The recoil distance Doppler-shift technique: a valuable method for nuclear structure studies far from the valley of stability

- **Cologne compact plungers for RDDS @ JYFL, Argonne, LNL,...**
- **Recent experimental campaigns**
  → Structure of mid-shell Te isotopes
  → Structural evolution in neutron deficient nuclei around A=170
- **New Cologne CATHEDRAL spectrometer**

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German Research Foundation

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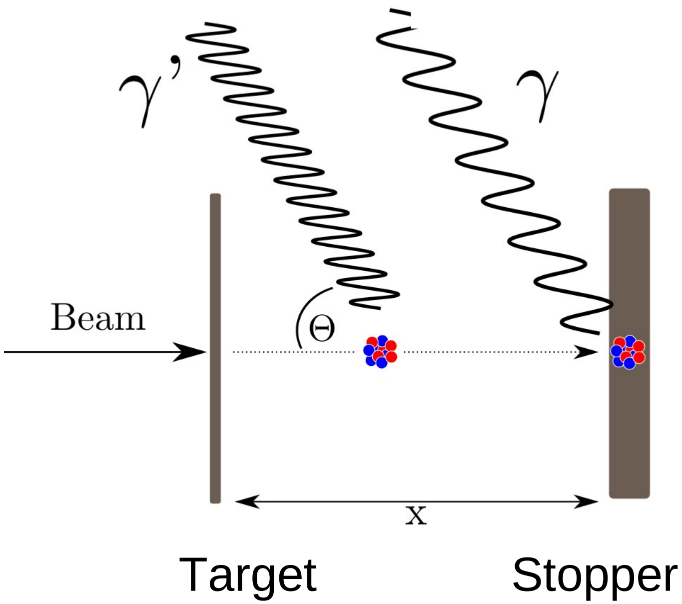
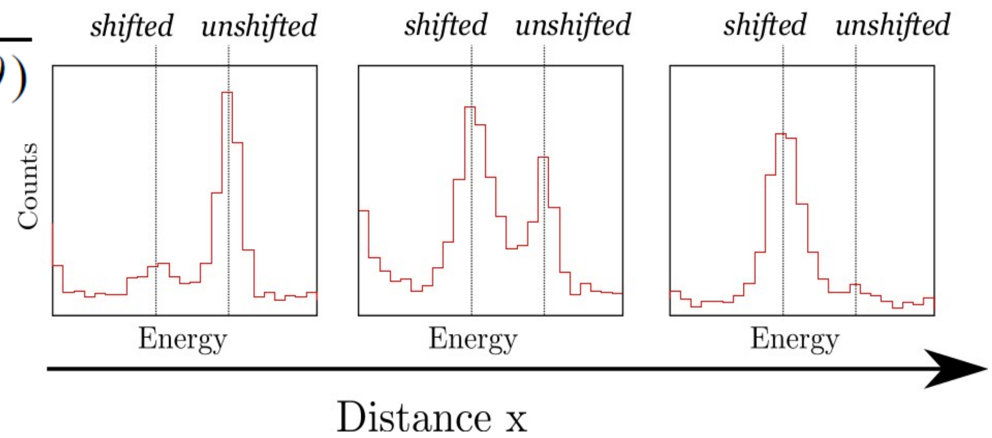
C. Müller-Gatermann
Argonne National Laboratory, USA

The recoil distance Doppler-shift (RDDS) technique



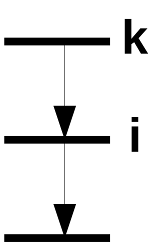
$$E = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\theta)}$$



Analysis: e.g., differential decay curve method DDCM

A. Dewald et al., Z. Phys. A 334, 163 (89)

A. Dewald et al., Prog. Part. Nucl. Phys 67, 786 (12)



$$\tau_i(x) = \frac{1}{v} \cdot \frac{-R_i(x) + \sum_k b_{ki}\alpha_{ki}R_k(x)}{\frac{d}{dt}R_i(x)}$$

RDDS: level lifetimes in ps range:

→ absolute transition strengths

→ independent of reaction mechanism (but recoil velocity > 1%c)
fusion-evaporation, Coulex, direct reactions, transfer,...

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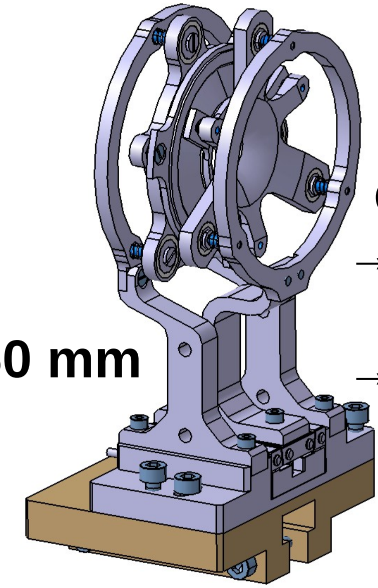
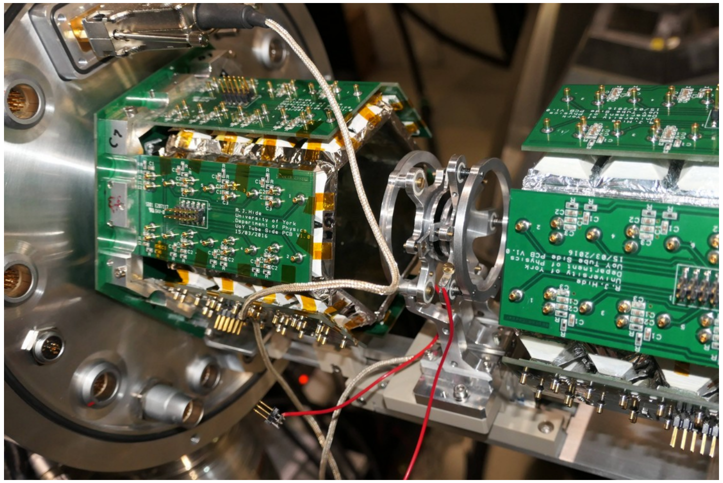
Cologne compact plungers

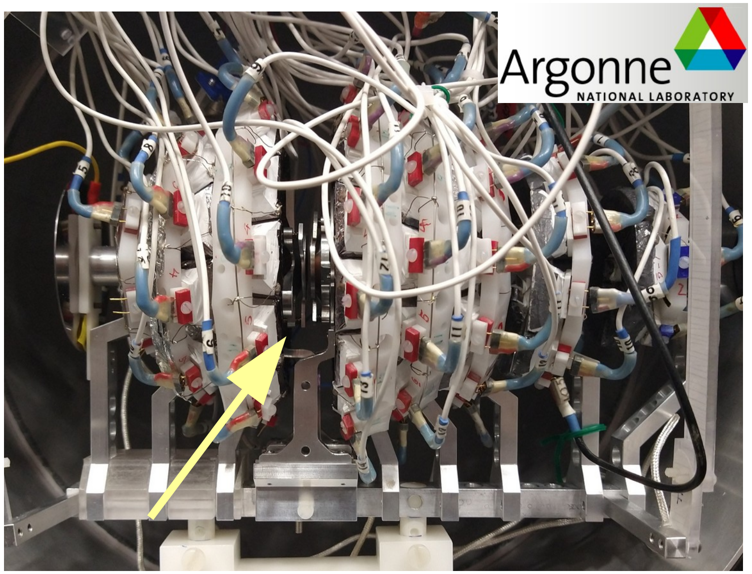


60 mm

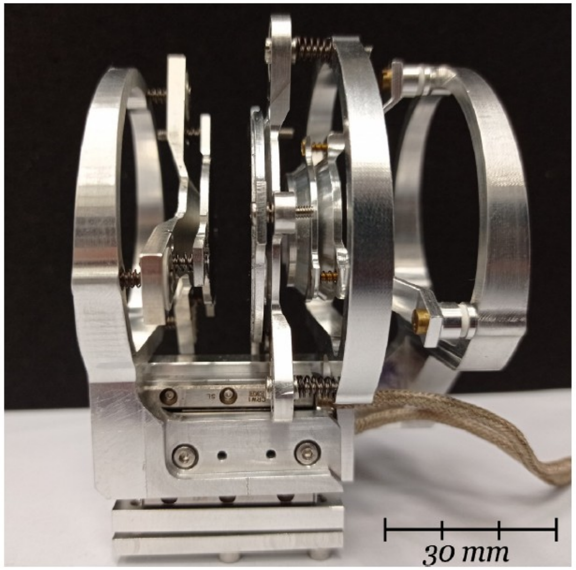
Compact:
→ Use with charged particle arrays
→ use at grazing angles



APPA Plunger, JYFL
JYTube + JUROGAM III + MARA/RITU



iCAPS plunger + Microball
integrated Cologne-Argonne plunger setup
GAMMASPHERE/GRETINA (+ AGFA/FMA)



3-foil plunger
CoCoDiff
AGATA + PRISMA
M. Beckers et al.,
NIM A 1042 (22) 167418

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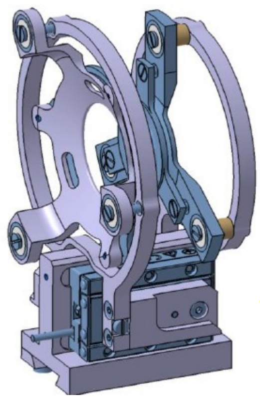
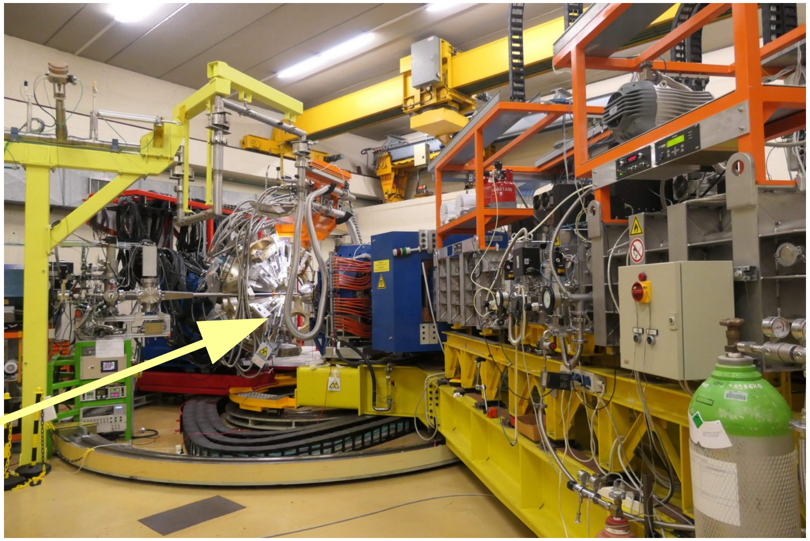
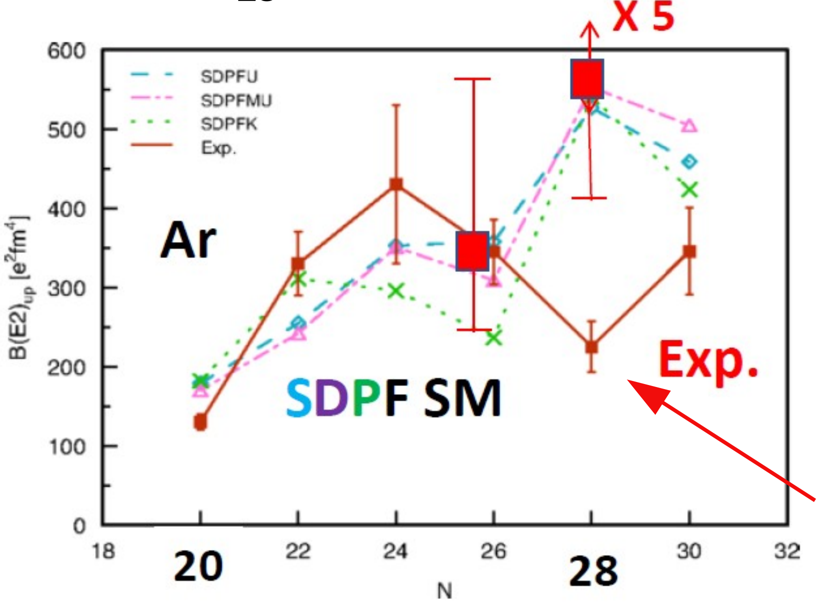
Structural evolution around ^{48}Ca

Experiment at LNL, April 2024
RDDS $^{46-48}$Ar, DSAM ^{50,51}Ca
multinucleon transfer
^{48}Ca @ 330 MeV, ^{238}U target
modified CoCoDiff Plunger
+ AGATA + PRISMA





$^{46}Ar_{28}$: a conundrum



→ SDPF shell model: breakdown of N=28
PRC 55, 1266 (97), PRC 93, 044333 (19)

→ large mixing closed shell – 2p-2h bandhead
E. Caurier et al., NPA 742, 14 (04)

Existing data: no conclusion
RDDS + MNT @ GANIL
D. Mengoni et al., PRC 82, 024308 (10)
Coulex @ LISE/GANIL
S. Calinescu et al. PRC 93, 044333 (19)

