Absolute electromagnetic transition rates in semi-magic N = 50 and 126 isotones as a test for $(g_{9/2})^n$ single particle calculations.

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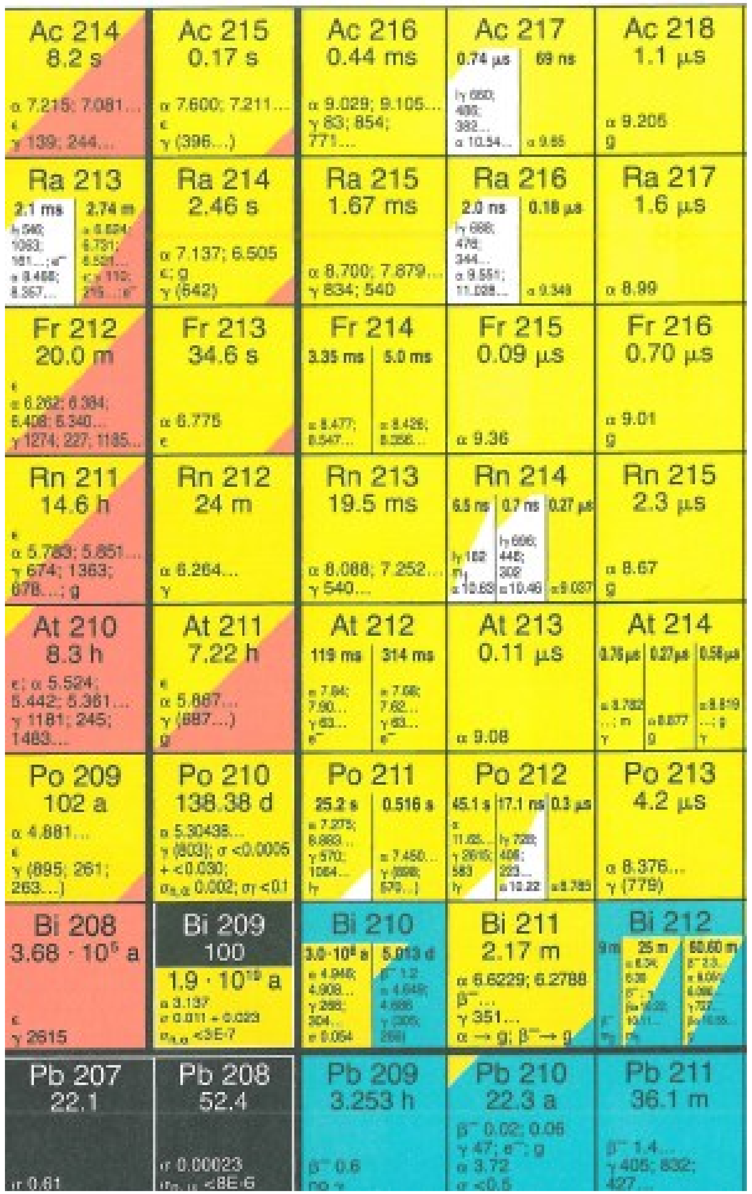
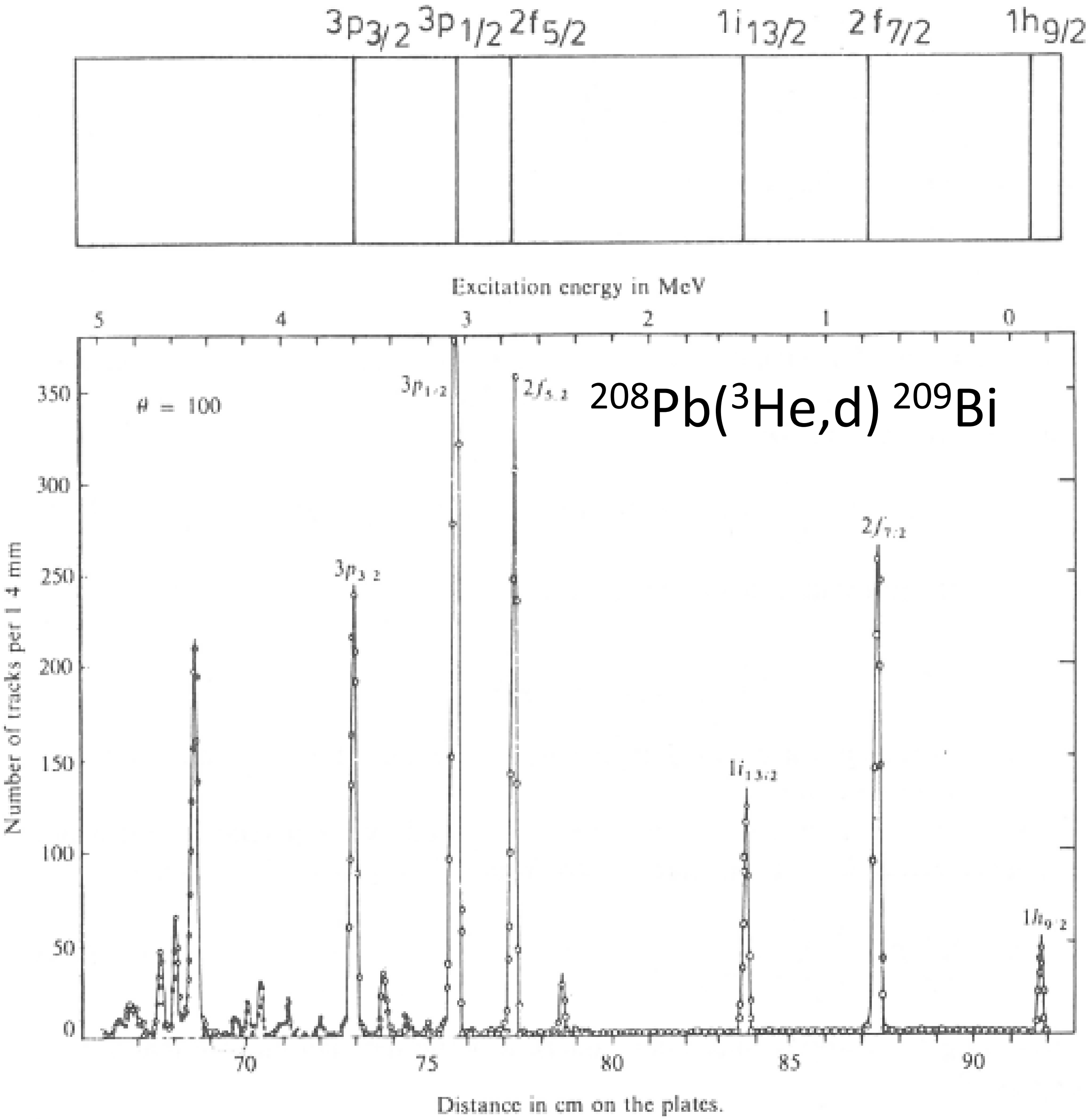
1. Motivation
2. Studies of 211-At
3. Ongoing experiments on N = 50 isotones
4. Conclusions and outlook

