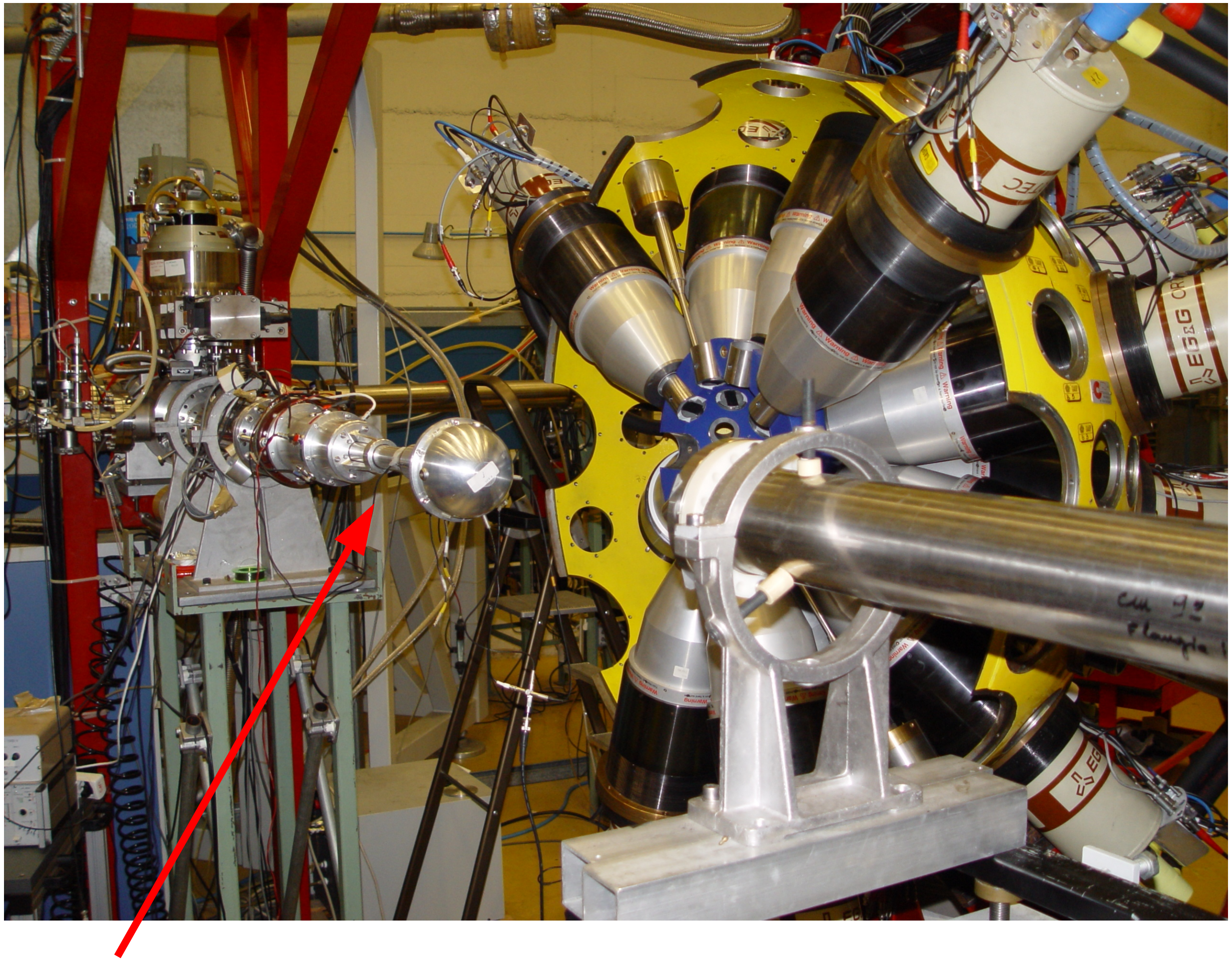
Reaction: ^{150}Nd(^{36}S,6n)^{180}Os
^{150}Nd(^{36}S,5n)^{181}Os

Beam E(^{36}S)=185 MeV

Target: 2 mg/cm^2 ^{150}Nd
on 2.2 mg/cm^2 Ta
Stopper: 10.7 mg/cm2 Au

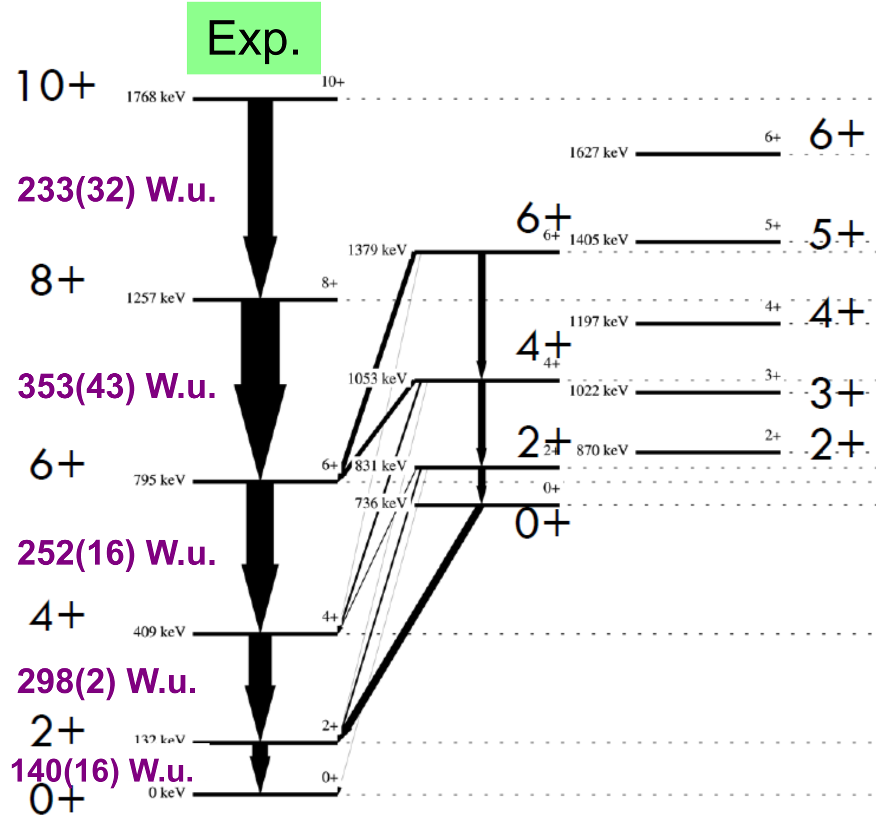
v/c = 1.78(4) %

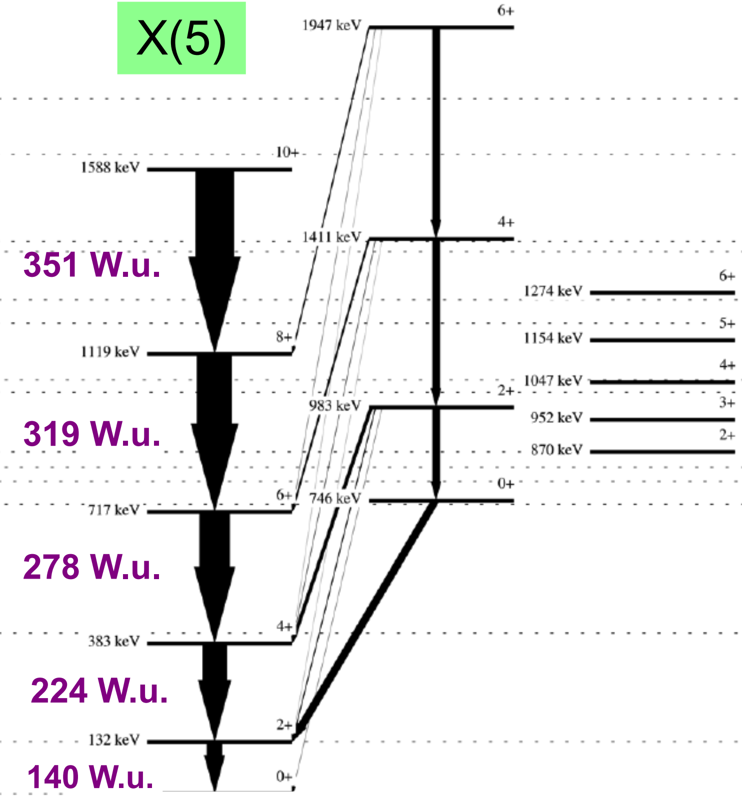
Lifetimes of yrast states up to 16_1^+
7 lifetimes of negative parity states