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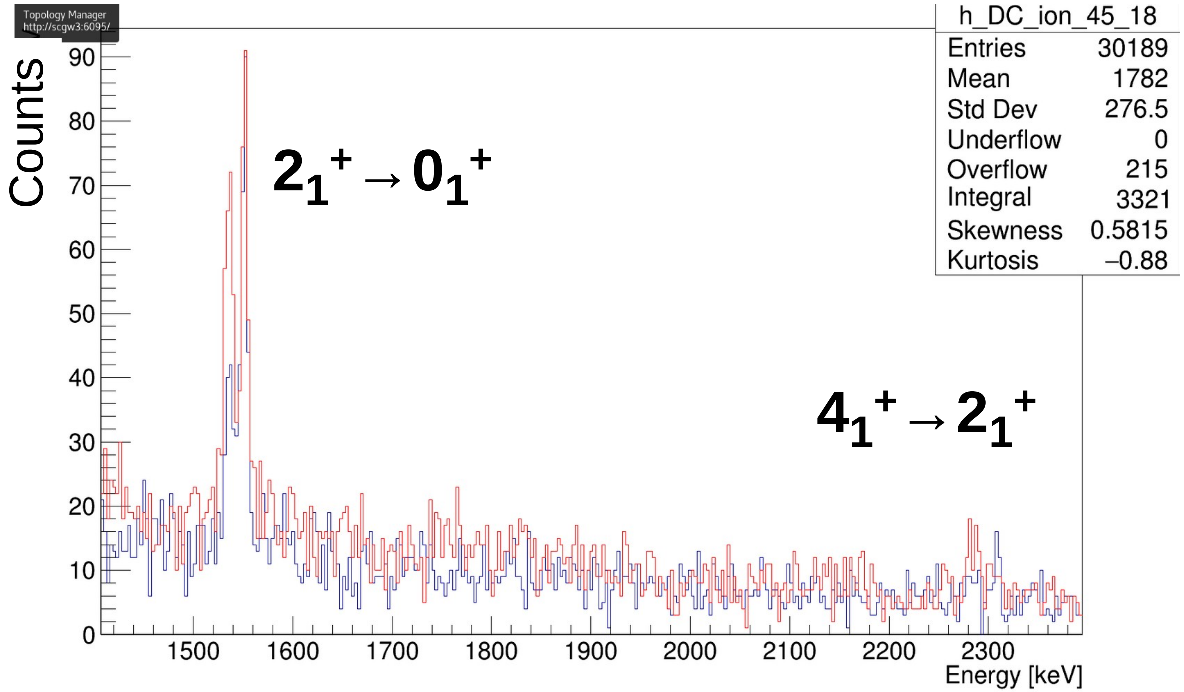
RDDS spectra ^{46,48}Ar, LNL April 2024

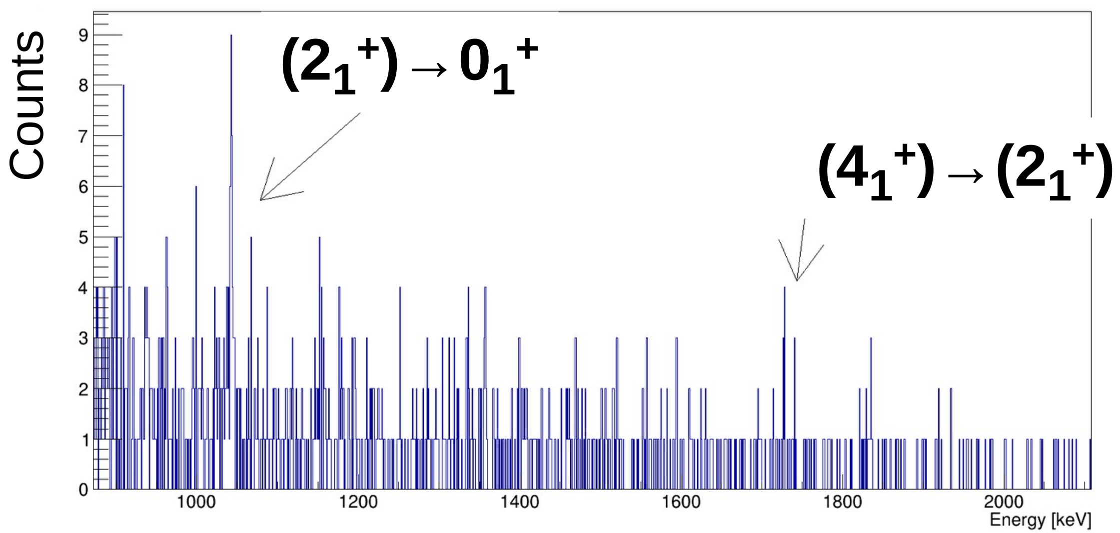


^{46}Ar

30 μm, 5 μm

+ 20 μm offset

48 h /distance



^{48}Ar

sum 5 μm, 30 μm

Analysis ongoing...

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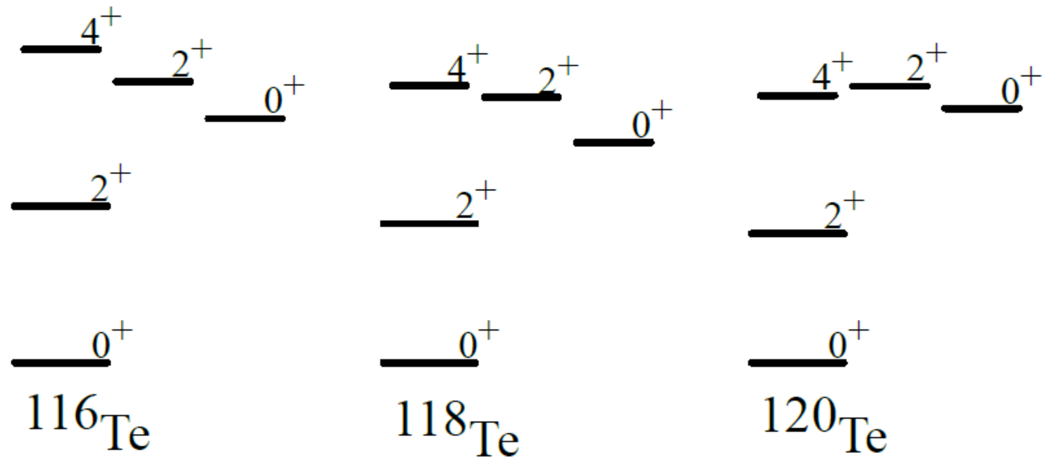
Structure of mid-shell Te isotopes

Level schemes Te (N=52) similar to Cd (N=48): vibrators?

→ known: shape coexistence in Cd

P. Garrett et al., Prog. Part. Nucl. Phys. 124, 103931 (22)



Detailed investigation of $^{116-120}$Te @ Cologne

F. von Spee, PhD thesis, Univ. of Cologne (2024)

^{100}Mo(^{23}Na,4np)^{118}Te RDDS

^{112}Sn(^{12}C,^{8}Be)^{116}Te RDDS

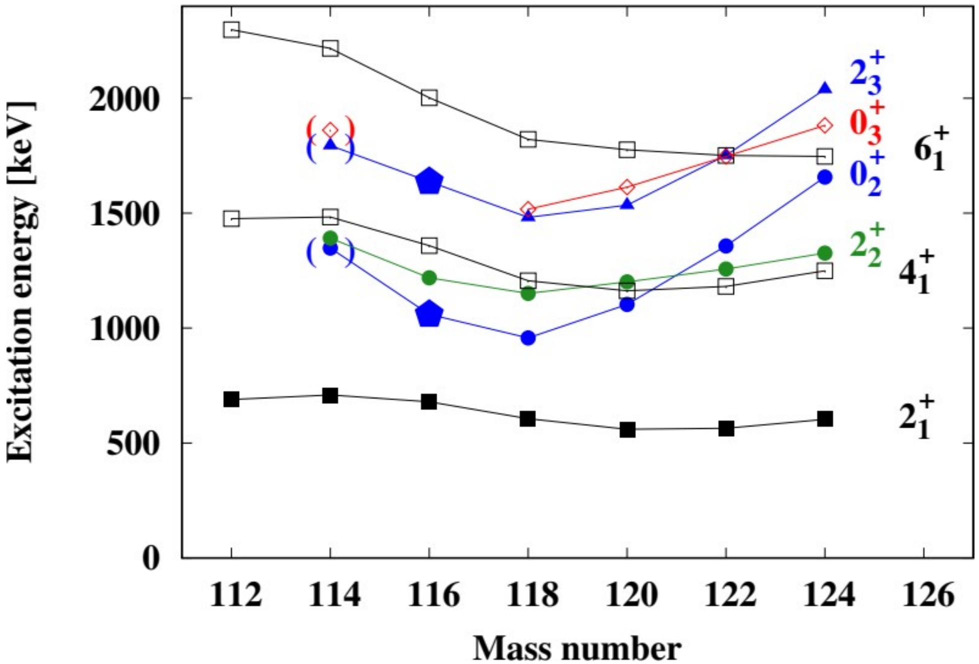
^{114}Sn(^{12}C,^{8}Be)^{118}Te RDDS

^{116}Sn(^{12}C,8Be)^{120}Te RDDS

^{107}Ag(^{12}C,3n)^{116}I $\xrightarrow{\beta}$ ^{116}Te angular corr.

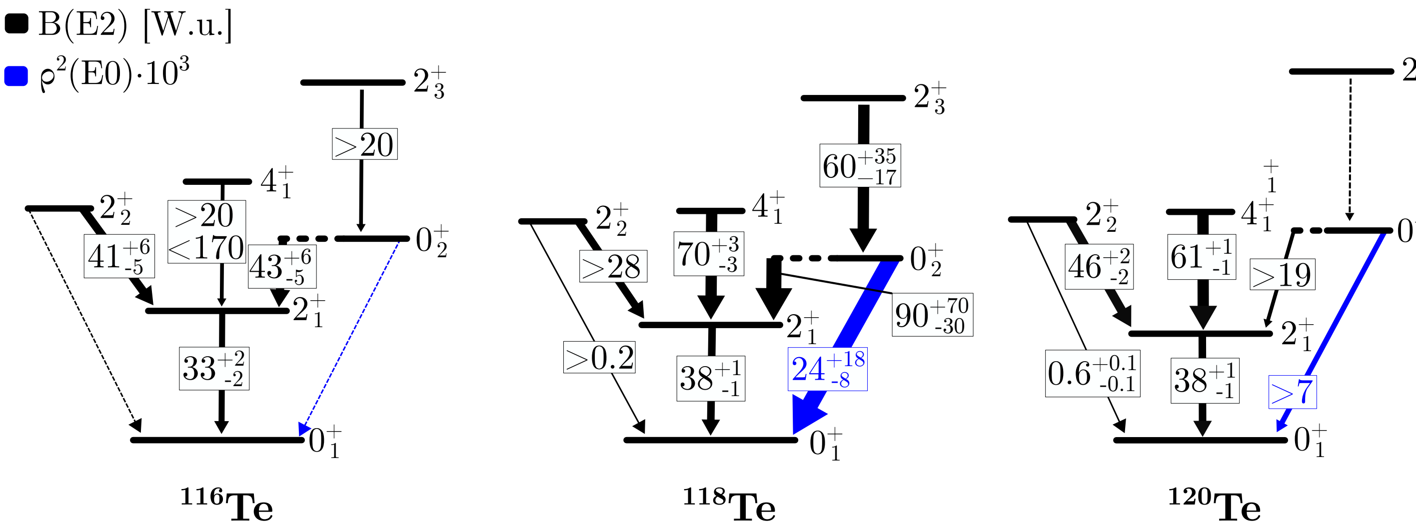
^{108}Ag(^{12}C,3n)^{118}I $\xrightarrow{\beta}$ ^{118}Te angular corr.

Signatures shape coexistence in Te:
1. parabolic energy systematics 0_2^+



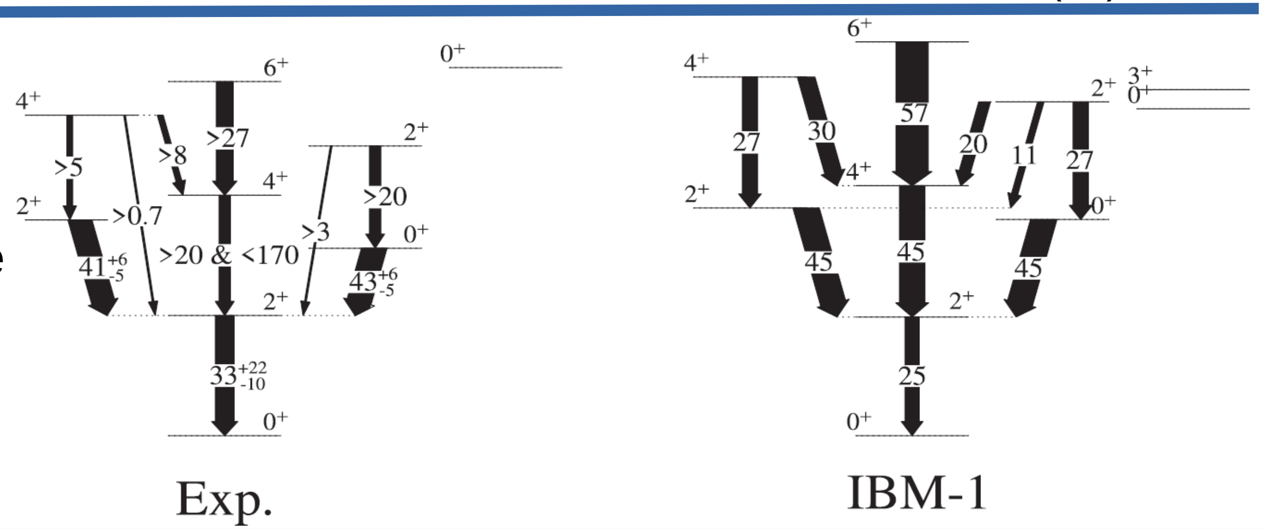
Structure of mid-shell Te isotopes

Signatures shape coexistence in Te:
2. ^{118}Te: large ρ^2(E0) value $0_2^+ \rightarrow 0_1^+$: change of mean square charge radius
3. collective in-band transitions of intruder structure