1. Motivation

N= 126 Isotones





Two approaches can be followed:

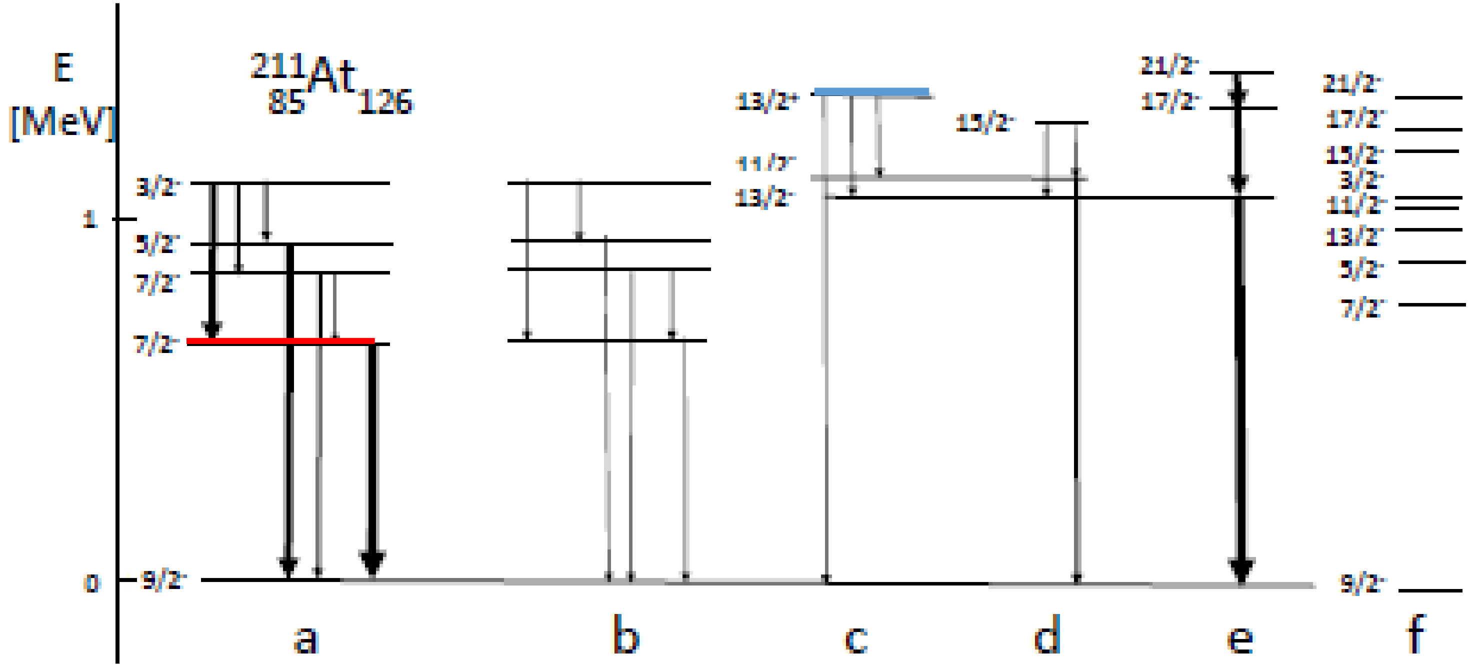
Untruncated **numerical full shell model calculations** with the modified Kuo-Herling Particle (KHP) interactions and all proton orbits between Z= 82 and Z=126.

Analytical single-j calculations with a seniority conserving interaction or with empirical two-body matrix elements.

$$\underbrace{E(j^3[I]J)}_{\text{Energy of state in } ^{211}\text{At}} = 3 \underbrace{\sum_R}_{\text{Sum over states in } ^{210}\text{Po}} \underbrace{[j^2(R)jJ|\}j^3[I]J]^2}_{\text{CFP}^2} \underbrace{E(j^2R)}_{\text{Energy of state in } ^{210}\text{Po}}$$

A de Shalit and I. Talmi, The Nuclear Shell Model (1963)

First detailed study of ^{211}At at ISOLDE and the Stockholm cyclotron.