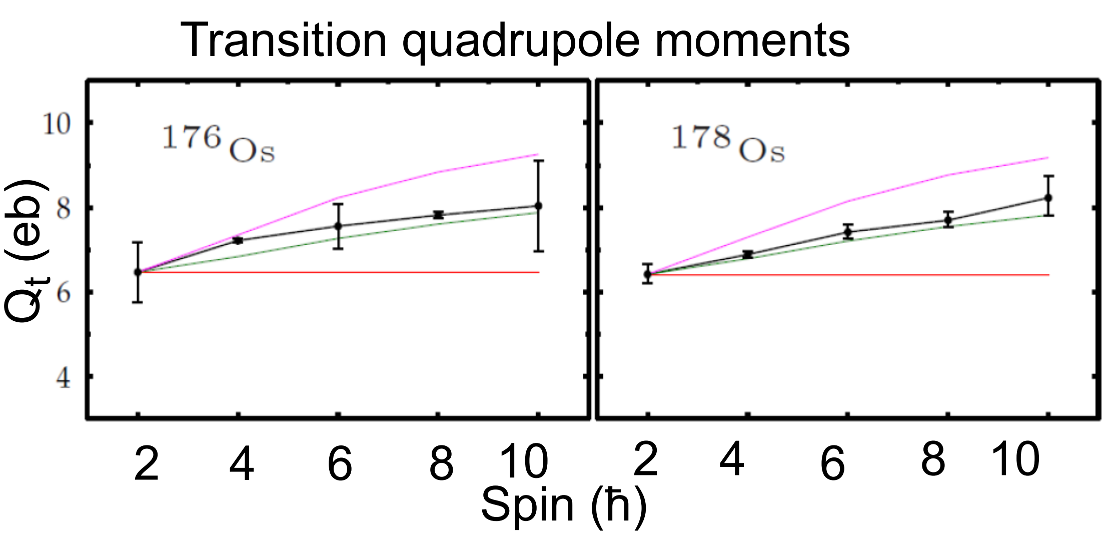


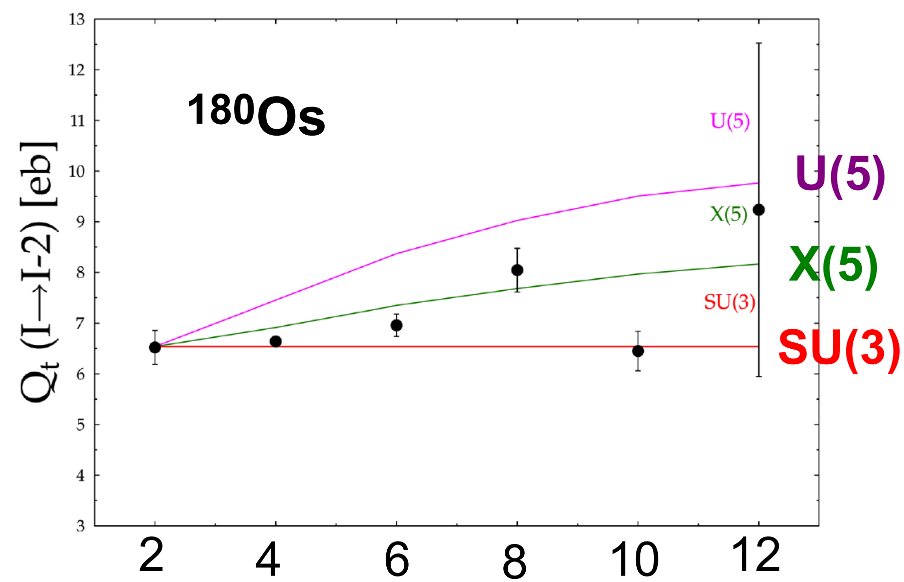
Cologne plunger

^{180}Os: X(5) properties?