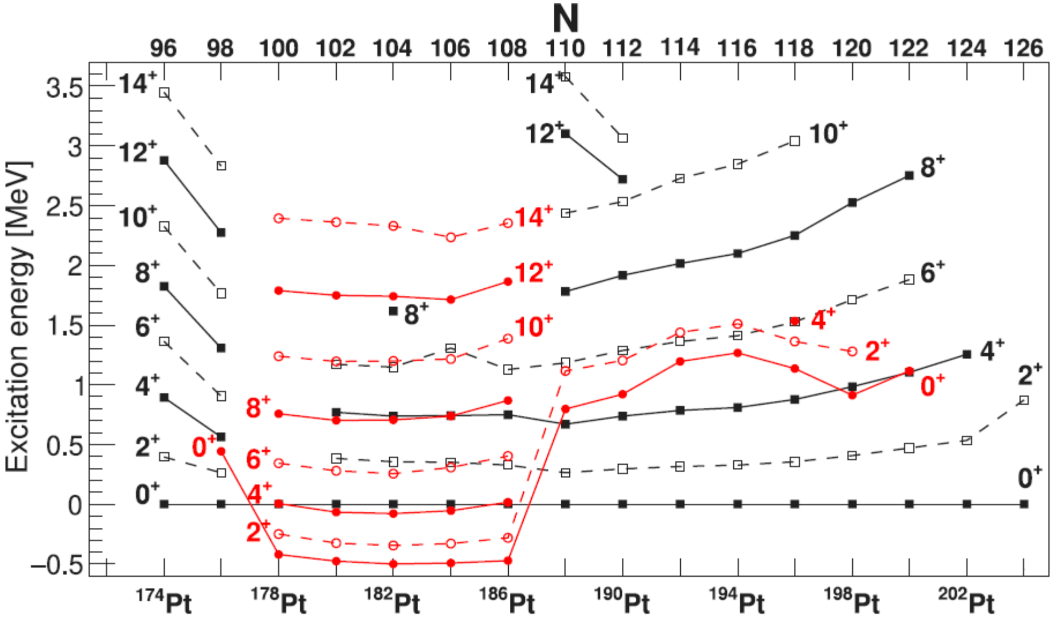
F. von Spee, PhD thesis, Univ. of Cologne (2024)
Walker et al., J. Phys. G 13, L195 (87)

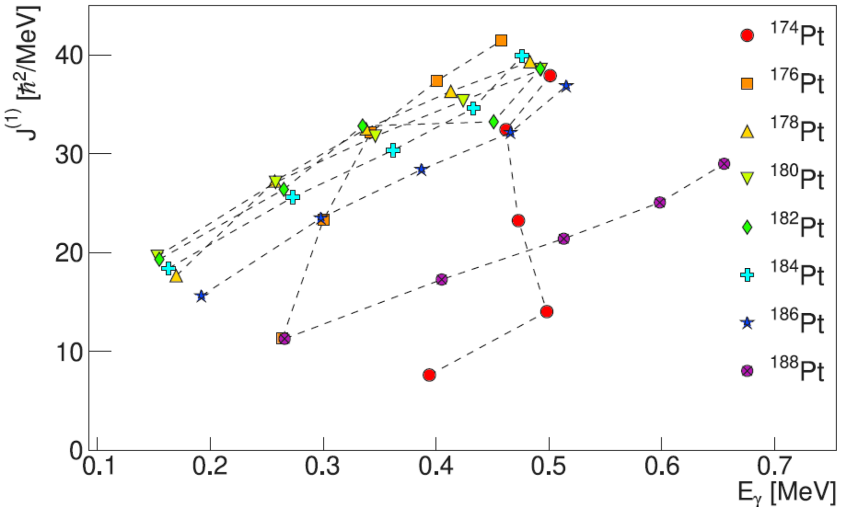
But:
U(5) limit IBM-1
→ reasonable description of lowest levels of ^{116}Te
F. von Spee et al., PRC 109, 024305 (24)



Structural evolution in n-deficient nuclei around A=170

Shape evolution in n-deficient Pt?





P.E. Garrett et al., Prog. Part. Nucl. Phys. **124**, 103931 (2022)

→ $^{178\text{-}186}$Pt:
well deformed config. below weakly deformed

→ supported by B(E2), kinematic moments of inertia

→ what happens for A<178?

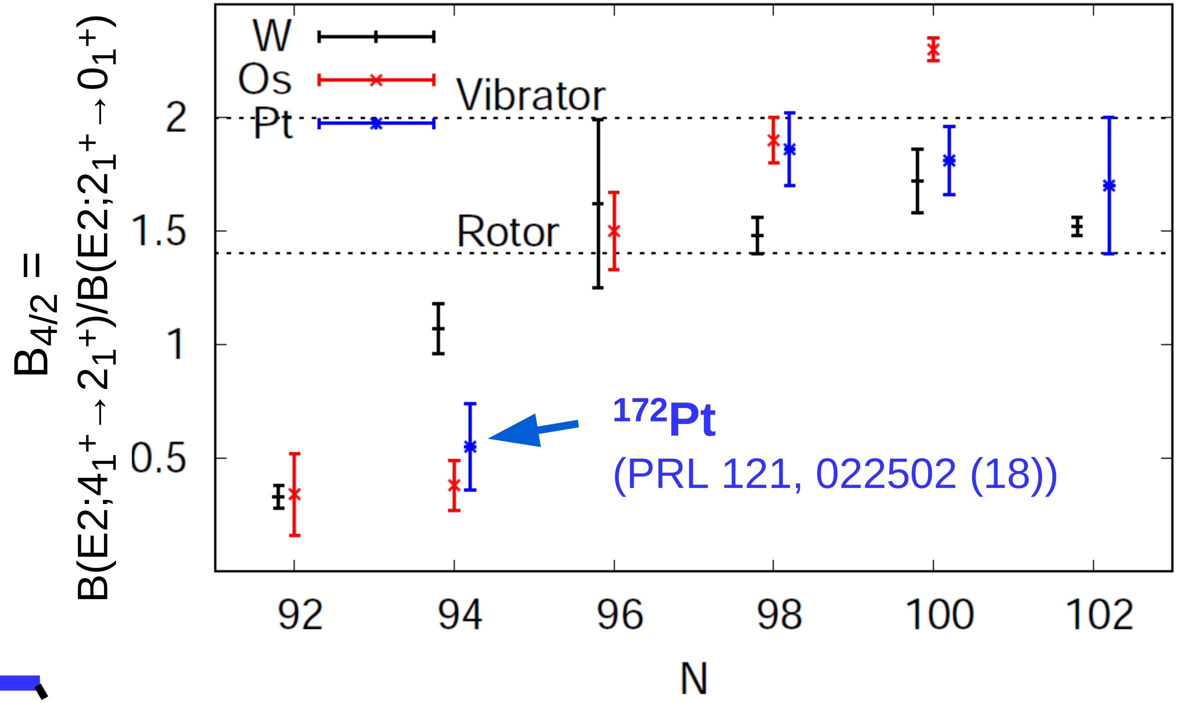
→ measure yrast B(E2)

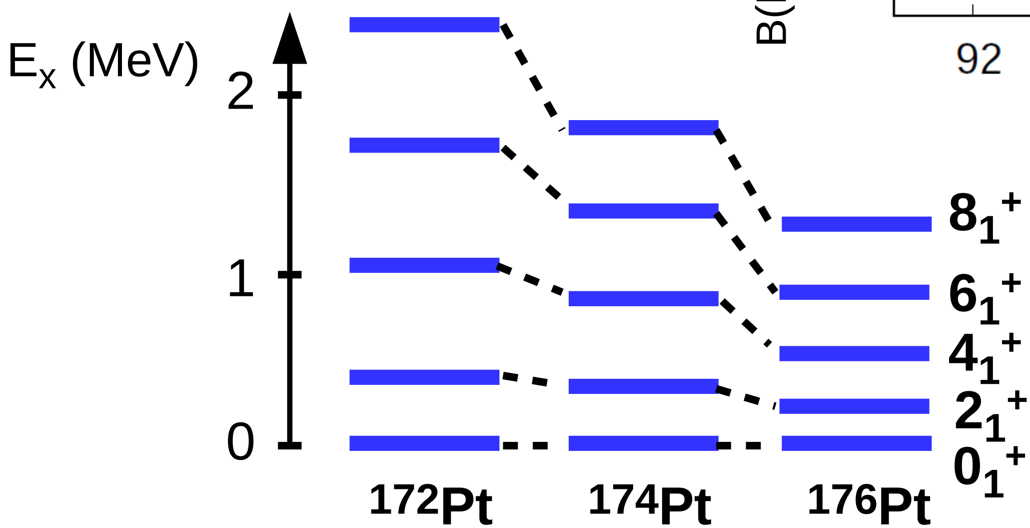
Structural evolution in n-deficient nuclei around A=170

Shape evolution in n-deficient Pt?

„Island“ of $B_{4/2}<1$ for $N\leq94$
→ cannot be explained in any collective model!
^{172}Pt: $N_\nu = 12$

→ ^{172}Pt: $B_{4/2} = 0.55\ (19)$
B. Cederwall et al., PRL 121, 022502 (18)
no other B(E2) known





Yrast energies:
rapid, but smooth transition

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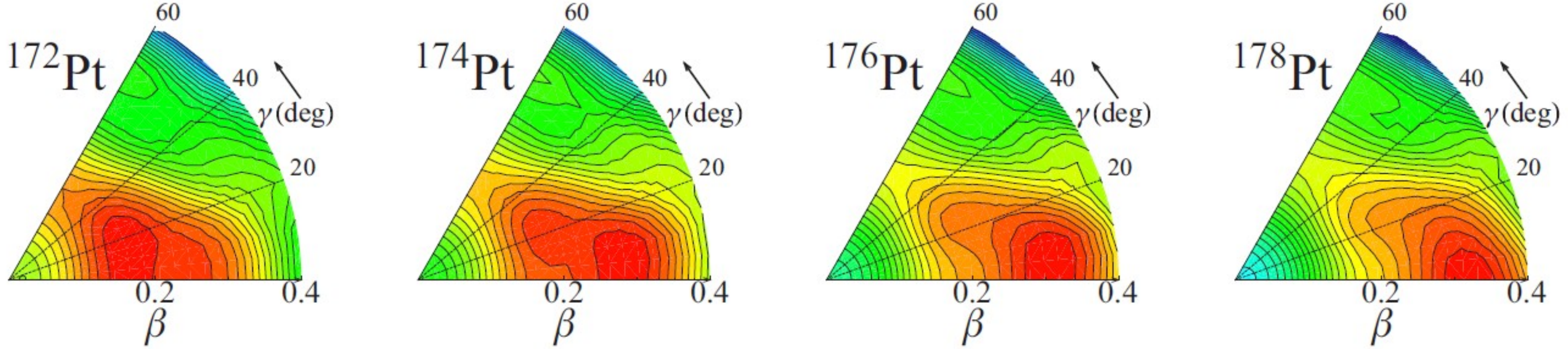
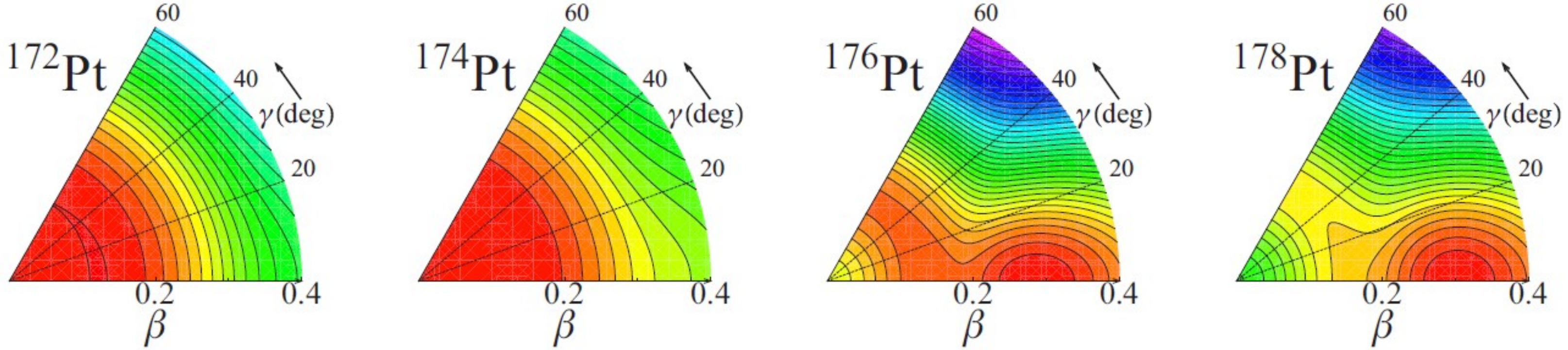
Structural evolution in n-deficient nuclei around A=170

Calculations: Garcia-Ramos et al., PRC 89, 034313 (14)

IBM with configuration mixing: smooth transition to weakly prolate deformation



Hartree-Fock Bogoliubov: sharp transition prolate (^{178}Pt) – spherical (^{174}Pt)



Precise B(E2) values needed for $^{172-176}$Pt!