$(\pi 1h_{9/2})^3$

$(\pi 1h_{9/2})^2 \pi 1i_{13/2}$

$(\pi 1h_{9/2})^2 \pi 2f_{7/2}$

^{211}Rn
β decay

^{209}Bi(α,2n) ^{211}At
reaction

$(\pi 1h_{9/2})^3$

Bergström et al. Phys Lett. B 32 (1970)476

Recently, this approach was extended to electromagnetic quadrupole transition rates by Piet Van Isacker.

Assumptions:

Seniority is conserved.

The effective charges in one-body E2 operator of the two-j nucleus can be state dependent.

The effective charges in the quadrupole moment of the state with spin R are the same as those for *B(E2;R→R-2)* = B_R in the two-particle nucleus.

Then the following relation can be obtained:

$$B(\mathrm{E2}; j^3[I]J \to j^3[I']J') = \left(\sum_R g_j(J, I, J', I', R)\sqrt{B_R} \right)^2$$

First application to ^{135}I as $(\pi 1g_{7/2})^3$ Spagnoletti et al. Phys. Rev. C 95 (2017) 021302

State dependent effective charges are needed in ^{210}Po.

J_i^π	E_x (MeV)		$B(E2; J_i \to J_f)$(e^2fm^4)				
	Expt	SM	J_f^π	Expt	SM1-gh^a	SM2-gh^b	SM^b
2_1^+	1.181	1.200	0_1^+	136(21)^c	263	137	133
4_1^+	1.427	1.466	2_1^+	335(14)	302	157	169
6_1^+	1.473	1.482	4_1^+	229(7)	209	109	116
8_1^+	1.557	1.533	6_1^+	84(3)	84	44	46

[a] With $e_\pi = 1.51e$.

[b] With $e_\pi = 1.09e$.

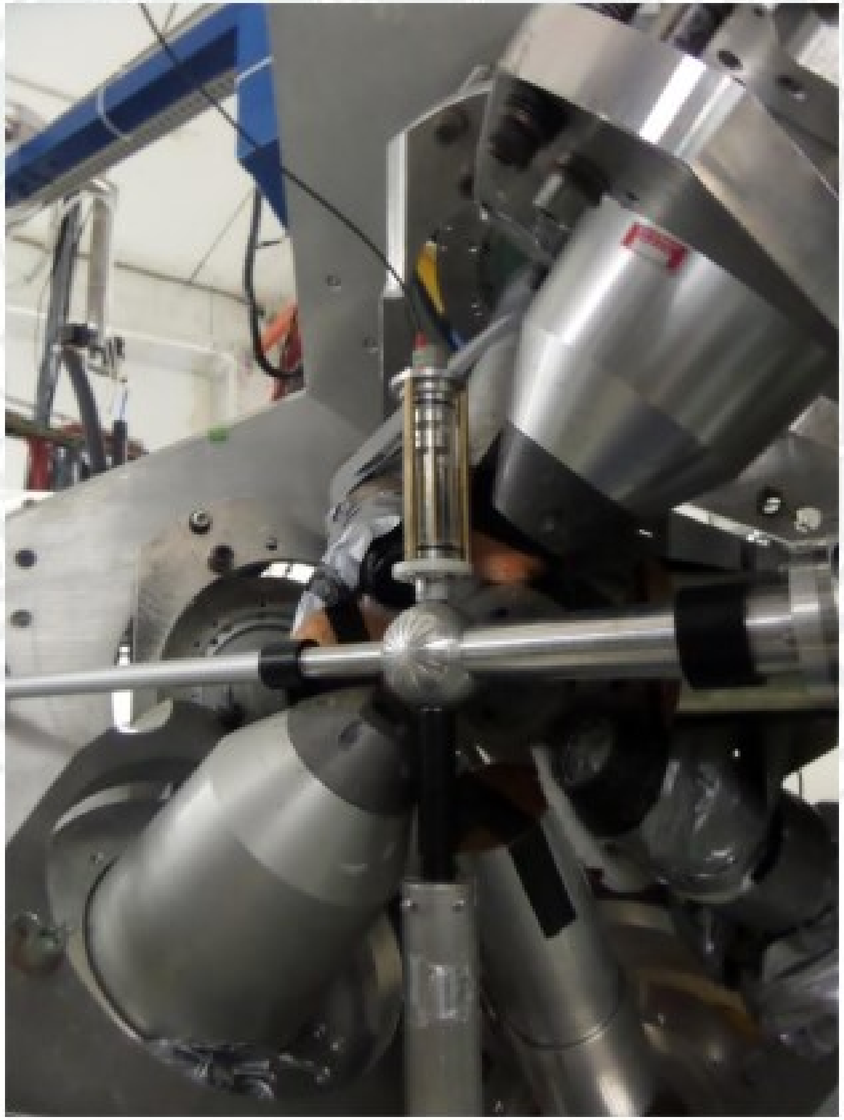
[c] From Ref. [36].