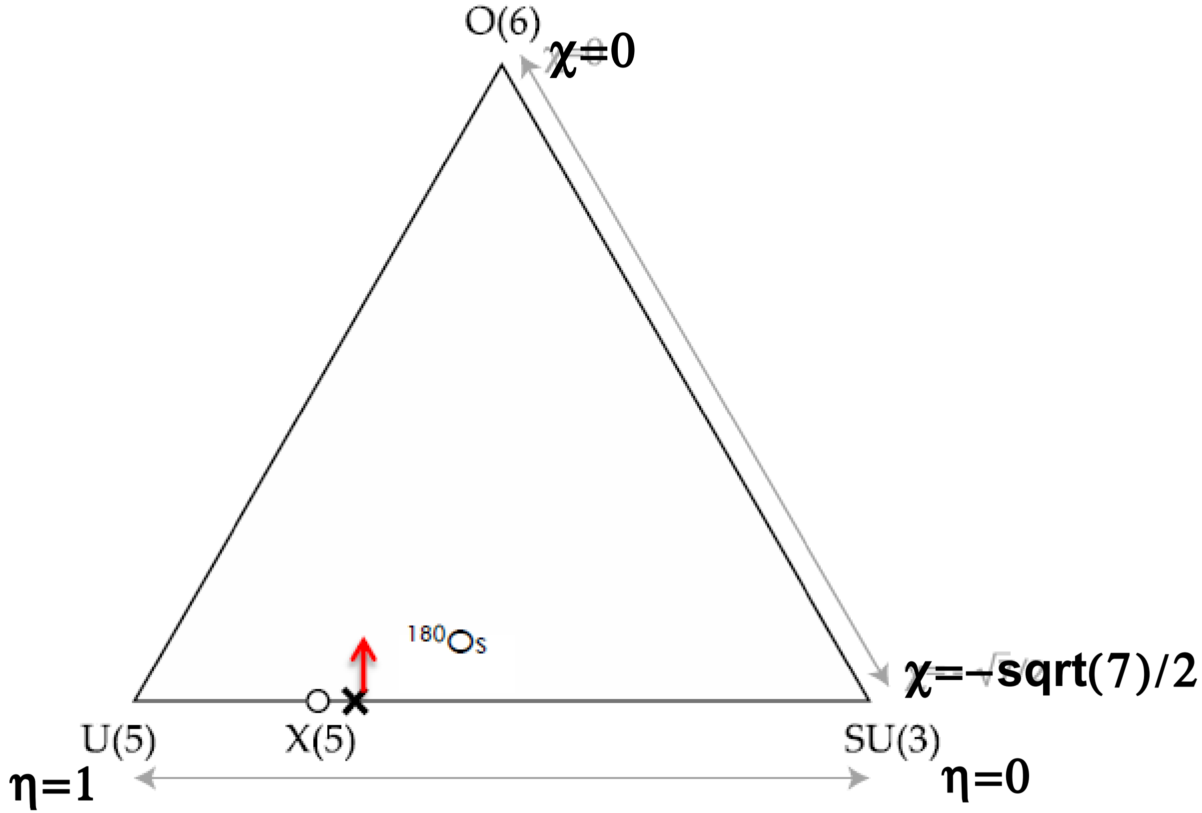


^{180}Os in the IBM

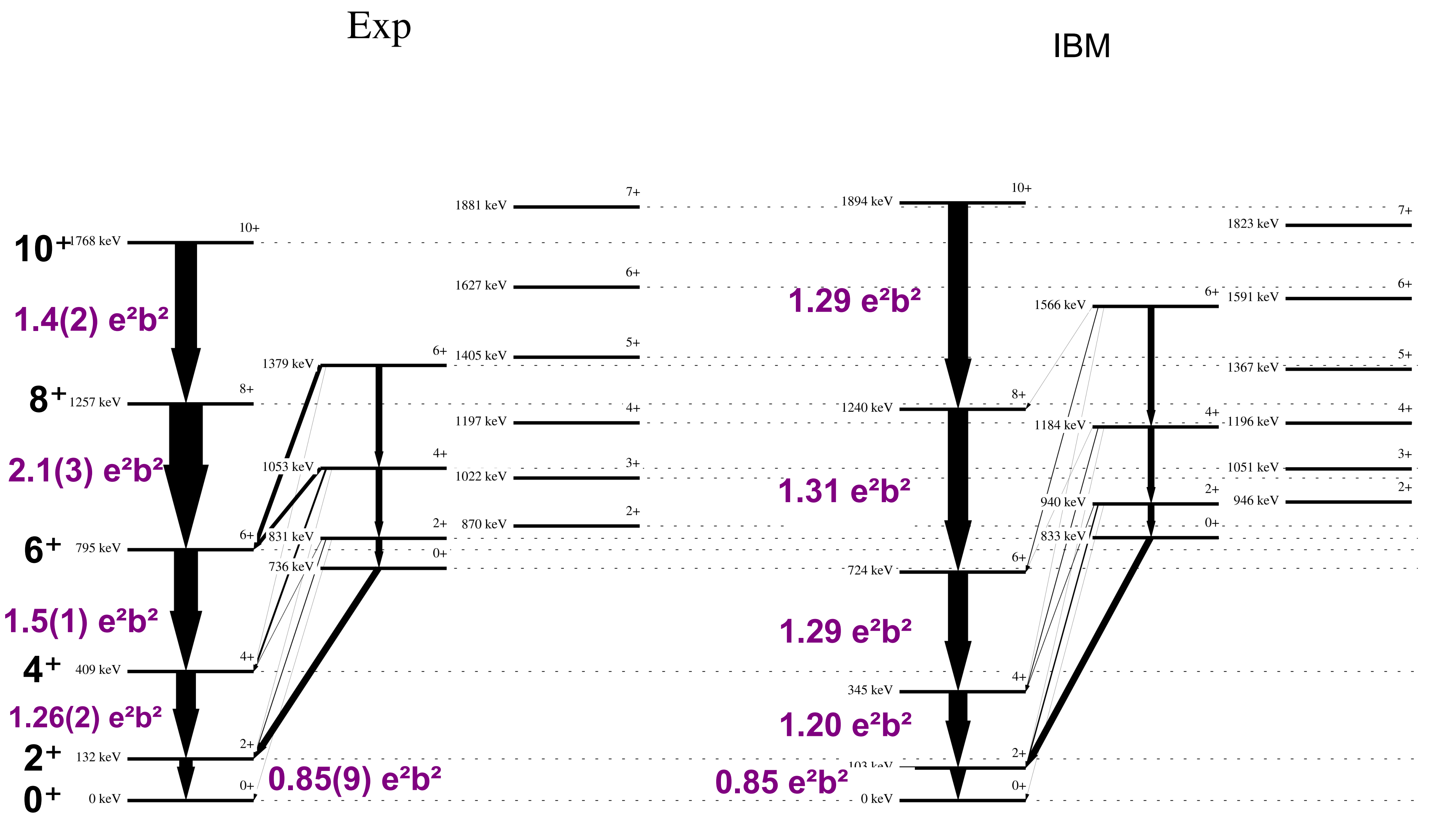
→ Fit in IBM in transition U(5) – SU(3) (χ = -sqrt(7)/2):
No sufficient description of interband transition strength ratios
$I_\beta \rightarrow I_g$, $I_\beta \rightarrow (I+2)_g$

→ use O(6) admixture, i.e., χ > -sqrt(7)/2
vary η, χ for best reproduction of relative yrast B(E2) values

$$H = \varepsilon C_1[U(5)] + \delta C_2[SU(3)] + \gamma C_2[O(3)] + \alpha C_2[O(6)]$$



^{180}Os in the IBM



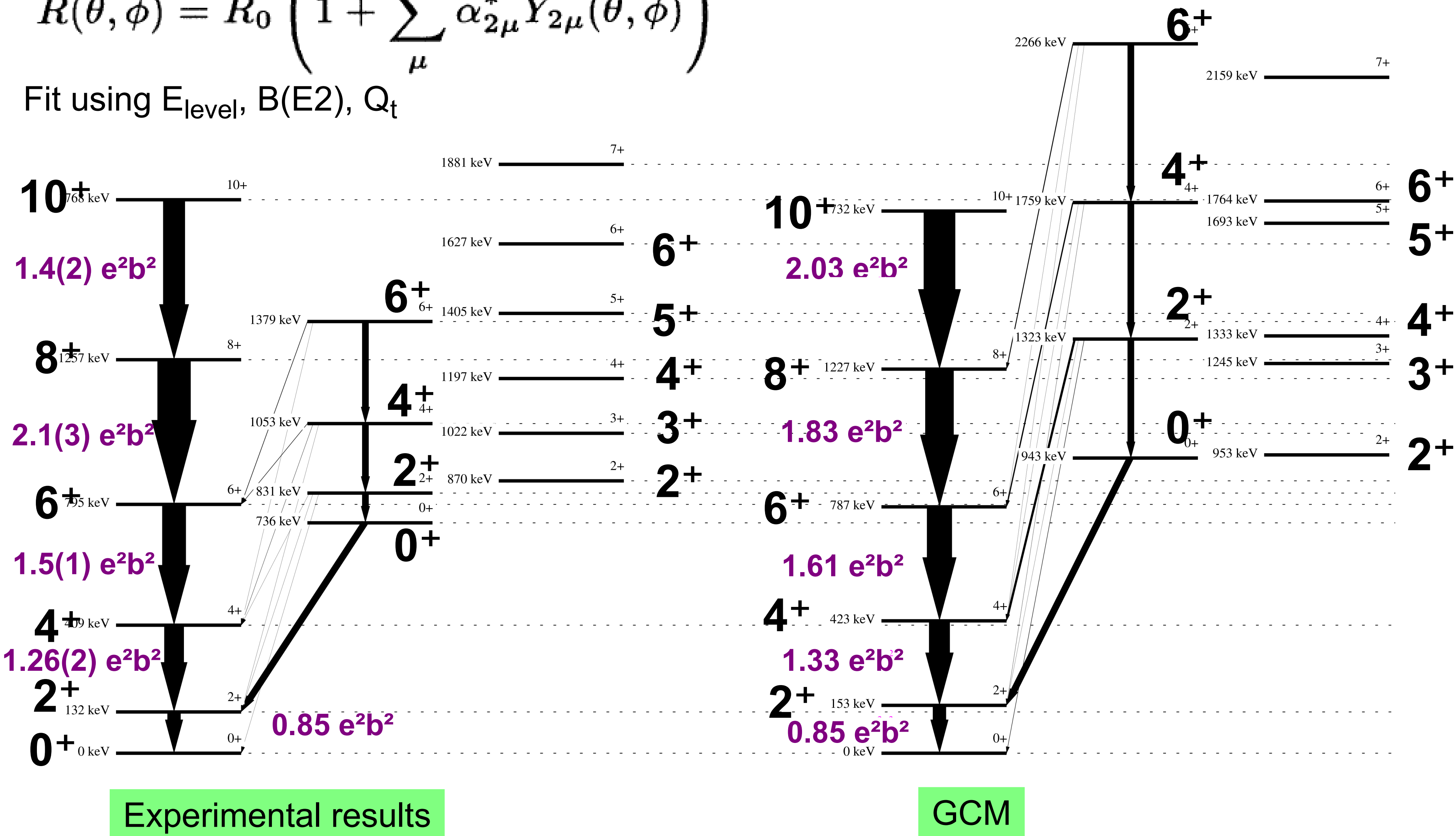
IBM in transition U(5) – SU(3) with small O(6) contribution: good description of exp. data