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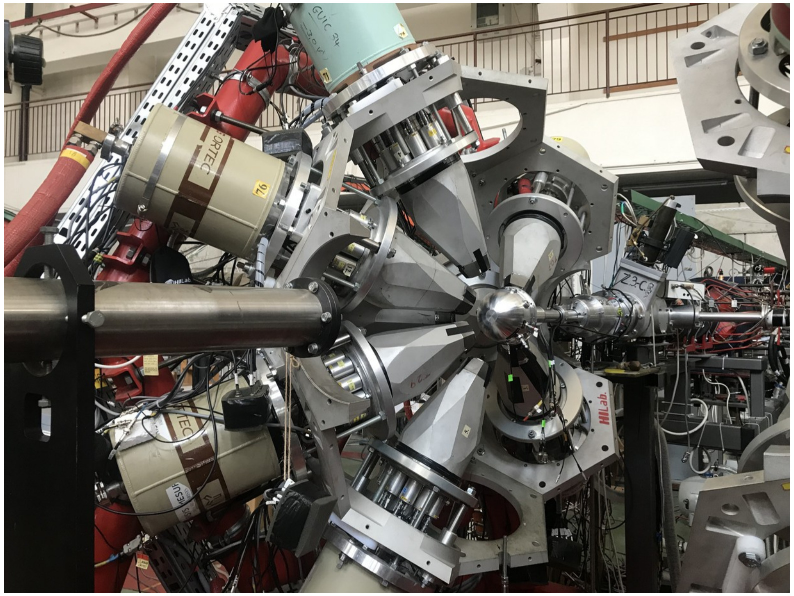
Experiment on $^{176}Pt_{98}$ at HIL, Warsaw



$^{148}Sm(^{32}S,4n)^{176}Pt$ @ 170 MeV

Target: 0.75 mg/cm^2 ^{148}Sm on 1.5 mg/cm^2 Ta

Cologne plunger + EAGLE spectrometer

10 distances 0 – 600 μm

$\gamma\gamma$ coincidences:

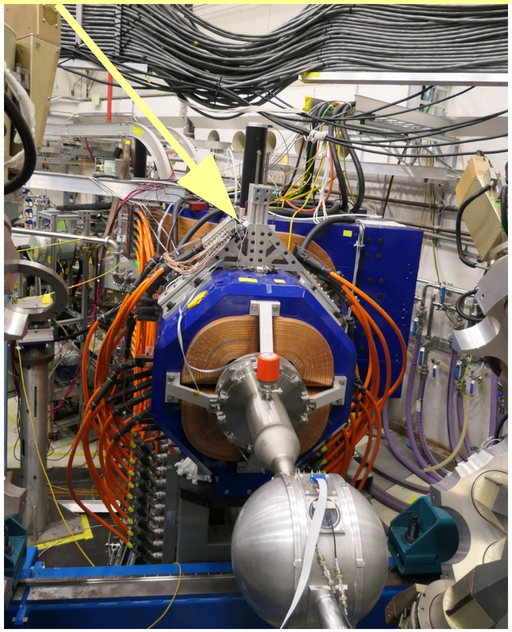
→ exclude problems from unobserved feeding

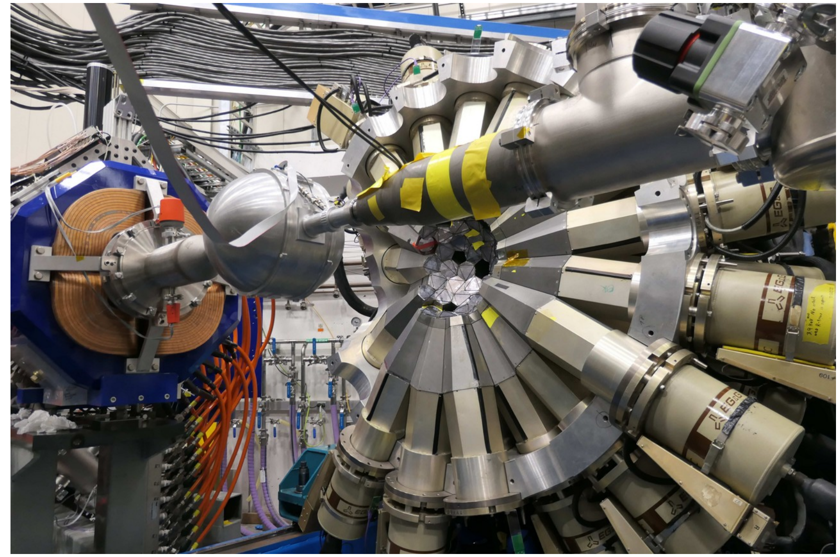
→ no assumptions on feeding!

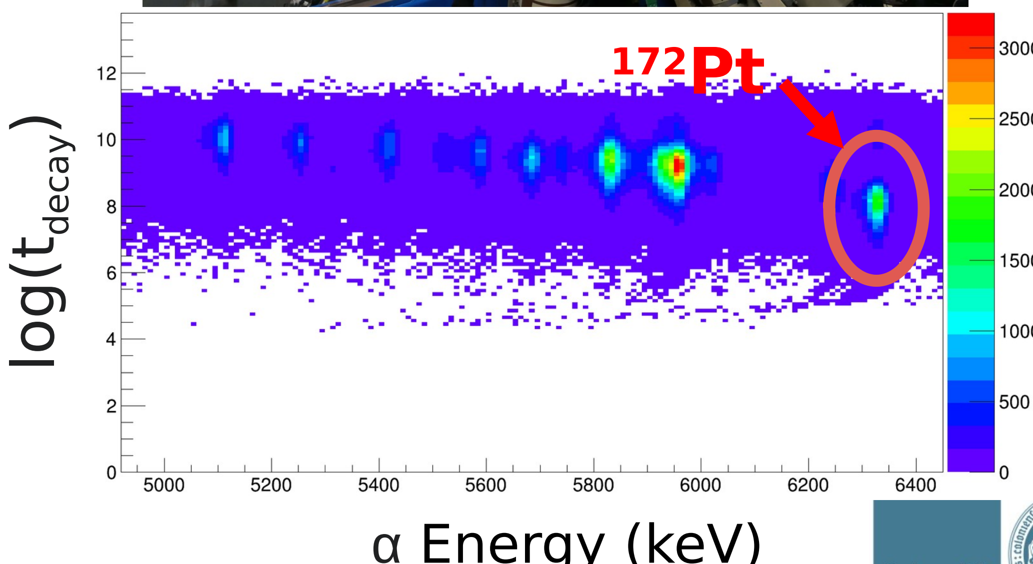
This work			Dracoulis et al., J. Phys. G 12, L97 (86)	
J_i^π	$\tau(J_i^\pi)$	$B(E2; J_i^\pi \rightarrow J_i^\pi\text{-}2)$	$\tau(J_i^\pi)$	$B(E2; J_i^\pi \rightarrow J_i^\pi\text{-}2)$
2_1^+	41.0 (41) ps	$231\,^{+26}_{-21}$ W.u.	109 (10) ps	$87\,^{+9}_{-7}$ W.u.
4_1^+	15.0 (25) ps	$347\,^{+70}_{-50}$ W.u.	32 (3) ps	$163\,^{+17}_{-14}$ W.u.
6_1^+	12.1 (50) ps	$232\,^{+163}_{-68}$ W.u.	16.2 (15) ps	173^{+18}_{-15} W.u.
$\gamma\gamma$ coincidences			γ-ray singles → feeding?	

Experiment on $^{172}Pt_{94}$ at Argonne
iCAPS plunger + GAMMASPHERE + AGFA

Argonne Gas Filled Analyzer
dipole + aberration corr.







^{92}Mo(^{83}Kr,3n)^{172}Pt

8 distances 3 – 400 μm

16 h/distance

γγ coincidences

+ α decay tagging (AGFA):

^{172}Pt 10^{-5} of total cross section

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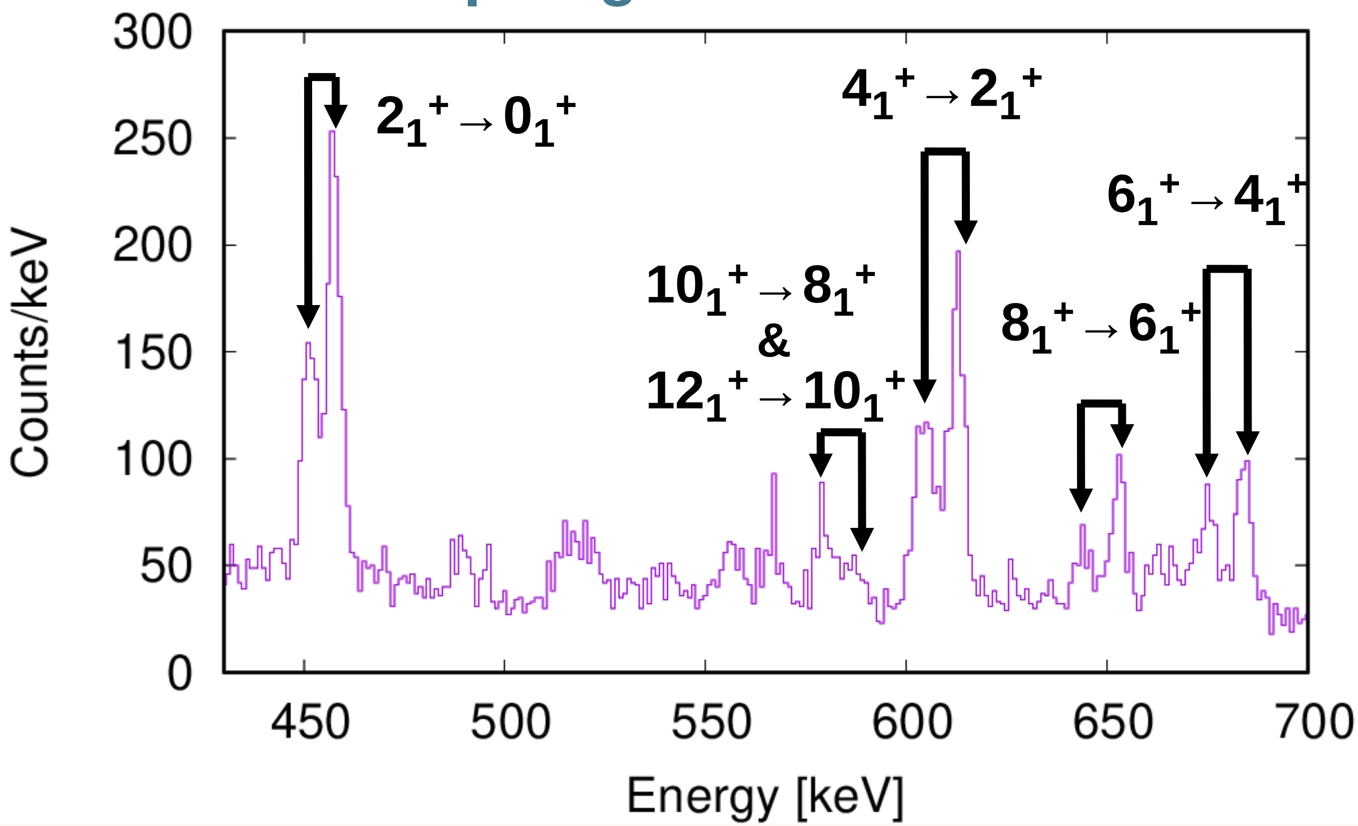
Experiment on $^{172}Pt_{94}$ at Argonne
iCAPS plunger + GAMMASPHERE + AGFA



Preliminary
(C.D. Lakenbrink γ-ray singles)
$\tau(2_1^+)$= 35 (10) ps
$\tau(4_1^+)$= 6.5 (10) ps
$\tau(6_1^+)$= 6.5 (10) ps
$\tau(8_1^+)$= 10 (5) ps

$^{92}Mo(^{83}Kr,3n)^{172}Pt$ with high efficiency of GAMMASPHERE

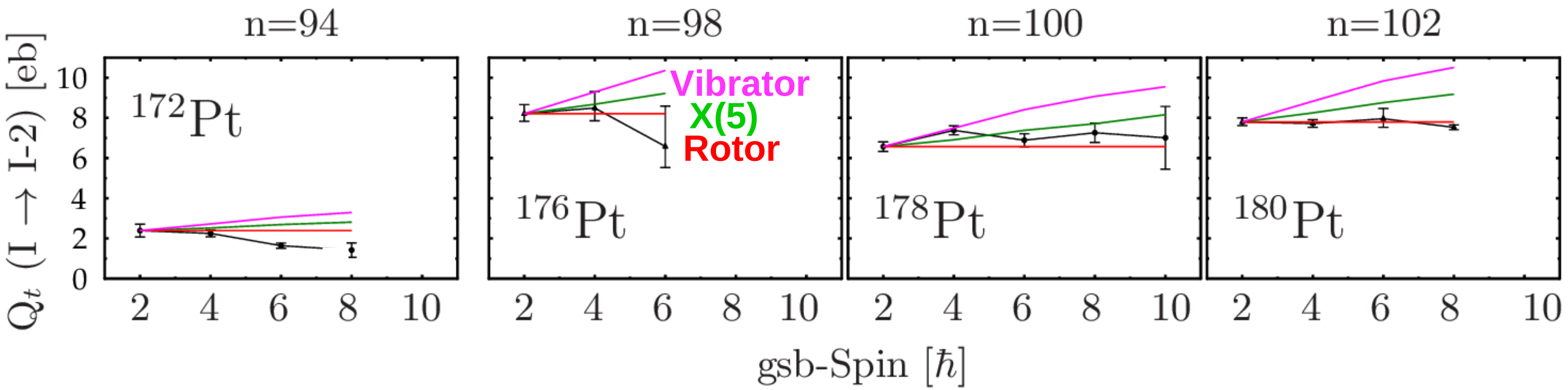
Spectrum ^{172}Pt @ 400 μm, 1 HPGe ring, α decay tagging ^{172}Pt (AGFA)

→ Analysis ongoing (PhD thesis C.-D. Lakenbrink, Cologne): **$\tau(2_1^+, 4_1^+, 6_1^+, 8_1^+)$**

$\tau(2_1^+, 4_1^+)$ γγ coincidences!