D. Kocheva et al., Eur. Phys. Journ. A 53 (2017) 175

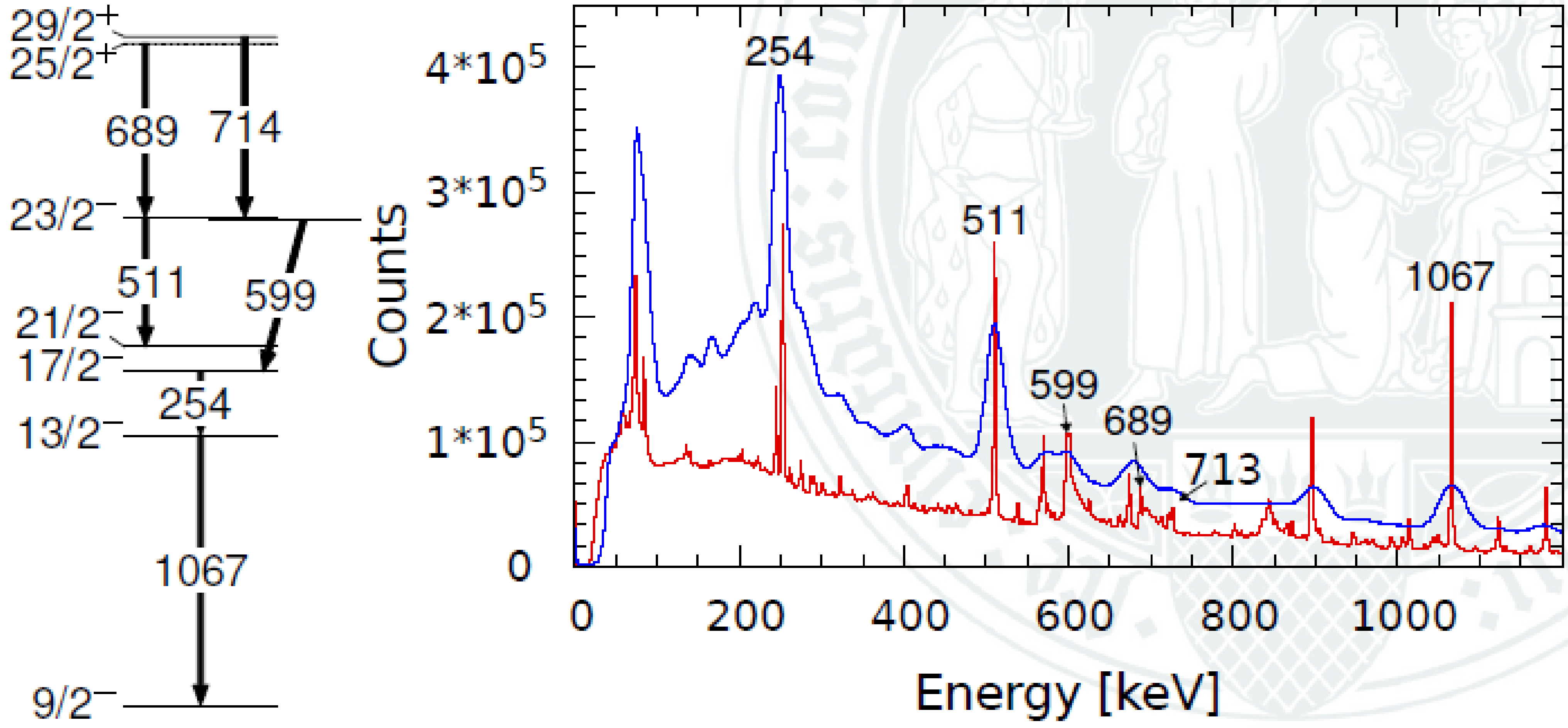
2. Studies of 211-At

2.1 Fast timing results

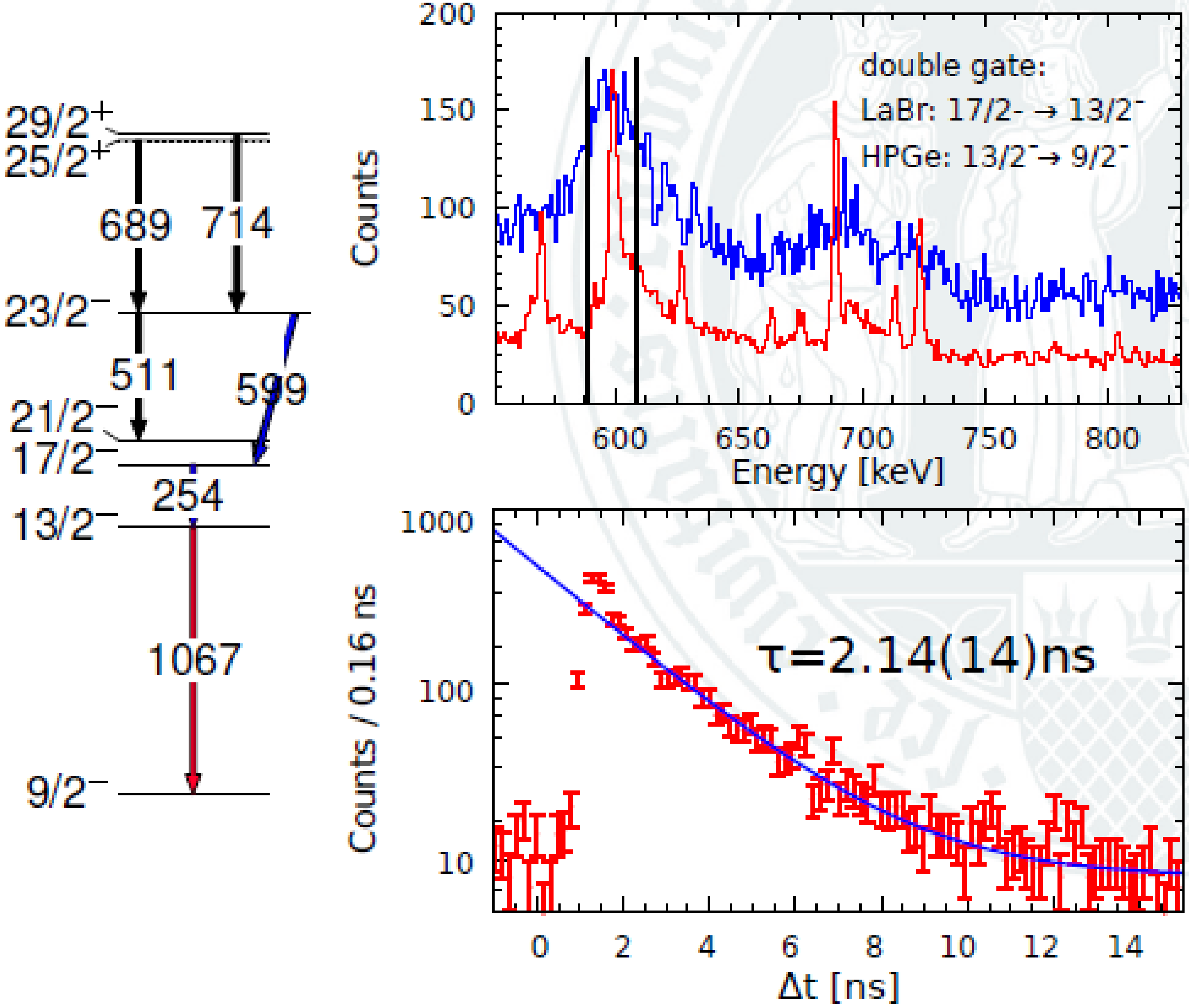
- $^{208}Pb(^{6}Li,3n)^{211}At$ @ 34 MeV
- Target:
- 54 mg/cm^2 208*Pb*
- 100 mg/cm^2 181*Ta* backing
- I= 5 pnA
- 8 HPGe + 9 ø1.5x1.5'$LaBr_3$ (6 BGO)