^{180}Os in the General Collective Model (P. Petkov)

GCM: Quadrupole surface oscillations

$$R(\theta,\phi) = R_0 \left(1 + \sum_{\mu} \alpha^*_{2\mu} Y_{2\mu}(\theta,\phi)\right)$$

Fit using E_{level}, B(E2), Q_t



Results ^{180}Os

- Lower yrast states can be described with X(5)
- IBM in transition U(5) – SU(3) with small O(6) admixture results in reasonable decription
- GCM describes yrast states well.
  Predictions of GCM hint for shape shase coexistence,
  e.g. prediction of gamma-soft 0_3^+ (not observed)
  0_2^+ prolate def.

Outline

1. Introduction

2. The plunger technique

3. Other lifetime techniques used by our group:
   a. Fast timing
   b. Doppler-shift attenuation method

4. Shape coexistence in neutron deficient Hg isotopes

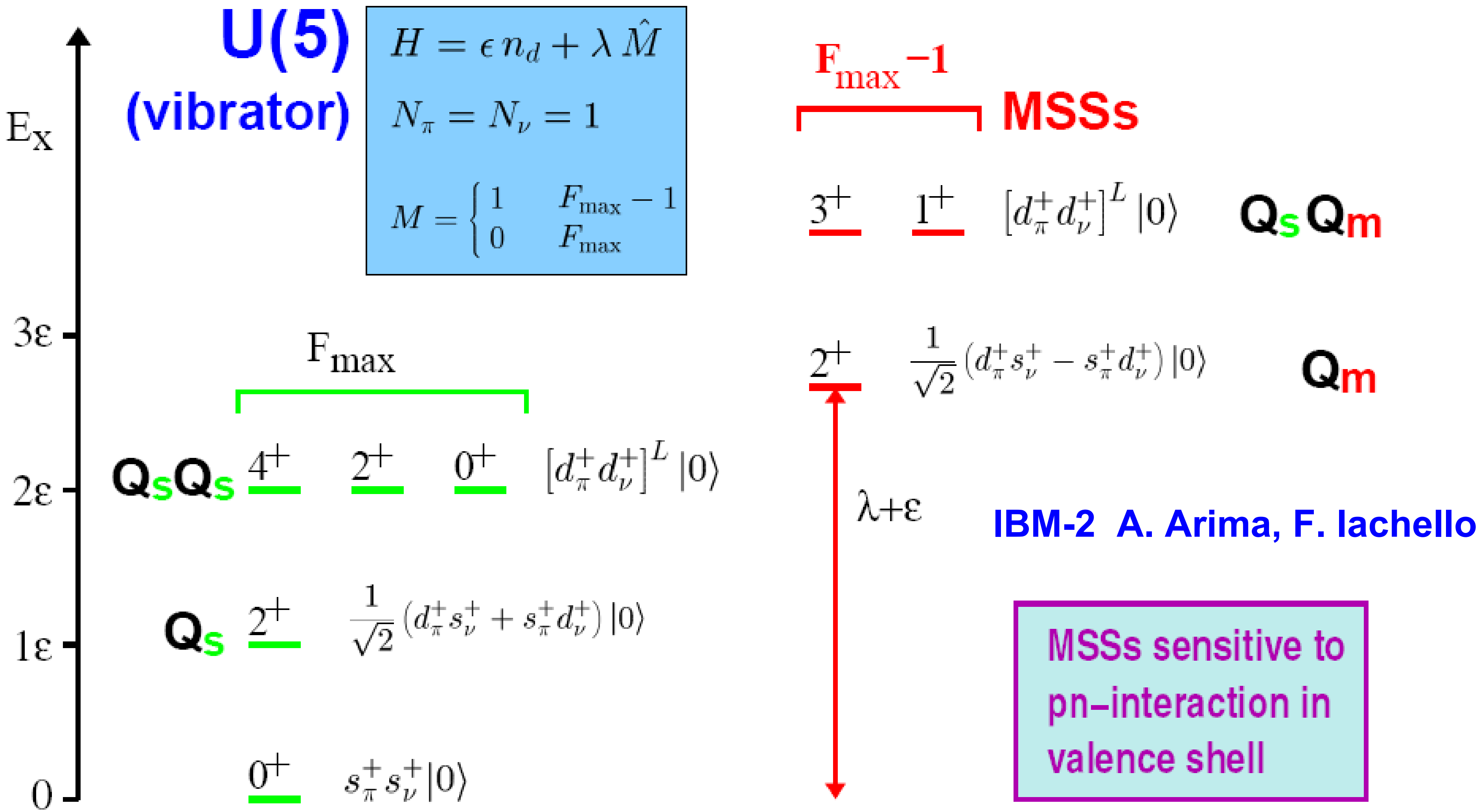
5. Critical point symmtries in the A=180 mass region

6. Search for isovector excitations in the vicinity of ^{208}Pb

Definition of mixed-symmetry states

One-phonon $2^+_{1,ms}$ fundamental quadrupole-collective isovector excitation in the valence shell for spherical vibrational nuclei

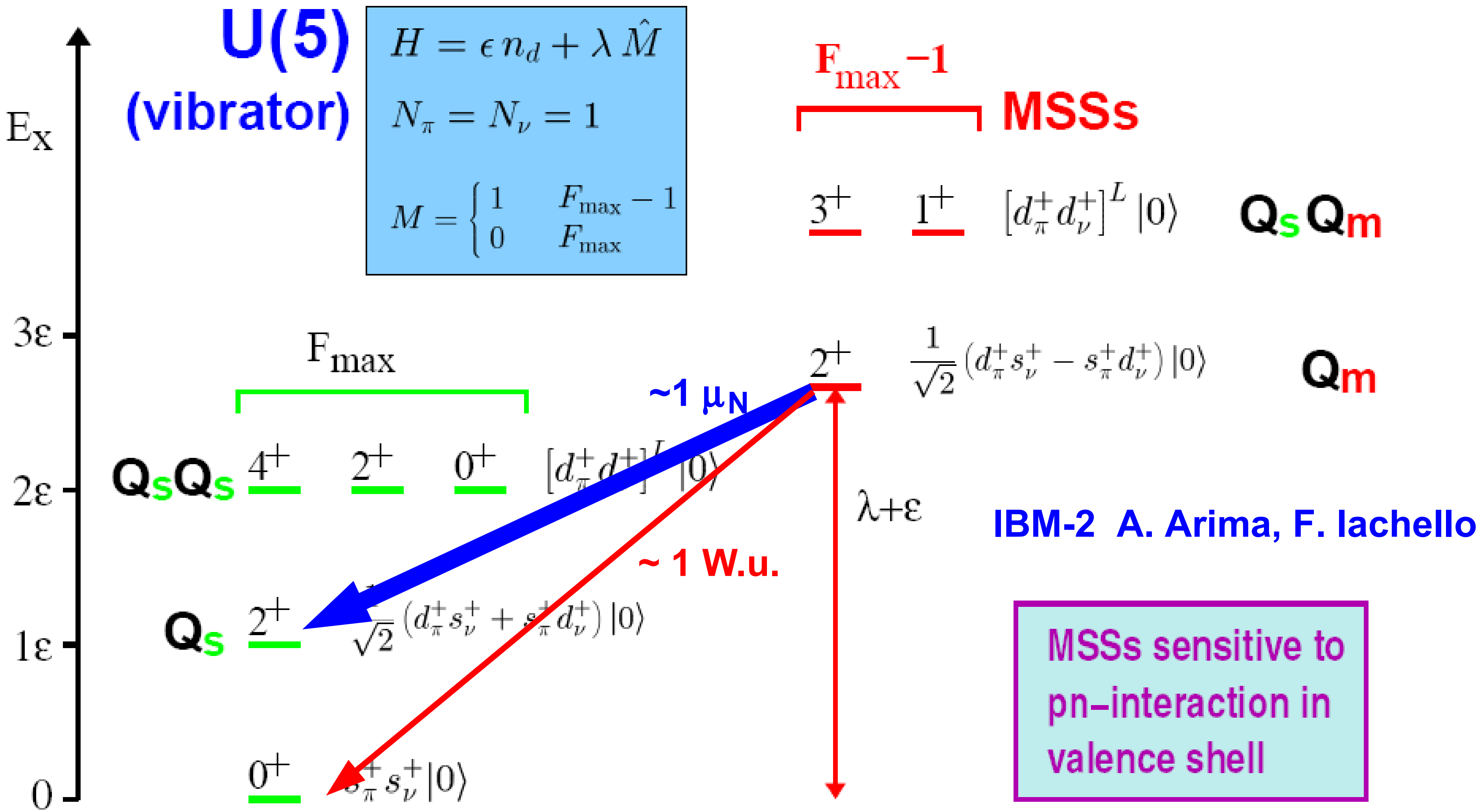
Simple Example: Harmonic Oscillator, N=2