B. Cederwall et al., PRL 121, 022502 (18):
same reaction @ JYFL, γ singles + α decay tagging: $\tau(2_1^+, 4_1^+)$ → **$B_{4/2}$ = 0.55(19)**

Q_t plots $^{172-180}$Pt



→ ^{178,180}Pt rotor like *^{178}Pt: C. Fransen et al., EPJ Web Conf, 223, 01016 (19)*
^{180}Pt: C. Müller-Gatermann et al., NIM A 920, 95 (19)

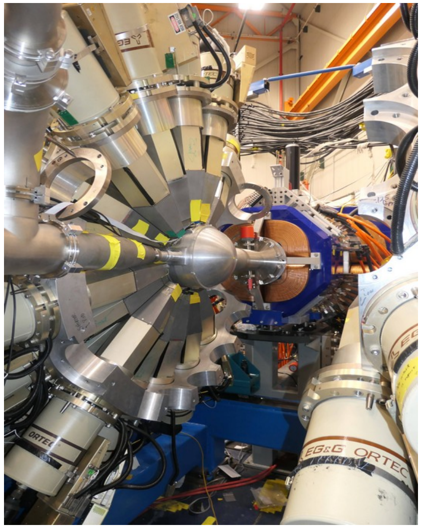
→ ^{176}Pt still collective, 2_1^+, 4_1^+ rotor like? (IKP Cologne, HIL Warsaw)

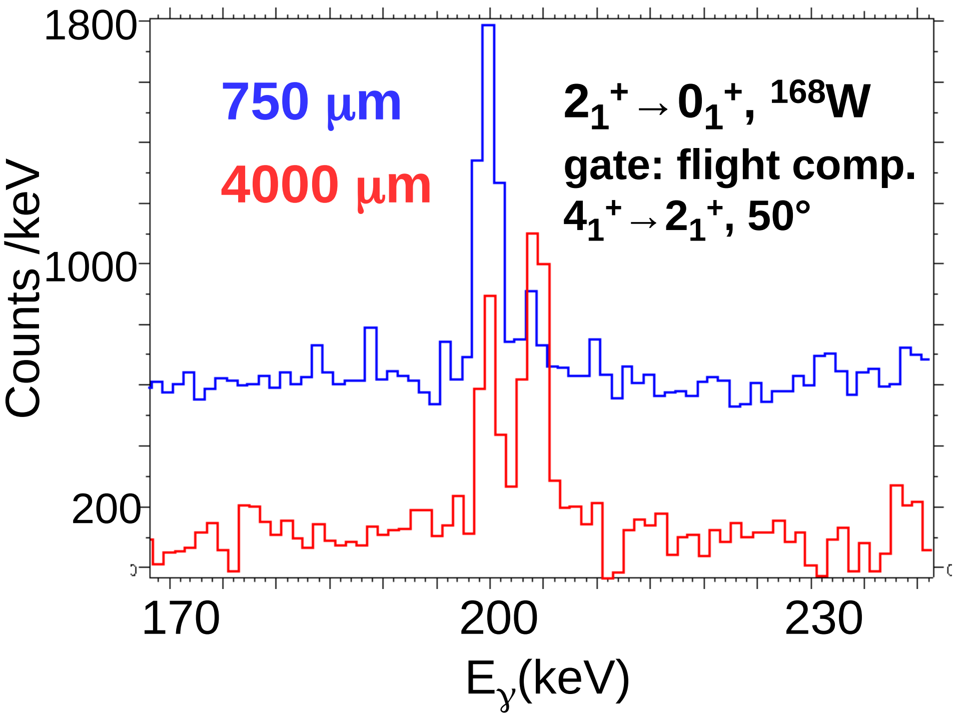
→ ^{172}Pt: **Low collectivity yrast band (poster C.D. Lakenbrink)**

	^{172}Pt, prelim.	**^{176}Pt**
B(E2;$2_1^+ \rightarrow 0_1^+$)	20^{+8}_{-4} W.u.	231^{+26}_{-21} W.u.
B(E2;$4_1^+ \rightarrow 2_1^+$)	25^{+5}_{-3} W.u	347^{+70}_{-50} W.u.
$B_{4/2}$	1.3 (6) / old: 0.55(19)	1.50 (30)
$B_{6/4}$	0.60 (17)	0.67 (52)

Experiments on n-deficient nuclei around A=170: $^{168}W_{94}$

Cologne Plunger @ GAMMASPHERE, ANL
→ $^{108}Pd(^{64}Zn,2p2n)^{168}W$
→ 50 HPGe for RDDS: ε= 5% @ 1.3 MeV
→ 12 distances 10 µm – 6400 µm
→ $v_T(^{168}W)$ = 3.3% c = 10.2 µm/ps





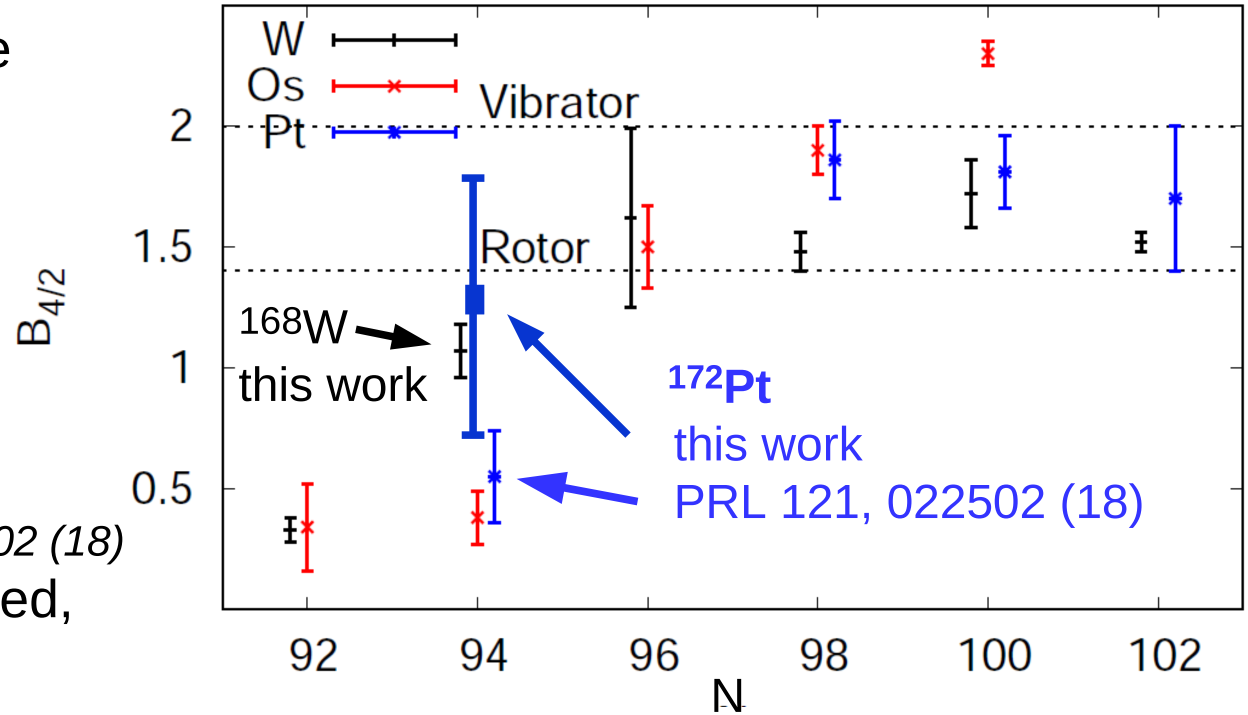
This work: γγ coinc.	Dracoulis et al., PRC 29, 1576R (84)
$\tau(2_1^+)$ 386 (30) ps	307 (15) ps
$\tau(4_1^+)$ 22.5 (23) ps	17 (4) ps
$\tau(6_1^+)$ 14.9 (17) ps	<10 ps
$B_{4/2}$ 1.07 (14)	1.10 (33)
$B_{6/4}$ 0.38 (6)	<0.4

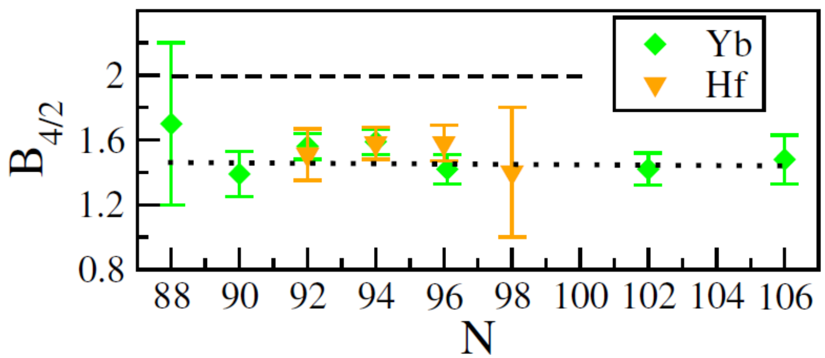
Structural change W – Os – Pt below n midshell

W, Os, Pt: N>94 collective
N≤94: $B_{4/2} \leq 1$
seniority symmetry
→ only expected near
closed shells.
Here: $N_p \geq 4$, $N_n \geq 8$

Shell model W – Os – Pt:
Cederwall et al., PRL 121, 022502 (18)
→ $\nu f_{7/2}$, $\nu h_{9/2}$ strongly mixed,
nearly degenerate
→ attractive ν-π $\nu h_{9/2} - \pi h_{11/2}$
monopole interaction

But: $B_{4/2}$<1 requires very weak
ν-π quad.-quad. interaction
^{168}W: just at transition!
→ **$B_{6/4}$= 0.38 (6)**
→ **structural change for 6_1^+?**





$B_{4/2}$: Yb, Hf rotational

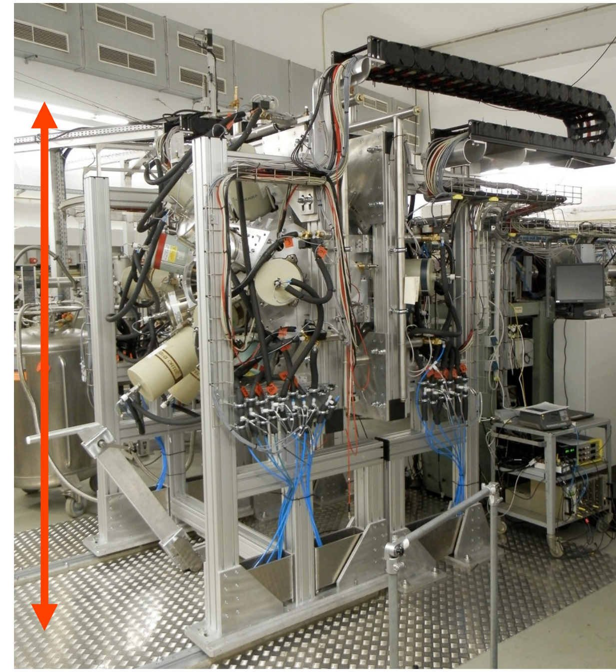
B. Cederwall et al., PRL 121, 022502 (18)

A new spectrometer for lifetime measurements at Cologne

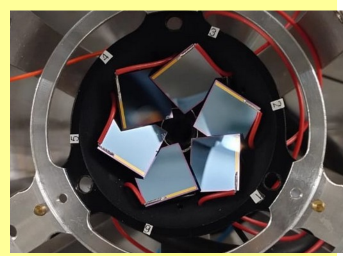
COLOGNE CATHEDRAL

Coincidence **A**rray at the **T**andem accelerator for **H**igh-**E**fficiency **D**oppler **R**ecoil **A**nd **L**aBr fast-timing measurements

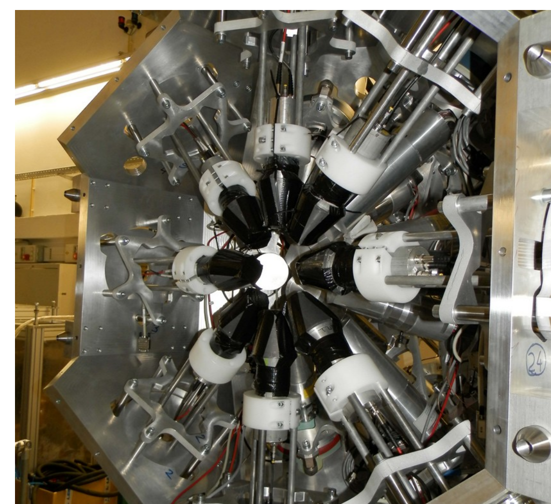
Stefan Thiel, CF; IKP Cologne



→ γ-ray Doppler-shift experiments
→ 33 detector positions:
  24 HPGe, 6 each @ 30°, 55°, 125°, 150°
  8 $LaBr_3(Ce)$ for simultaneous fast-timing
→ charged particle detector array:
  particle-γ-γ coincidences:
   RDDS with γγ coincidences
   in transfer reactions