Triple coincidences and scheme

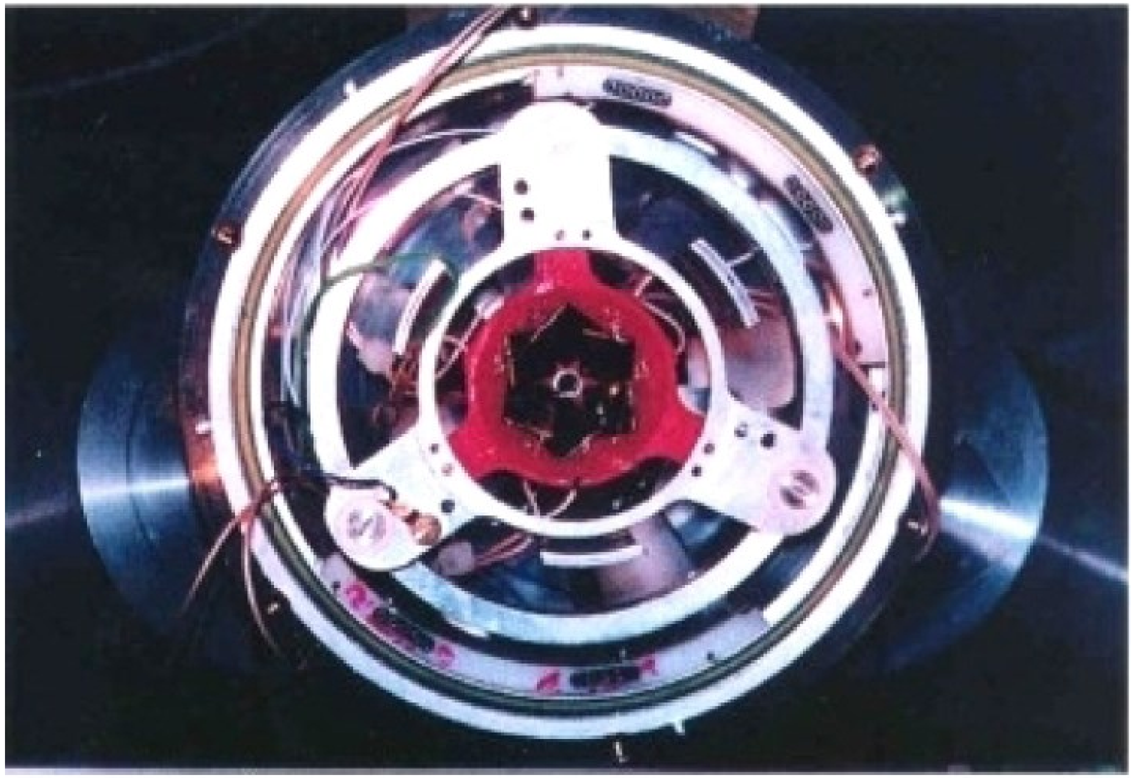


The 17/2⁻ excited state



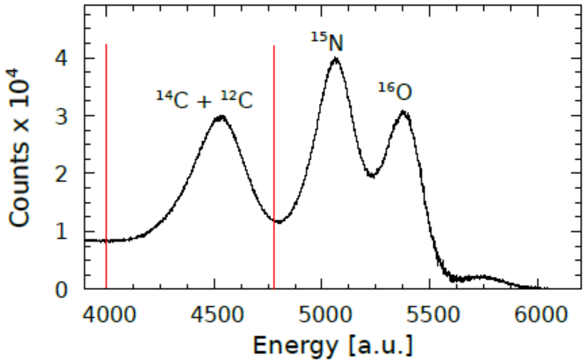
2.2 Recoil Distance Doppler Shift (RDDS) experiment at the Cologne Tandem.