Definition of mixed-symmetry states

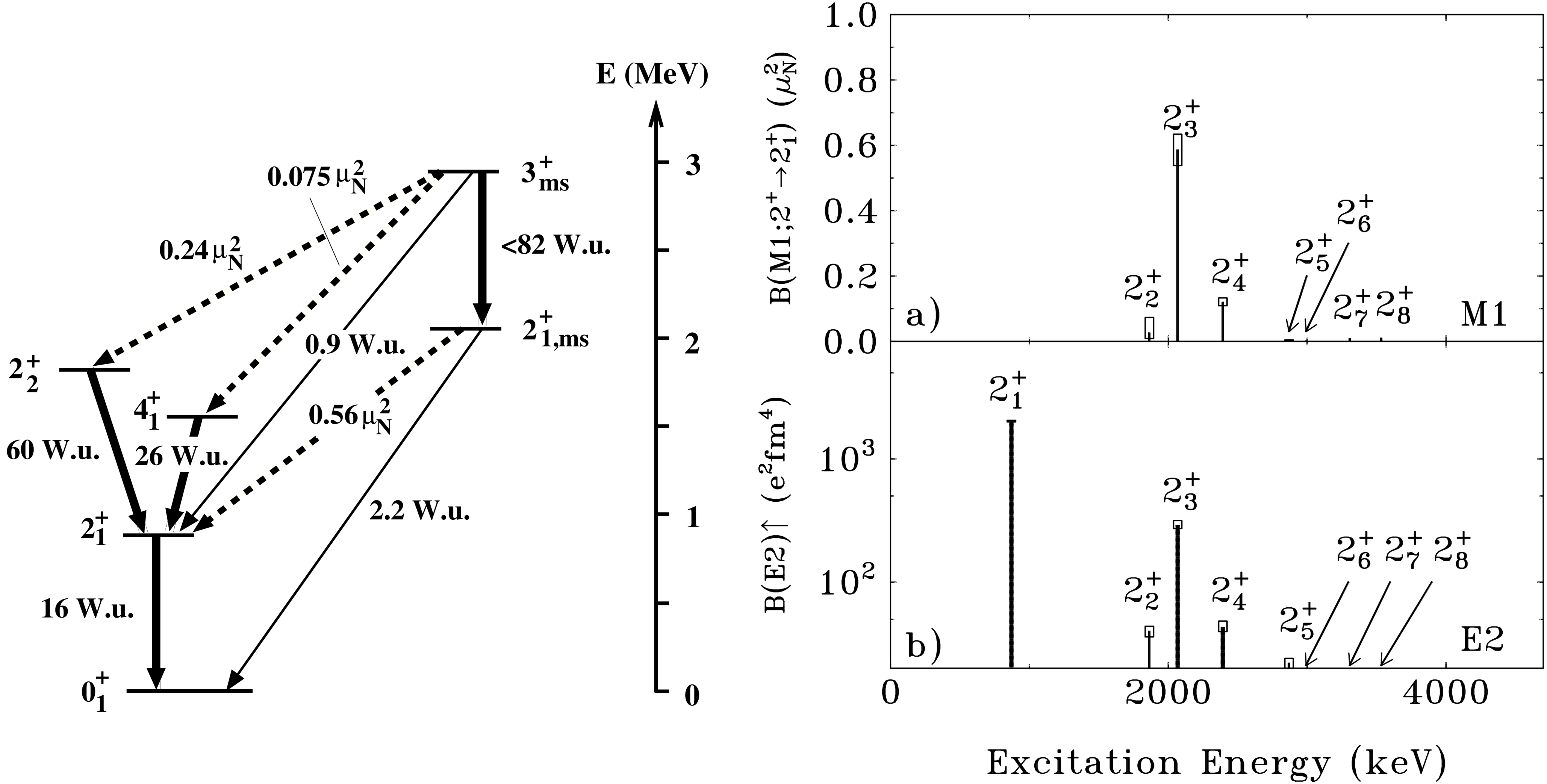
One-phonon $2^+_{1,ms}$ fundamental quadrupole-collective isovector excitation in the valence shell for spherical vibrational nuclei

Simple Example: Harmonic Oscillator, N=2



Best case so far: ^{94}Mo

94Mo (vibrator-like): $2_{1,ms}^{+}$ and nearly full multiplet of two-phonon MS states identified
C. Fransen et al. PRC 67, 024307 (03)



Do we expect similar isovector excitations in nuclei close to doubly-magic nuclei...?

Mixed-symmetry states in 208Pb region?

MSS in vibrator-like nuclei

A ≈ 90	A ≈ 130-140
^{94,96}Mo	^{132}Te
^{92}Zr	$^{128-134}$Xe
^{96}Ru	^{134}Ba
	$^{136-138}$Ce, ^{140}Ce
	^{140}Nd(?), ^{144}Nd

N. Pietralla, P. von Brentano, A.F. Lisetskiy, Prog. Part. Nucl. Phys. 60, 225 (2008).

Z	122	123	124	125	126	127	128	129	N
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%	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%
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%	213Bi 45.59 M β-: 97.80% α: 2.20%
82	204Pb ≥1.4E+17 Y 1.4% α	205Pb 1.73E+7 Y ε: 100.00%	206Pb STABLE 24.1%	207Pb STABLE 22.1%	208Pb STABLE 52.4%	209Pb 3.253 H β-: 100.00%	210Pb 22.20 Y β-: 100.00% α: 1.9E-6%	211Pb 36.1 M β-: 100.00%	212Pb 10.64 H β-: 100.00%
81	203Tl STABLE 29.524%	204Tl 3.783 Y β-: 97.08% ε: 2.92%	205Tl STABLE 70.48%	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%	203Hg 46.594 D β-: 100.00%	204Hg STABLE 6.87%	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-