- γ-γ angular correlation measurements
- ε_{abs}(1.3 MeV) HPGe: 3.5%, LaBr: 0.6%



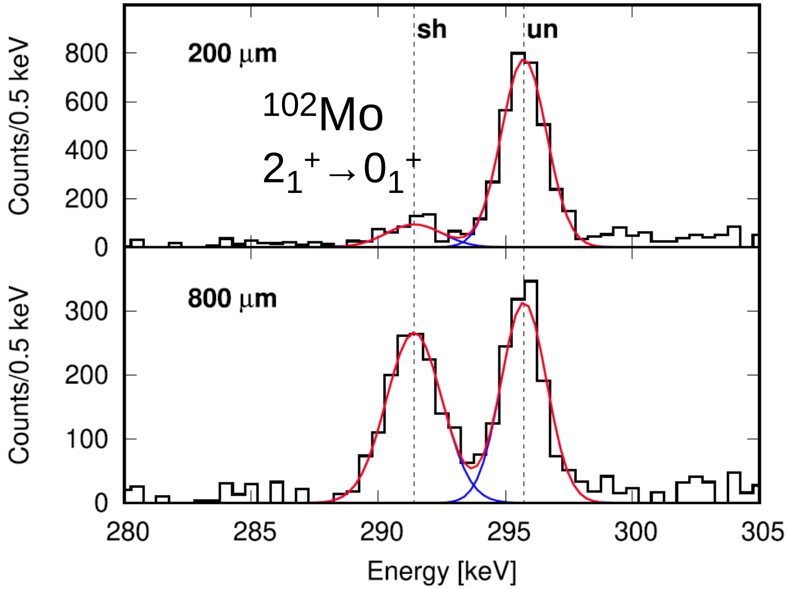
Commissioning CATHEDRAL spectrometer
^{100}Mo(^{18}O,^{16}O)^{102}Mo, Cologne plunger/RDDS + fast timing

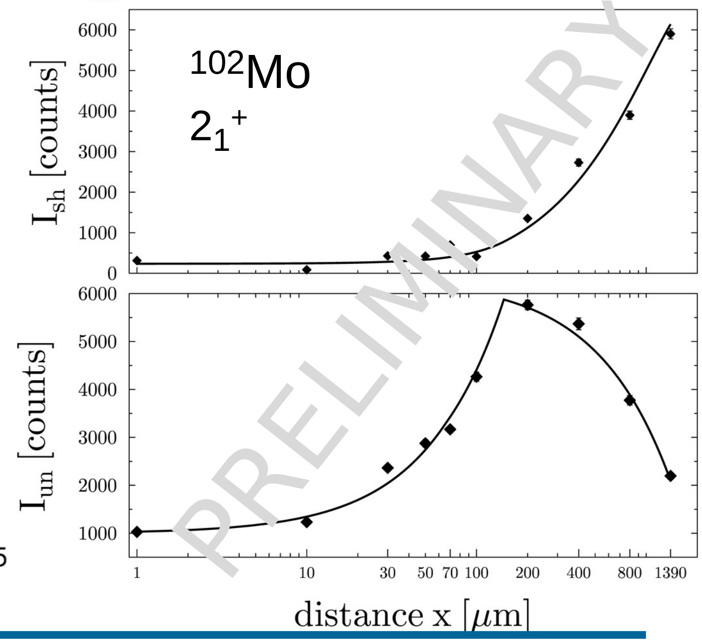
RDDS

Analysis of
$2_1^+ \rightarrow 0_1^+$

Gate: particle+
$(4_1^+ \rightarrow 2_1^+)_{sh}$

8 h / distance
C.D. Lakenbrink,
IKP Cologne

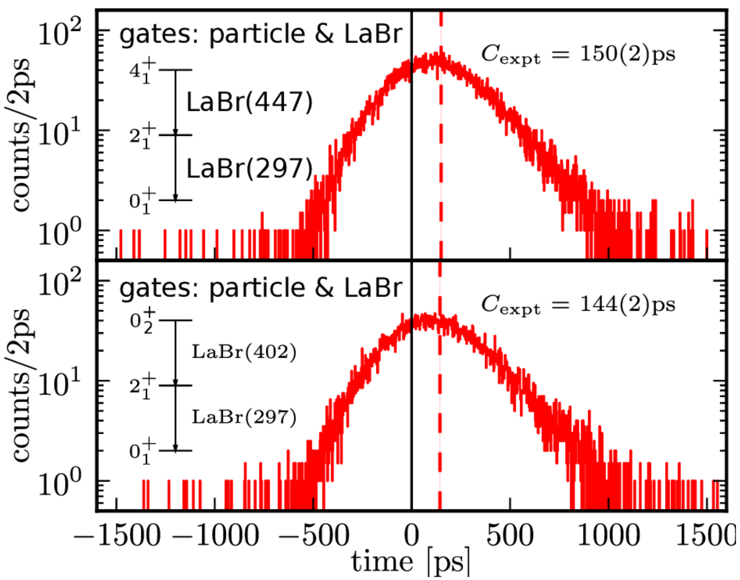




Fast timing

$4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$
$\tau(2_1^+)$ = 180(3) ps

$0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$
$\tau(2_1^+)$ = 186(4) ps
M. Ley, IKP Cologne



^{102}Mo
RDDS: $\tau(2_1^+)$ = 180(3) ps
FT: $\tau(2_1^+)$ = 182(2) ps

A. Esmaylzadeh et al., PRC 104, 064314 (21)
particle-γ: **$\tau(2_1^+)$ = 150(10) ps**
NNDC: **$\tau(2_1^+)$ = 180(6) ps**

Conclusion

- **Development of sophisticated compact plunger devices:**
  GAMMASPHERE/GRETINA+FMA/AGFA @ Argonne
  JUROGAM+MARA/RITU @JYFL
  PRISMA + AGATA @ LNL
- **Investigation of structure south-east and east of ^{48}Ca**
- **Hints for shape coexistence in mid-shell Te**
- **Structure in neutron-deficient nuclei around A=170**
  → shape evolution in Pt
  → region in Os – W – Pt with $B_{4/2}$<1 for N<96
- **New Cologne CATHEDRAL spectrometer**
  → combined γ-ray Doppler-shift measurements (RDDS, DSAM) and fast timing
  → high efficiency: particle-γ-γ coincidences

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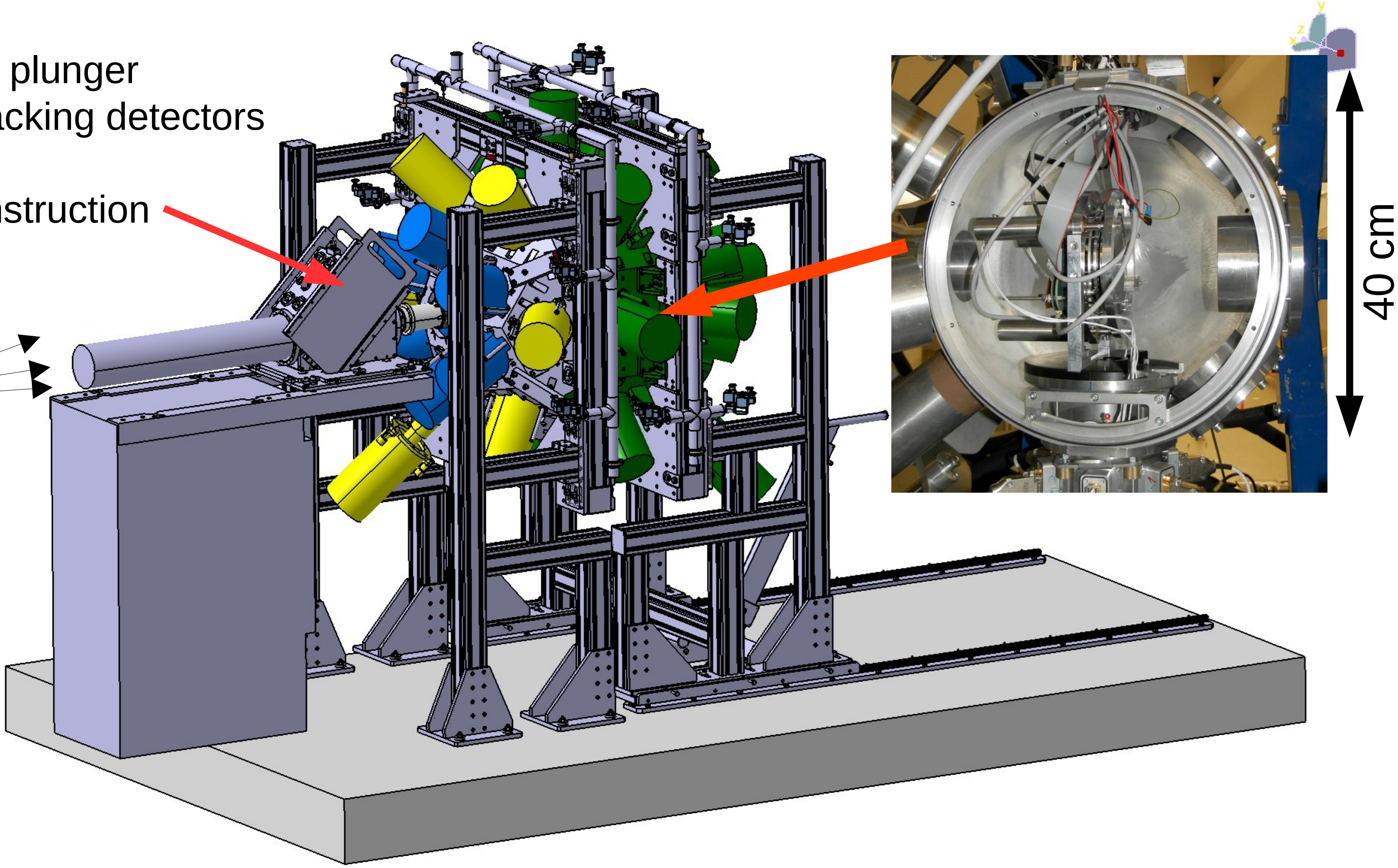
Commissioning of HISPEC plunger for FAIR @ Cologne

Future: HISPEC plunger
+ MCP beam tracking detectors
@CATHEDRAL
→ precise reconstruction
of kinematics

32S
85 MeV



Simulate large area beam (slowed down radioactive beam @ FAIR)
→ already done: commissioning HISPEC plunger @ Cologne
precision, repeatibility proven!

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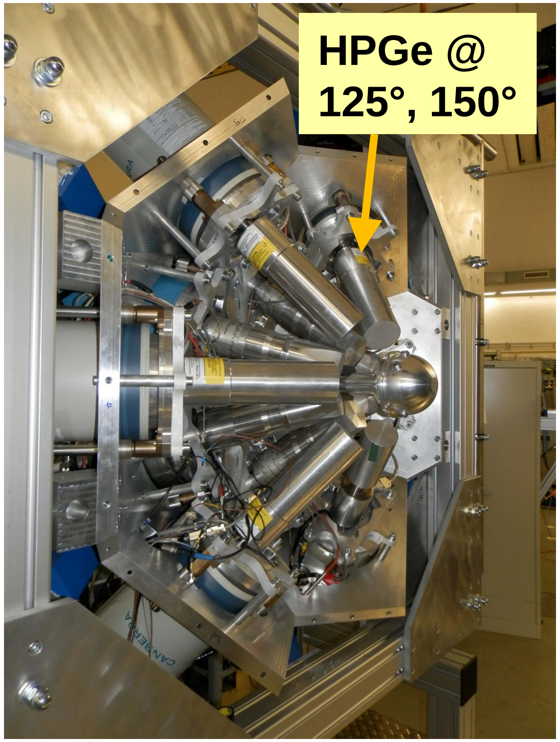
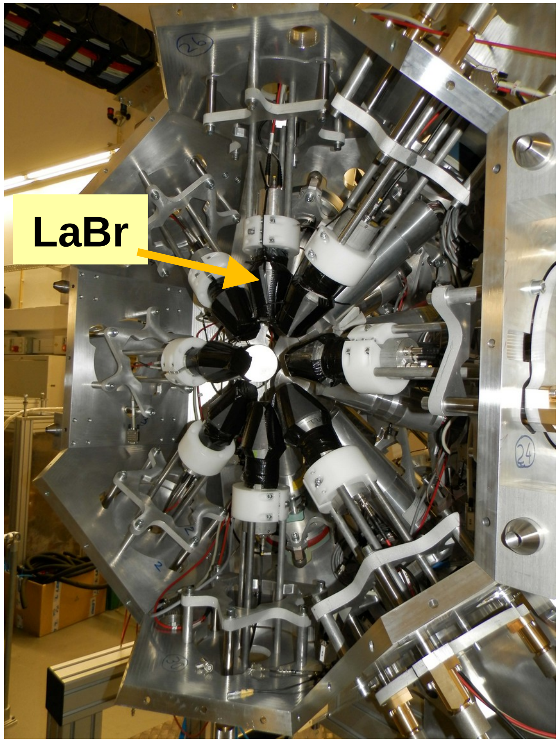
CATHEDRAL spectrometer: realization



Upstream:
detector rings 125°, 150°
+ Plunger chamber

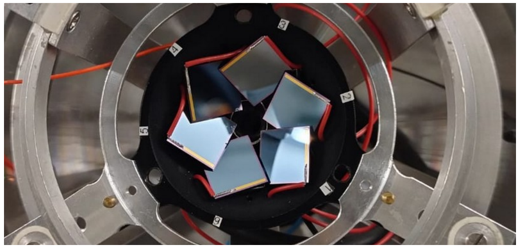


Downstream part
detector rings 30, 55°
8 LaBr3(Te) @ 90°

HPGe @
30°, 150°
hexagonal
crystals and
endcaps
→ max. eff.