^{209}Bi(^{16}O, ^{14}C) ^{211}At two-proton transfer reaction with 84 MeV ^{16}O beam and ^{14}C detection with solar cells mounted in the Cologne plunger. Eleven HpGe detectors were mounted in two rings at 45 and 142 degrees.
Target 1.1mg/cm^2 ^{209}Bi on 0.4 mg/cm^2 Mg backing. Stopper was 1.1 mg/cm^2 Mg.

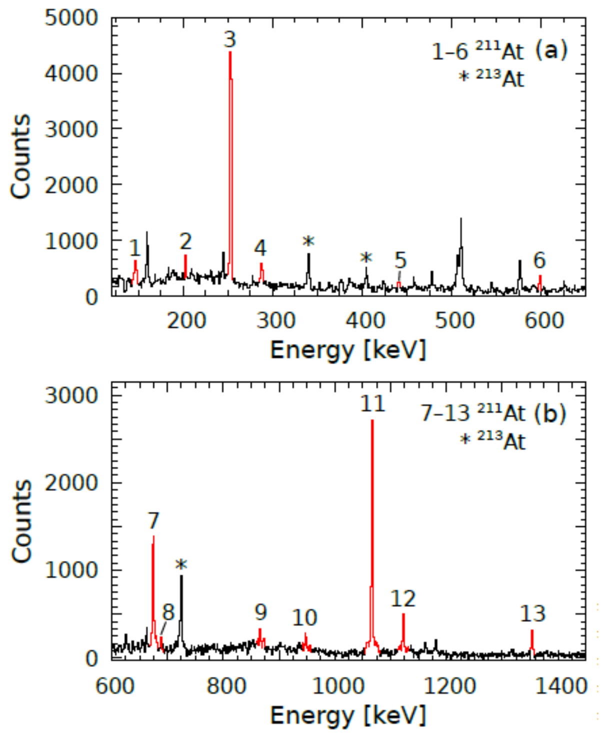


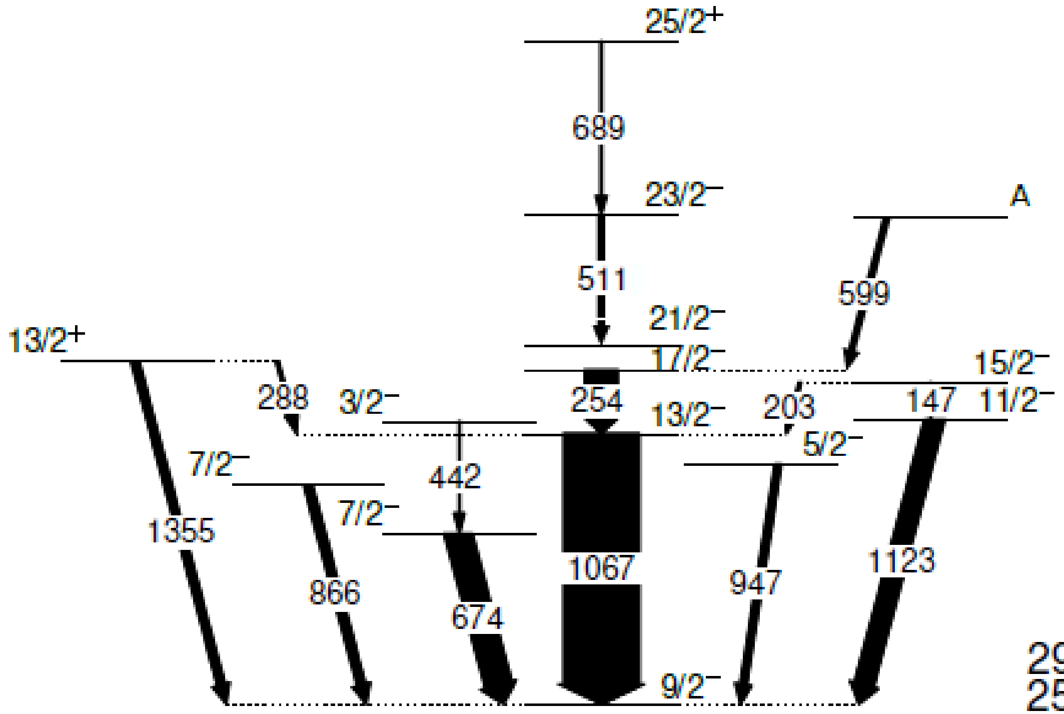
V. Karayonchev et al., Phys. Rev. C 106, (2022) 044321