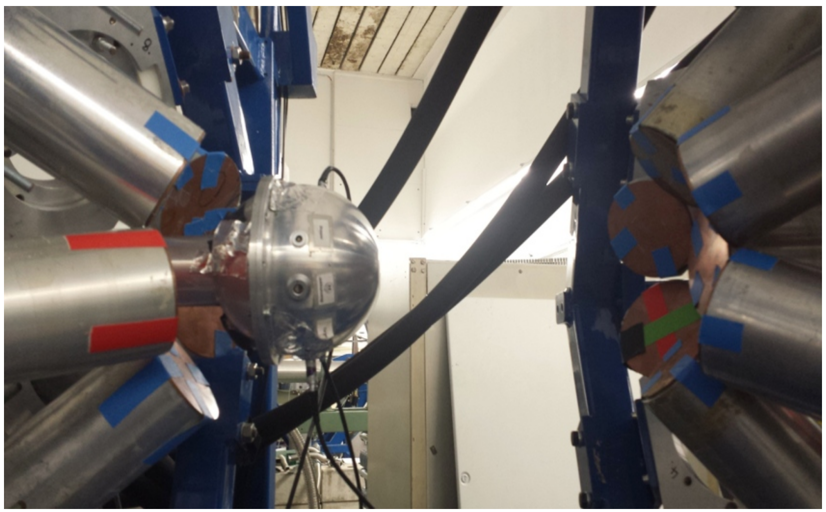
^{212}Po

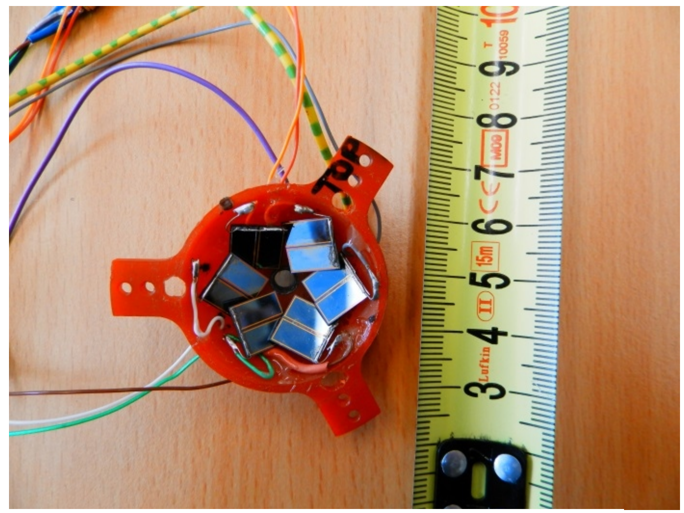
- Can we identify excited 2^+ states connected to the 2^+_1 state with strong M1 transitions?
- Can we interprete these states as MSSs?

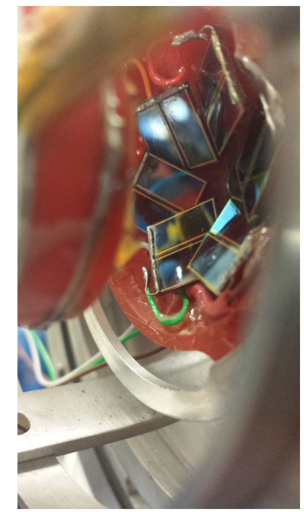
Experiment on ^{212}Po @ Cologne FN Tandem

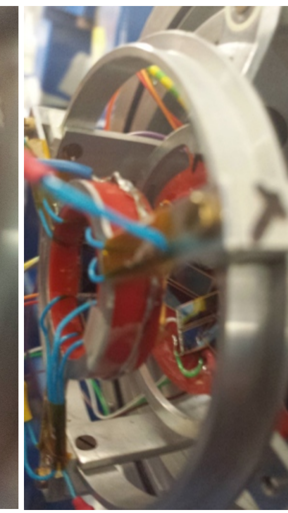
G. Rainovski, D. Kocheva, K. Gladnishki, M. Djongolov,
Sofia University, Bulgaria

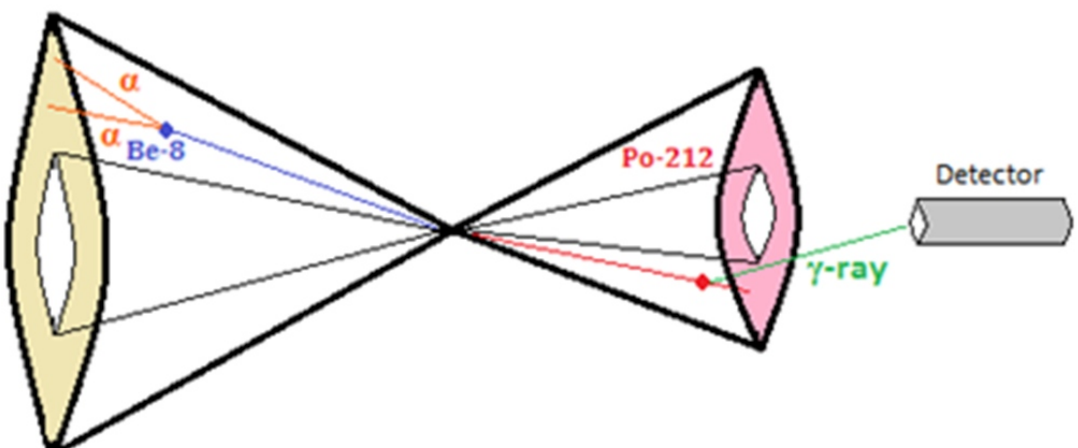
- Reaction ^{208}Pb(^{12}C,^{8}Be)^{212}Po @ 62 MeV ($V_{col} \approx$ 64 MeV), target 10 mg/cm^2 ^{208}Pb
  - 5 HPGe detectors at 142.3°, 6 HpGe at 35.0°, and 1 HPGe at 0°
  - array of 6 solar cells (10 mm × 10 mm), angular range 116.8° - 167.2°: trigger $\gamma-\alpha$ or $\gamma-\gamma$