γ-ray efficiency (^{226}Ra):

	24 HPGe	**8 LaBr3(Ce)**
351 keV	7.03 %	2.16 %
609 keV	5.05 %	1.11 %
1120 keV	3.60 %	0.69 %
1764 keV	2.70 %	0.43 %



PIN diodes (solar cells)
@ 115-165°
→ charge particles det.
transfer reactions

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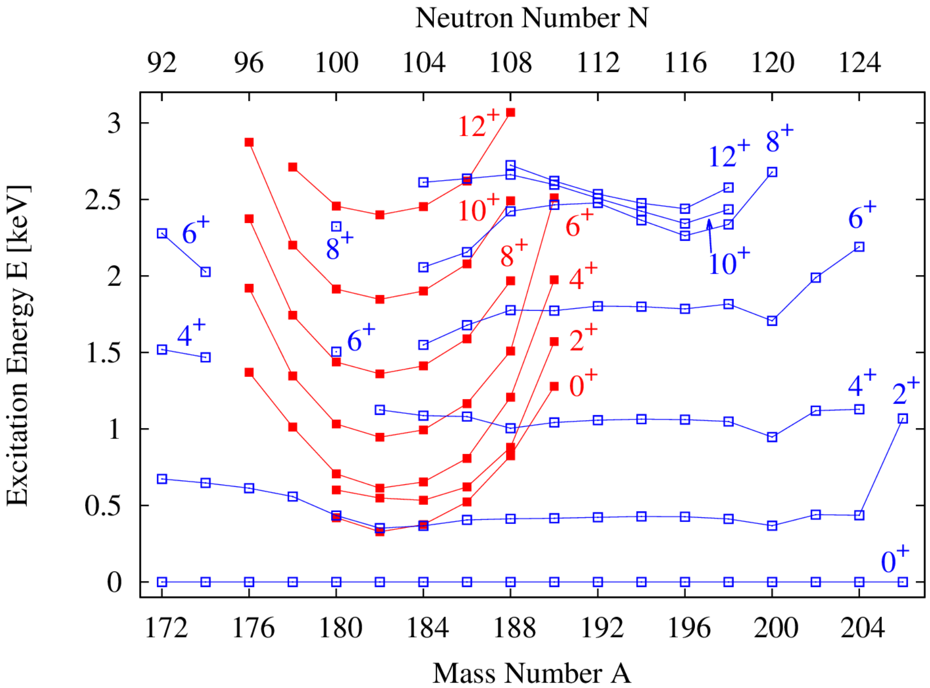
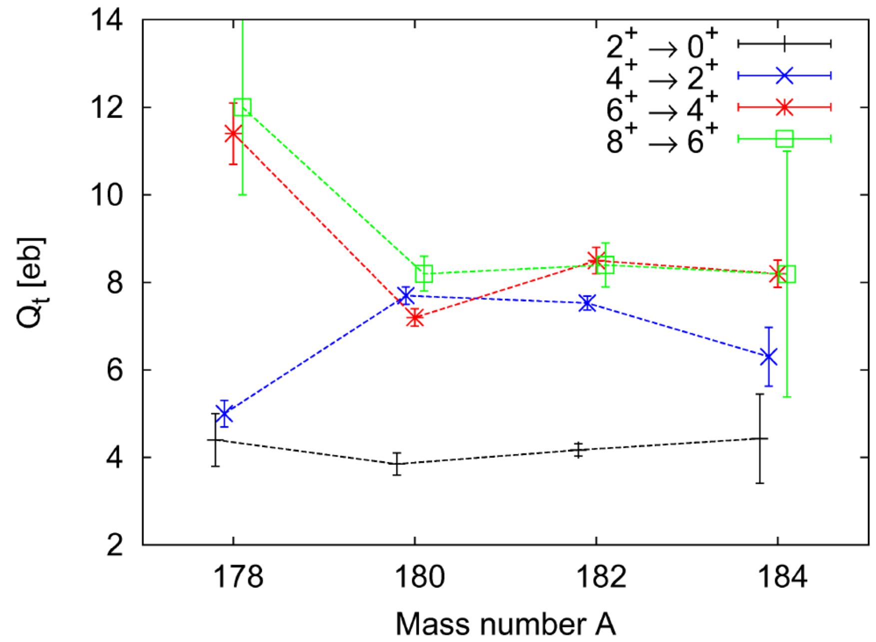
Structural evolution in n-deficient nuclei around A=170

→ Introduction: Shape coexistence in Hg





Hg: weakly deformed ground state conf., prolate intruder

→ level schemes

→ Q_t systematics

e.g. PRC 80, 014324 (09)

evolution towards intermediate def. in ^{178}Hg

C. Müller-Gatermann et al., PRC 99, 054325 (19)

Similar in Pt?

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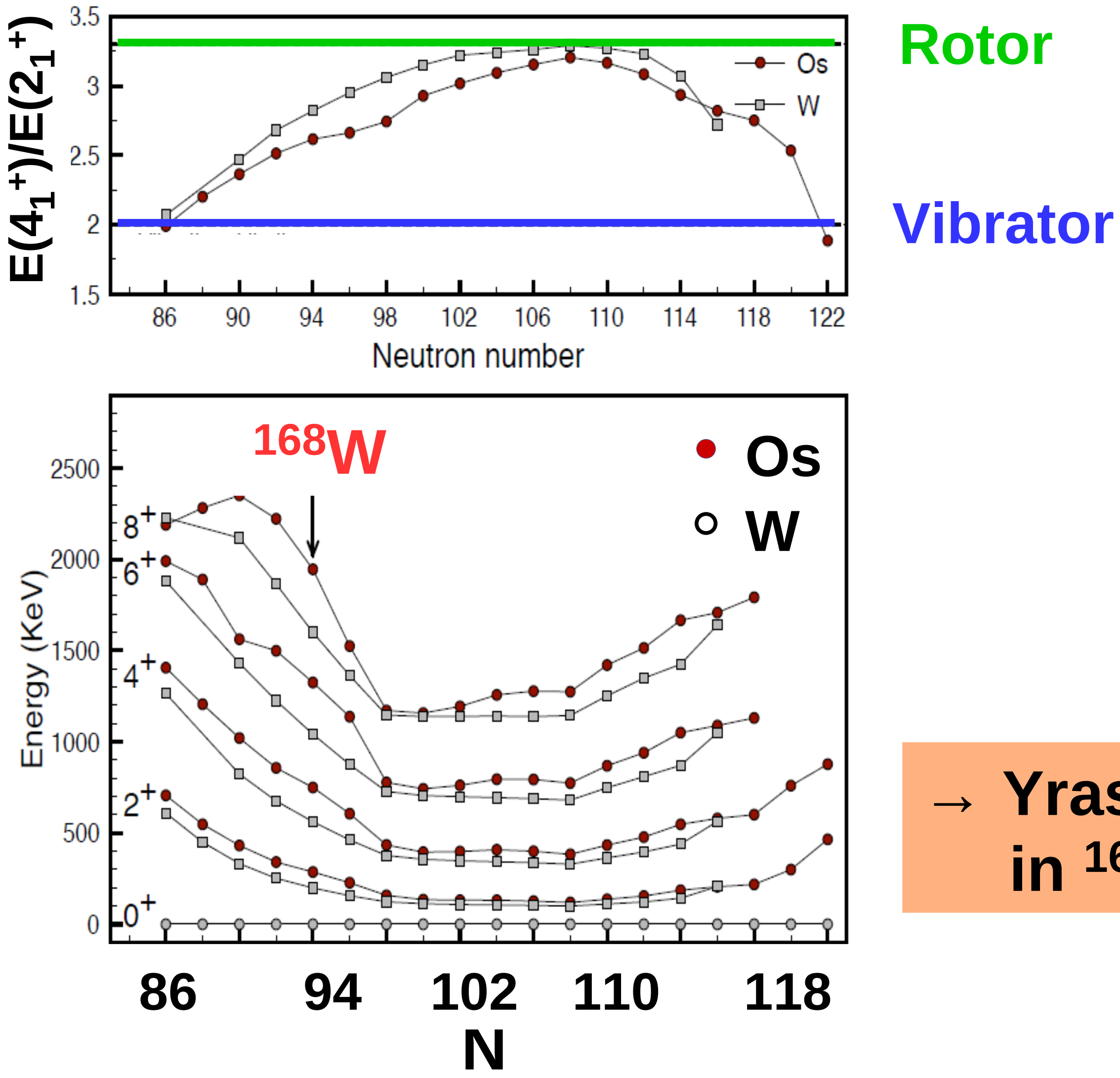
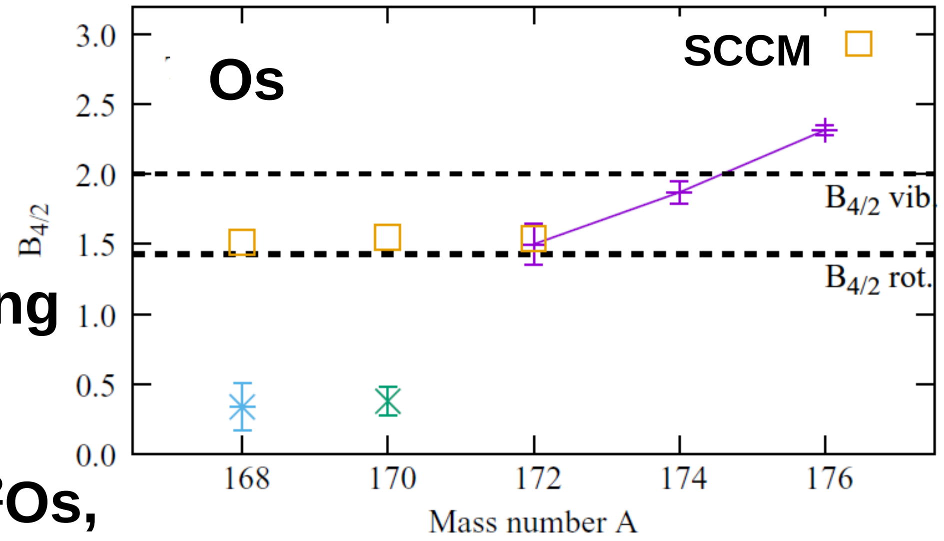
Neutron deficient W, Os: analogy to Pt?



→ Yrast B(E2) in ^{168}W

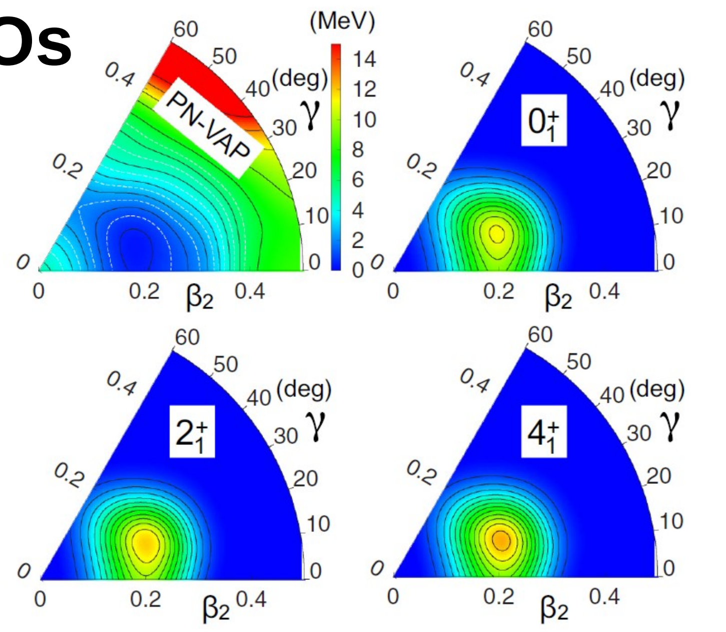
A. Goasduff et al., PRC 100, 034302 (19)

→ symm. conserving conf. mixing calc. (SCCM) for Os



→ reproduce $E(2_1^+)$, $E(4_1^+)$ $^{168-172}$Os, $B_{4/2}$ ^{172}Os

^{170}Os

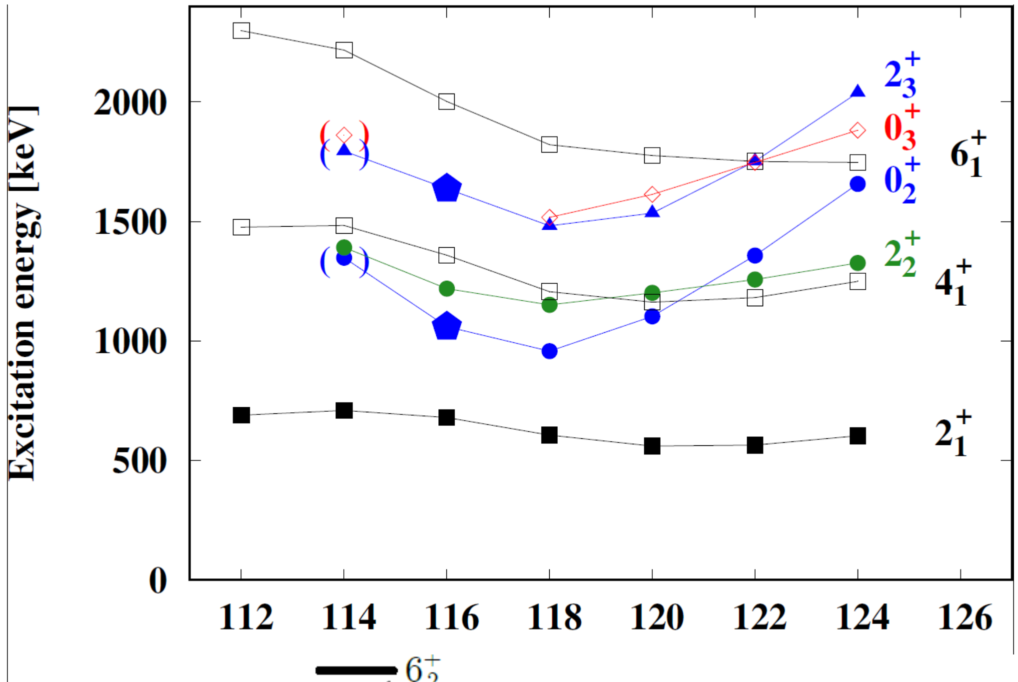


→ possible: $B_{4/2}<1$: 4_1^+ belongs to shape coexisting rotational band

→ no evidence from SCCM calc.