Particle gate

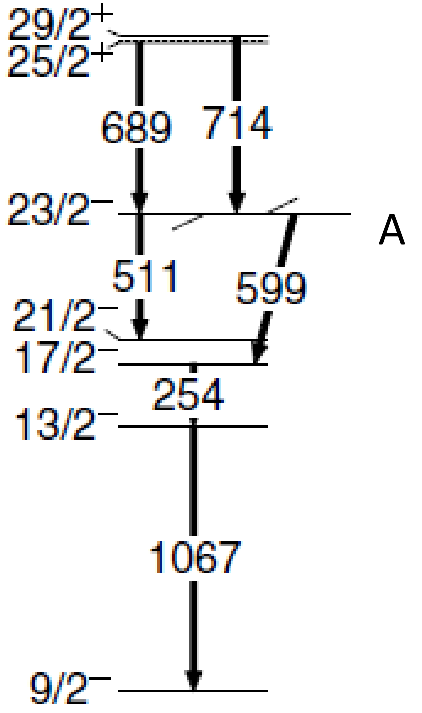


Gated single spectrum

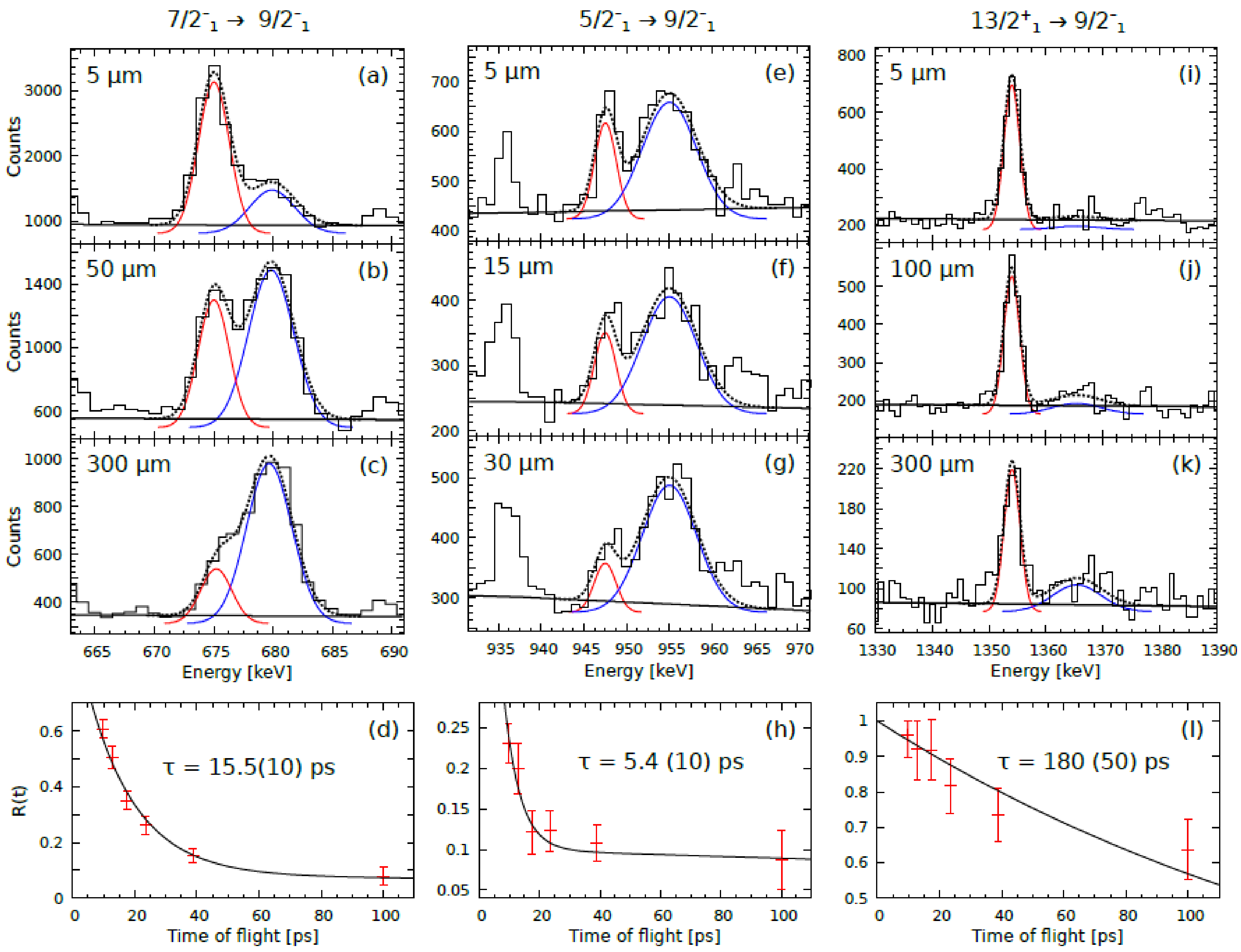




The low-spin states are much more populated in the (^{16}O, ^{14}C) two-proton transfer reaction than in the (6Li,3n) fusion evaporation reaction.



Results for forwards ring:



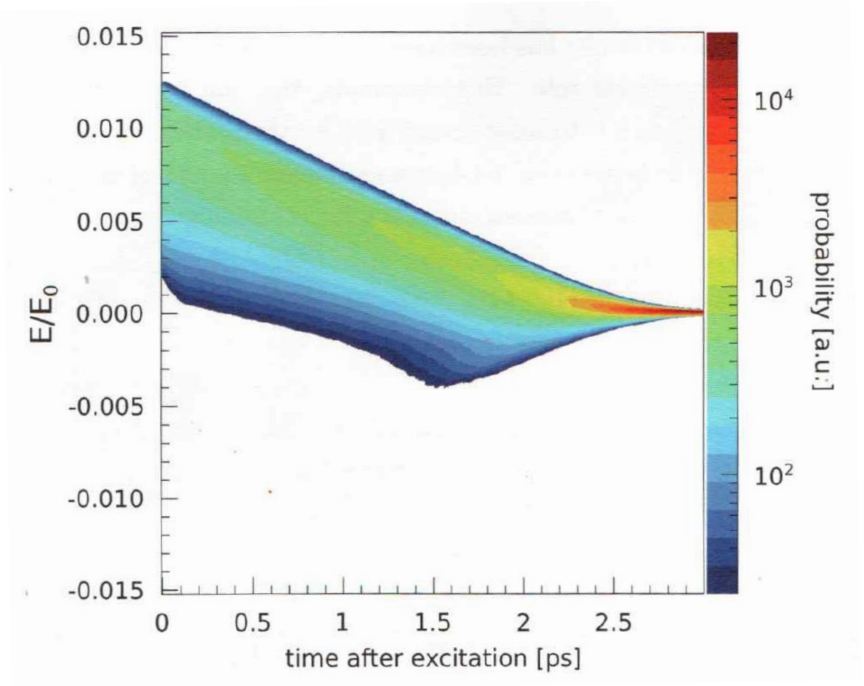
State	Lifetime [ps]		
	Forward	Backward	Adopted
	RDDS		
$7/2_1^-$	15.5(10)	14.5(10)	**15.0(7)**
$5/2_1^-$	5.4(10)	—	**5.4(10)**
$13/2_1^+$	180(50)	260(60)	**220(80)**