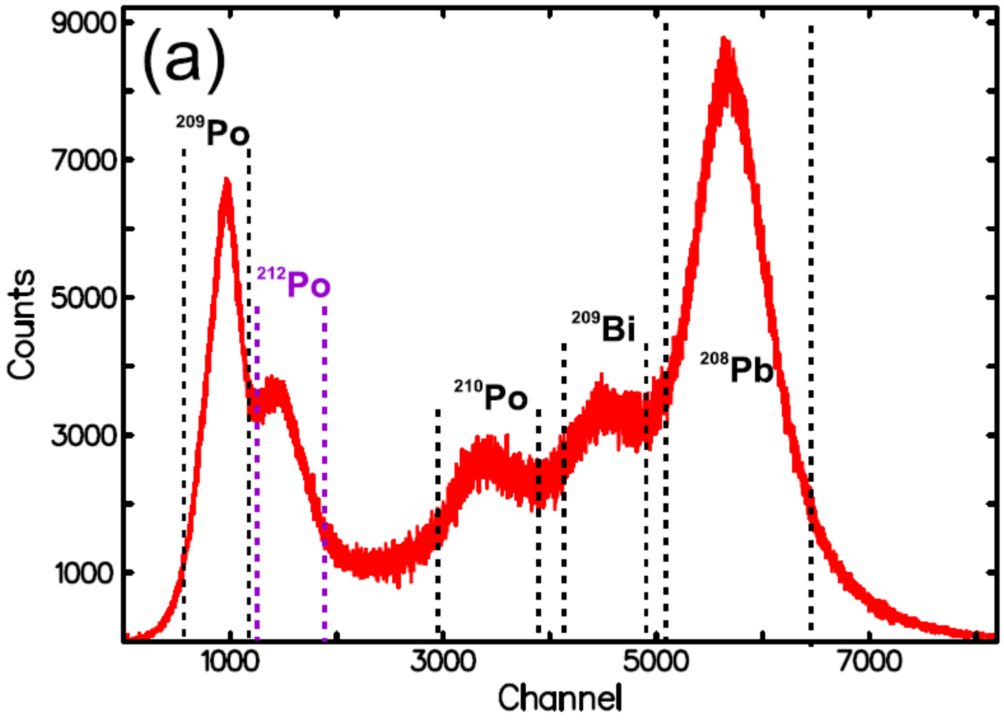


$$\langle \upsilon_0(^{212}\text{Po})/c \rangle \approx 0.9\%$$

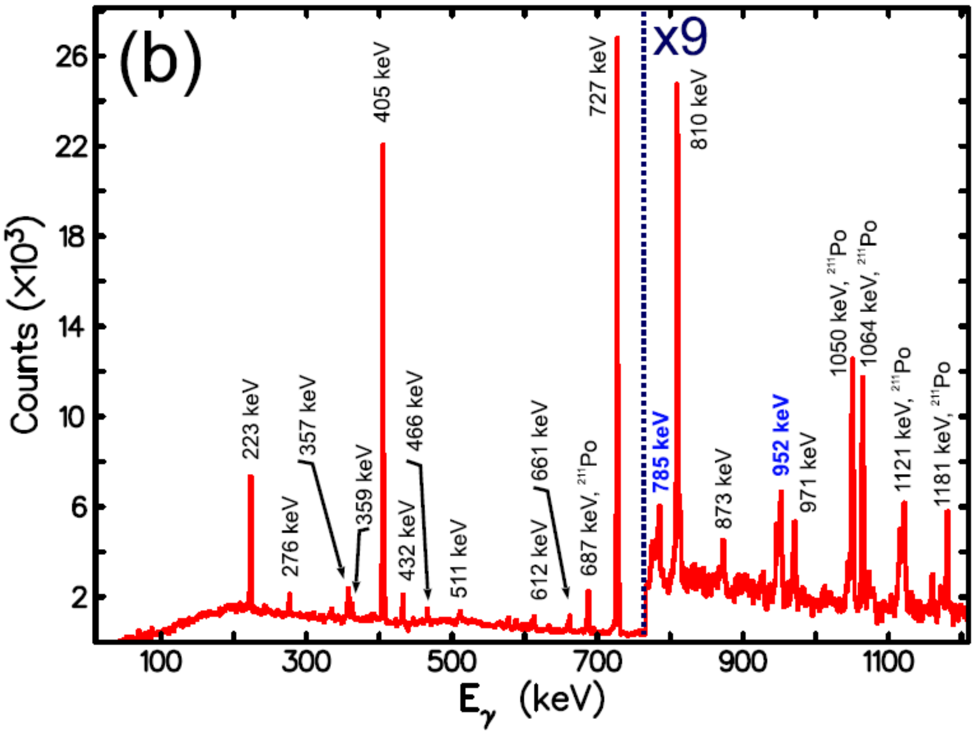
Experiment on ^{212}Po @ Cologne FN Tandem

G. Rainovski, D. Kocheva, K. Gladnishki, M. Djongolov,
Sofia University, Bulgaria

SOFIA UNIVERSITY "St. Kliment Ohridski"



Solar cell spectrum



γ-ray spectrum of ^{212}Po gated on ^{8}Be / 2α channel

DSAM lineshape fits ^{212}Po

785.3 keV

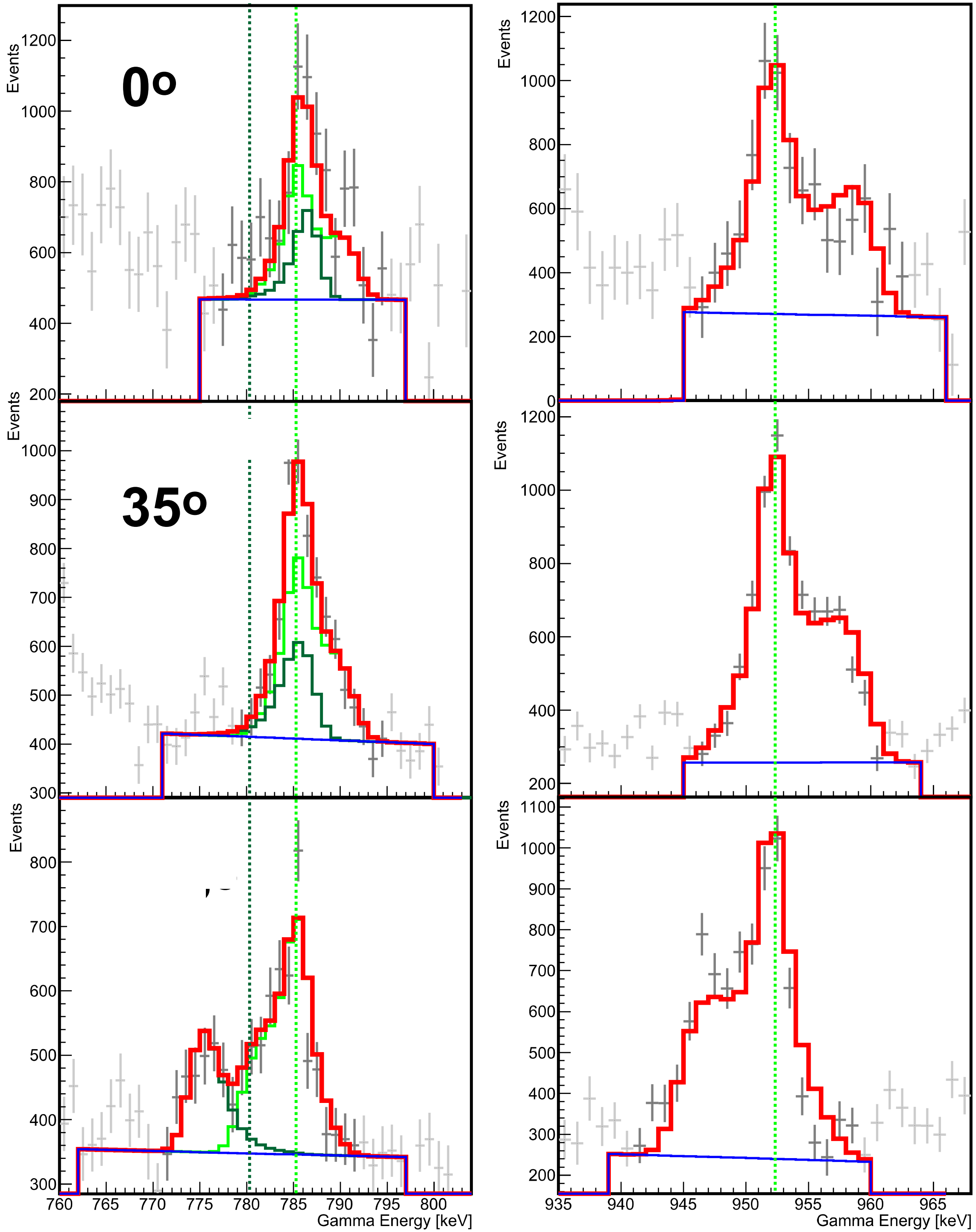
$2^+_2 \rightarrow 2^+_1$

2^+_2 @ 1512 keV

Fast feeding only

τ = 0.75(5) ps

δ=+0.09(3)
BR=100(1)/26(3)



952.1 keV

$2^+_3 \rightarrow 2^+_1$

2^+_3 @ 1679 keV

Fast feeding only

τ = 0.80(3) ps

δ=+0.65(50)
BR=100(19)/25(8)