→ similarities for $^{166-170}$W?

Shape coexistence in Te isotopes?

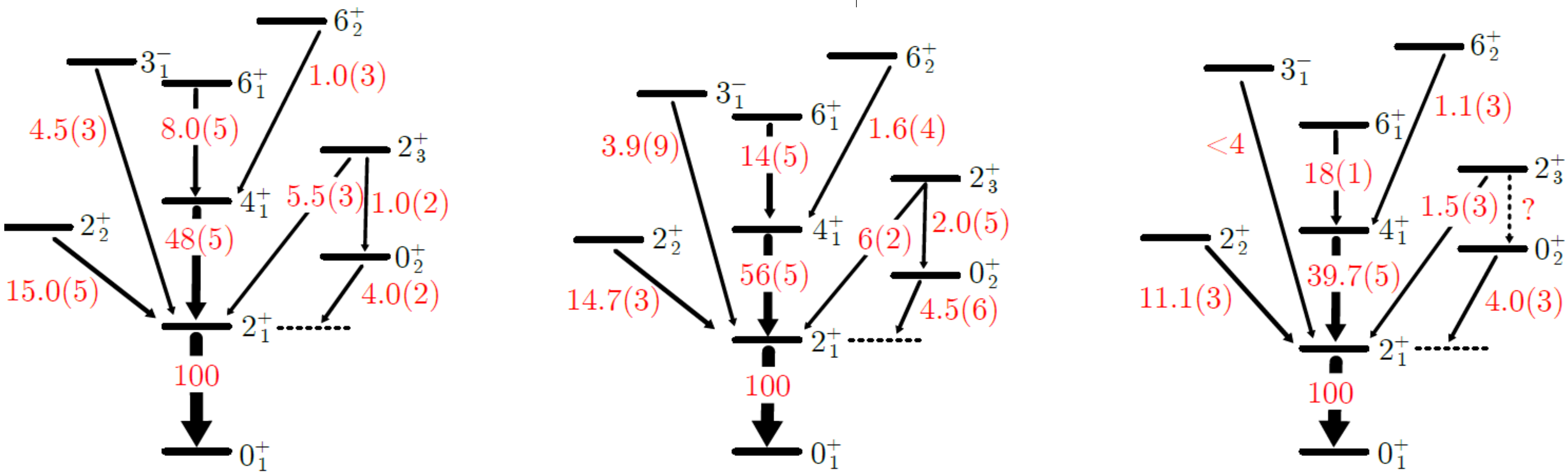


F. von Spee, IKP Cologne

Level schemes

0_2^+, 2_3^+: „typical“ for intruders

(cf. Hg, Pt,...)



^{116}Te ^{118}Te ^{120}Te

Commissioning CATHEDRAL spectrometer results fast timing ^{102}Mo, ^{100}Mo, ^{114}Sn

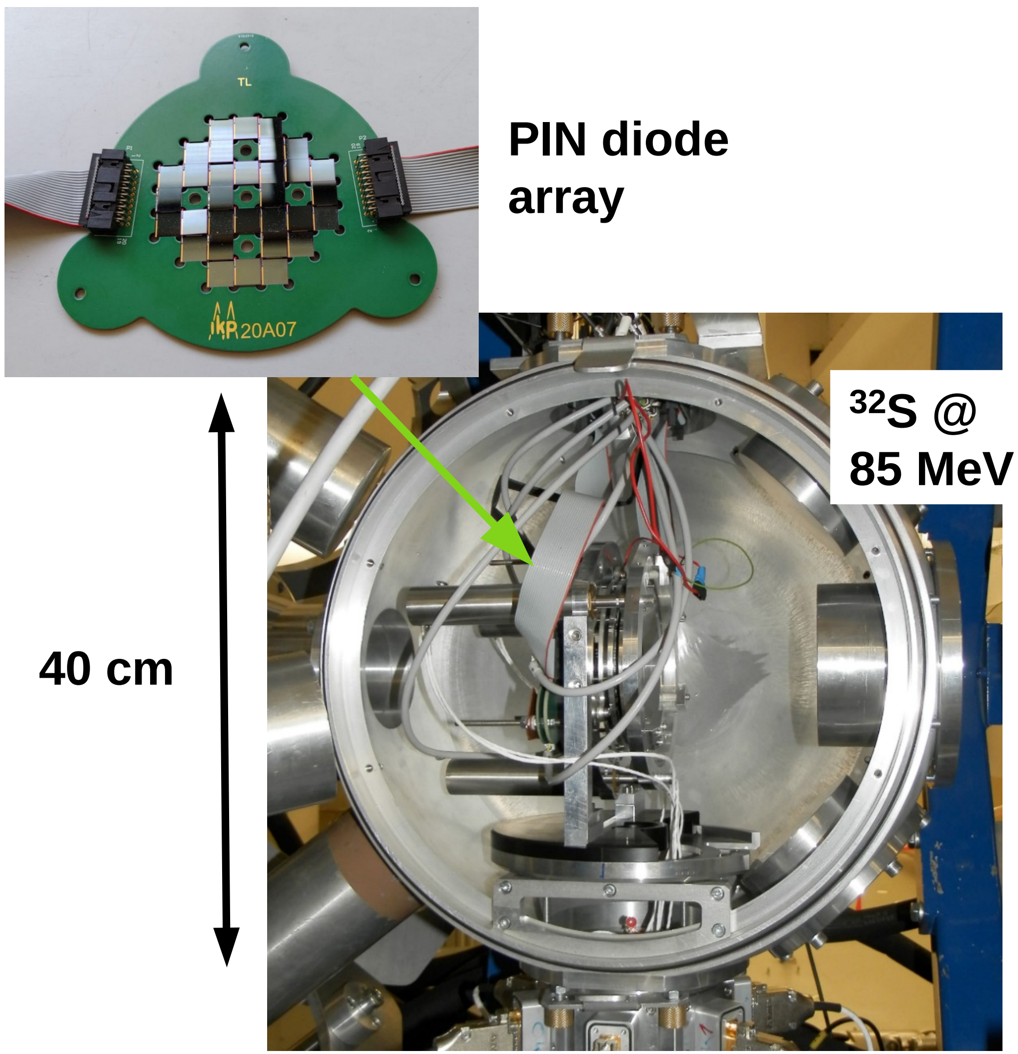
nucleus	state J^π	cascade keV	P/B feeder—decay	τ ps	$\tau_{adopted}$ ps	$\tau_{aliterature}$ ps
^{102}Mo	2_1^+	447—297 402—297	1.60(2)—2.24(2) 0.93(2)—1.84(2)	180(3) 186(4)	*182(2)*	180(6) [a]
	4_1^+	584—447	0.34(2)—0.53(2)	17(9)	*17(9)*	18(4) [a]
^{100}Mo	2_1^+	600—536	2.30(3)—5.02(5)	16(2)	*16(2)*	17.9(3) [b]
^{114}Sn	2_1^+	888—1300	18.0(3)—23.1(4)	< 4	*<(4)*	0.61(4) [c]
	4_1^+	628—888	10.77(11)—8.11(8)	4.7(14)	*4.7(14)*	7.6(6) [c]
	5_1^-	272—628	8.21(7)—9.53(8)	42.1(14)	*42.1(14)*	>2 [c]

[a] D. De Frenne, Nucl. Data Sheets 110, 8 (2009)
[b] B. Singh and J. Chen, Nucl. Data Sheets 172, (2021)
[c] J. Blachot, Nucl. Data Sheets 113, 2 (2012)

M. Ley
IKP Cologne

^{102}Mo RDDS: t(2_1^+) = 180(3) ps

Commissioning HISPEC Plunger for FAIR at Cologne



FN Tandem Cologne

Beam focusing on 5 points
20 mm apart

solar cell array:
detect backscattered particles

Coulex ^{181}Ta: beam ^{32}S @ 85 MeV

use known lifetimes of ^{181}Ta
$\tau(11/2^{+}) = 23(4)$ ps
$\tau(13/2^{+}) = 9.1(11)$ ps

Check parallelity with precision
~1 um

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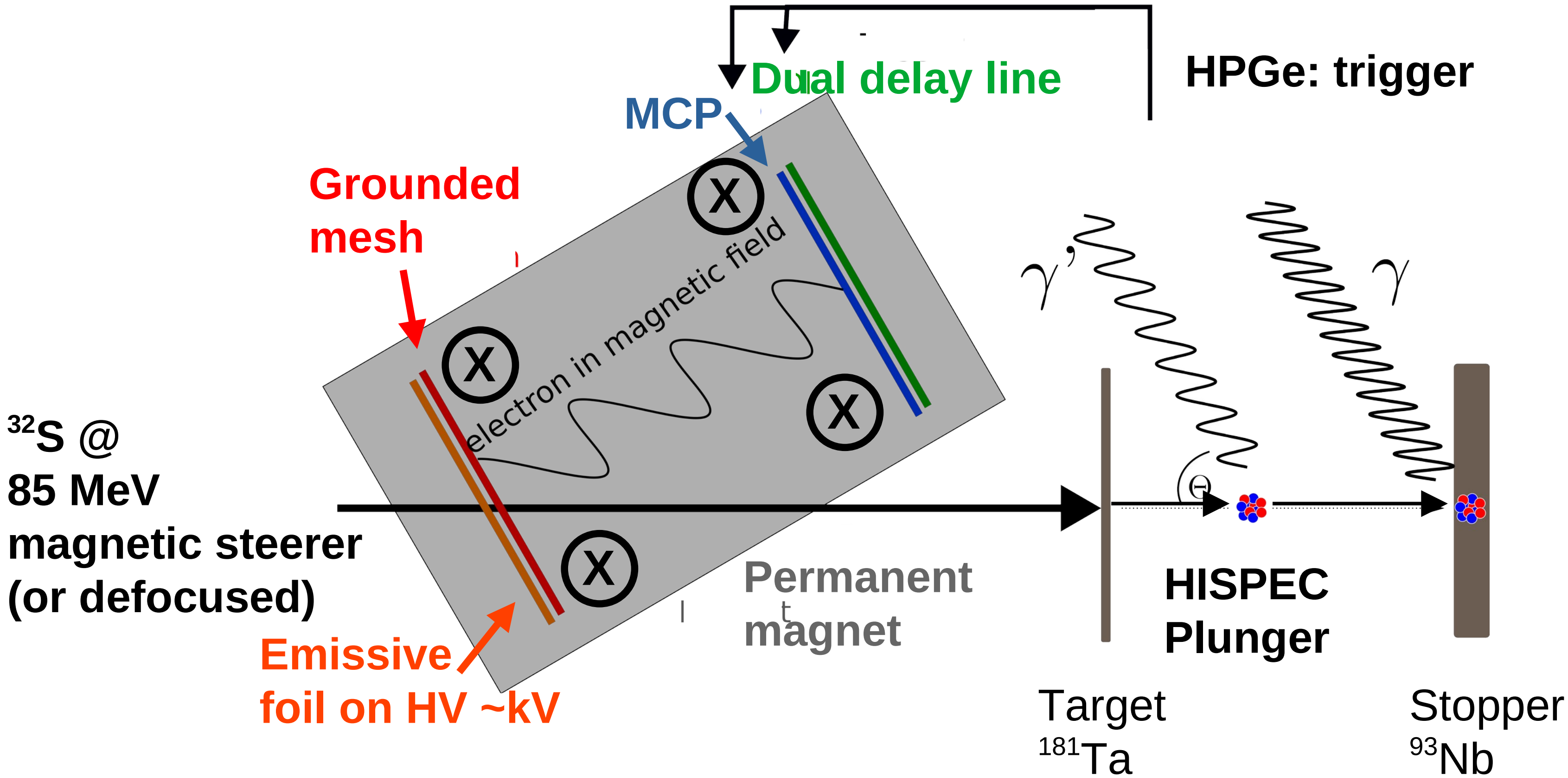
Experiment with HISPEC Plunger at Cologne with event-by-event reconstruction of kinematics



Beam tracking detector
-> reconstruct interaction point on target

Dennis Bittner, IKP Cologne

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