D. Kocheva,
G. Rainowski

DSAM lineshape fits ^{212}Po

785.3 keV

$2^+_2 \rightarrow 2^+_1$

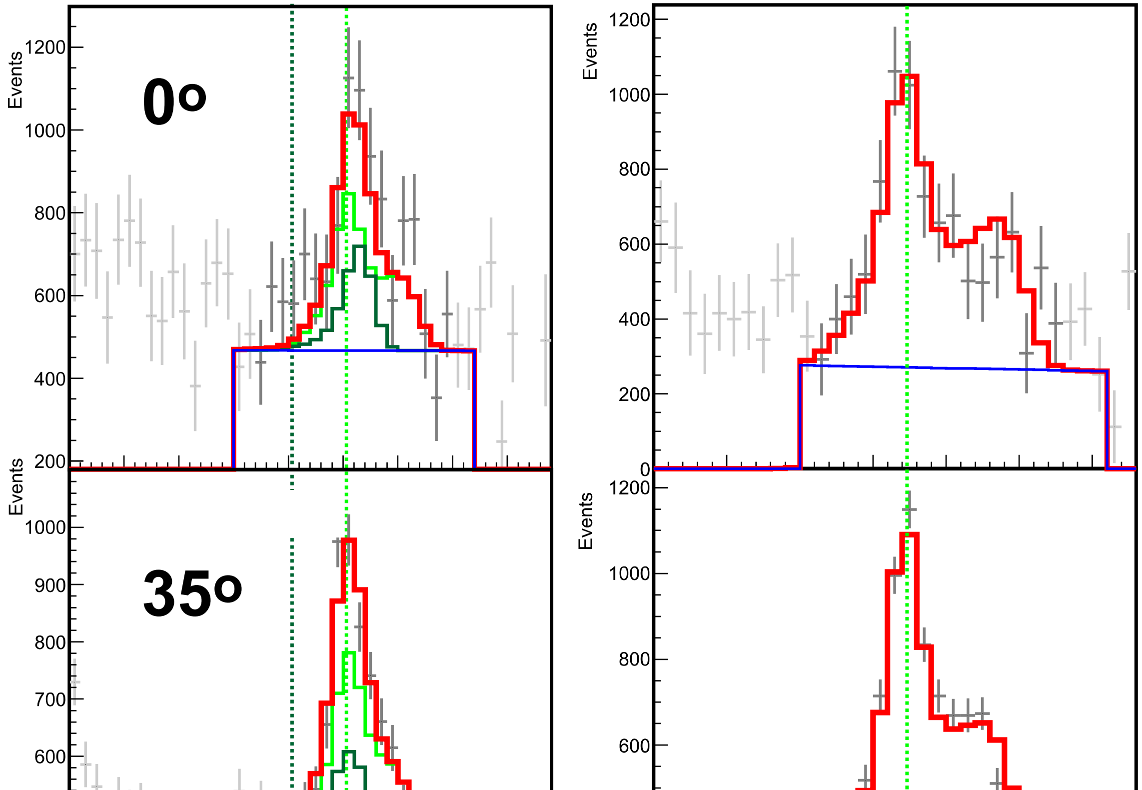
2^+_2 @ 1512 keV

Fast feeding only

τ = 0.75(5) ps

δ=+0.09(3)

BR=100(1)/26(3)



952.1 keV

$2^+_3 \rightarrow 2^+_1$

2^+_3 @ 1679 keV

Fast feeding only

τ = 0.80(3) ps

δ=+0.65(50)

BR=100(19)/25(8)

	2^+_2 @ 1512 keV	2^+_3 @ 1679 keV
B(M1;$2^+_i \rightarrow 2^+_1$) (μ_N^2)	0.119(8)	$0.042^{+0.027}$
B(E2;$2^+_i \rightarrow 2^+_1$) (e^2fm^4)	22(2)	278(255)
B(E2;$2^+_i \rightarrow 0^+_1$) (e^2fm^4)	28(4)	20(5)

Shell model calculation for 2_1^+, 2_2^+ in ^{212}Po

Single-shell approximation + empirical interaction from neighboring nuclei (**P. Van Isacker**)

$^{212}\text{Po}: \quad ^{208}\text{Pb} + \nu(2g_{9/2})^2 + \pi(1h_{9/2})^2$

Basis states: $|(2g_{9/2})^2 J_\nu, (1h_{9/2})^2 J_\pi; J\rangle \equiv |J_\nu J_\pi J\rangle$

$$\langle J_\nu J_\pi J | \hat{H} | J'_\nu J'_\pi J\rangle = (V_{\nu\nu}^{J_\nu} + V_{\pi\pi}^{J_\pi})\delta_{J_\nu J'_\nu}\delta_{J_\pi J'_\pi} + 4\sqrt{(2J_\nu+1)(2J_\pi+1)(2J'_\nu+1)(2J'_\pi+1)}\sum_R \begin{bmatrix} j_\nu & j_\pi & J_\pi & J_\nu \\ R & j_\pi & J & j_\nu \\ j_\nu & j_\pi & J'_\pi & J'_\nu \end{bmatrix} V_{\nu\pi}^R$$

$V_{\nu\nu}^{J_\nu}$: from the experimental spectrum ($0^+ – 8^+$) of ^{210}Pb (2ν in $2g_{9/2}$)

$V_{\pi\pi}^{J_\pi}$: from the experimental spectrum ($0^+ – 8^+$) of ^{210}Po (2π in $1h_{9/2}$)

} seniority spectra

$V_{\nu\pi}^R$: from the experimental spectrum ($0^- – 9^-$) of ^{210}Bi

$$|2_1^+\rangle = 0.488\,|J_\nu = 0, J_\pi = 2, J = 2\rangle + 0.819\,|J_\nu = 2, J_\pi = 0, J = 2\rangle + \ldots \quad \mathbf{87\%}$$

$$|2_2^+\rangle = 0.813\,|J_\nu = 0, J_\pi = 2, J = 2\rangle - 0.517\,|J_\nu = 2, J_\pi = 0, J = 2\rangle + \ldots \quad \mathbf{93\%}$$

→ **Consist of proton and neutron *S* ($J_{\nu(\pi)}$=0) and *D* ($J_{\nu(\pi)}$=2) pairs**

2^+_2 state at 1512 keV isovector excitation of ^{212}Po, but:
Both the experimental results and the theoretical description show that these are not collective states!

Conclusion

→ Transition strengths determined from level lifetimes allow to draw unique conclusions about nuclear structure.

→ Overview about methods for lifetime determination used by our group:
- Recoil Distance Doppler-shift method (Plunger)
- Fast timing with delayed $\gamma\gamma$-coincidences or e^- – γ coincidences
- Doppler-shift attenuation method

→ Shape coexistence in neutron deficient Hg isotopes

→ Hints for X(5) critical point symmetry in neutron deficient Os isotopes

→ Observation of isovector excitations in ^{212}Po

Collaboration

Universität zu Köln

A. Blazhev, T. Braunroth, A. Dewald, C. Fransen, R.-B. Gerst, A. Goldkuhle, A. Hennig, J. Jolie, J. Litzinger, C. Müller-Gatermann, J.-M. Regis, M. Rudigier, N. Saed-Samii, D. Wölk

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

T. Grahn, K. Auranen, P.T. Greenlees, A. Herzan, U. Jakobsson, R. Julin, S. Juutinen, J. Konki, M. Leino, P. Peura, P. Rahkila, P. Ruotsalainen, M. Sandzelius, J. Saren, C. Scholey, J. Sorri, S. Stolze, J. Uusitalo

SOFIA UNIVERSITY
"St. Kliment Ohridski"

D. Kocheva, G. Rainovski, K. Gladnishki, M. Djongolov

INRNE Sofia, Bulgaria

P. Petkov

Laboratori Nazionali di Legnaro

G. de Angelis, L. Corradi, E. Fioretto, A. Goasduff, A. Gottardo, D.R. Napoli, A. Stefano, J.J. Valiente-Dobon

University of Padova and INFN

D. Bazzacco, S. Lenzi, S. Lunardi, R. Menegazzo, D. Mengoni, G. Montagnoli

TECHNISCHE UNIVERSITÄT DARMSTADT

R. Stegmann, N. Pietralla, C. Stahl, L. Cortes, Th. Möller, C. Bauer, M. Scheck, V. Werner, C. Schramm, M. Lettmann