$$R_i(t) = I_i^u(t)/[I_i^s(t) + I_i^u(t)].$$

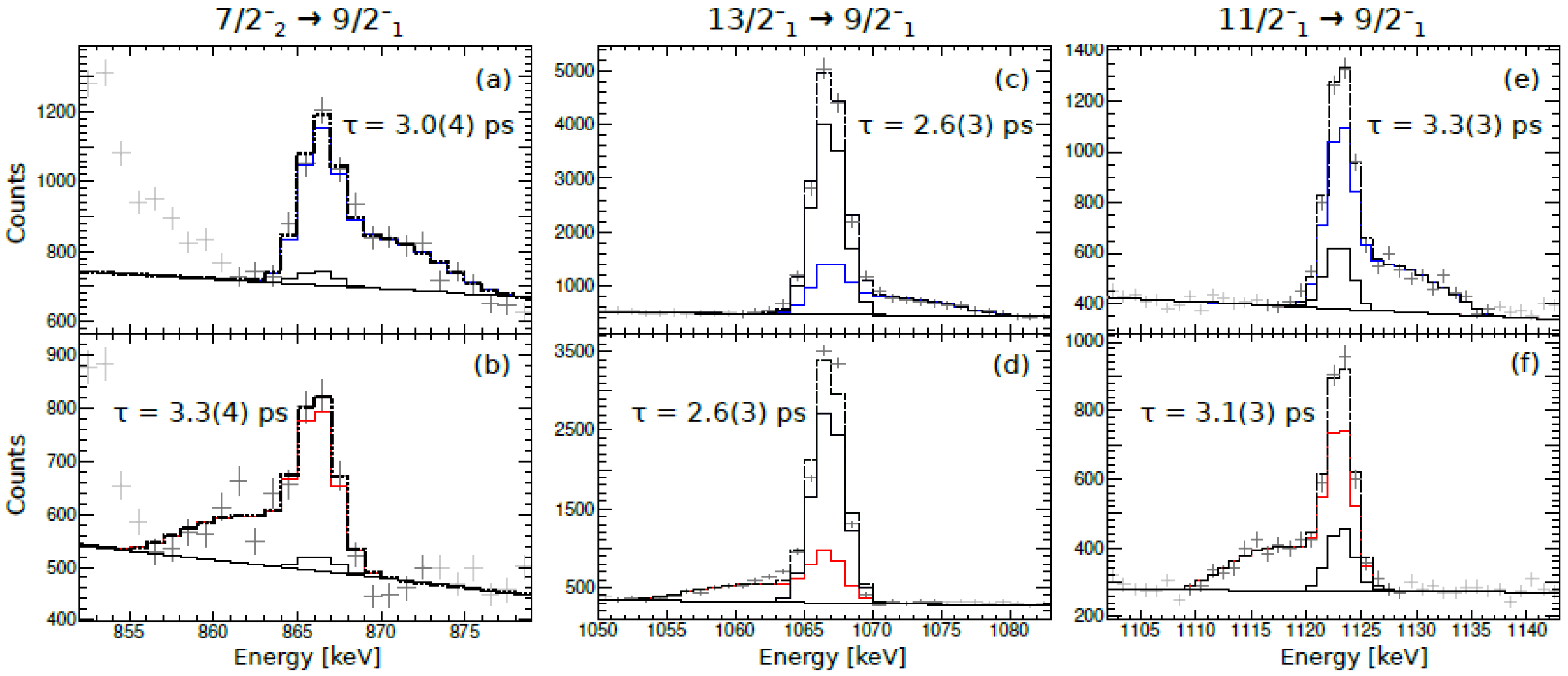
2.3 Doppler Shift Attenuation Method experiment at the Cologne Tandem

^{209}Bi(^{16}O, ^{14}C) ^{211}At two-proton transfer reaction with 84 MeV ^{16}O beam and ^{14}C detection with solar cells mounted in the Cologne plunger set up.
Target 0.5 mg/cm^2 ^{209}Bi on 1.5 mg/cm^2 Mg backing.

Analyse with APCAD code of Christian Stahl:



Results:



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Using the new lifetimes

State J^π	E_{feeder} (keV)	E_{decay} (keV)	HPGe gate (kev)	τ (expt.) (ps)	τ (lit.) (ps)
$13/2^-$	254	1067	511	$\leqslant 7$	$\leqslant 200$
$17/2^-$	599	254	1067	2140(140)	$\leqslant 100$
$23/2^-$	689	511	254 and 1067	56(5)	$\leqslant 300$

State	Lifetime [ps] Forward	Backward	Adopted
	RDDS		
$7/2_1^-$	15.5(10)	14.5(10)	**15.0(7)**
$5/2_1^-$	5.4(10)	—	**5.4(10)**
$13/2_1^+$	180(50)	260(60)	**220(80)**
	DSAM		
$7/2_2^-$	3.0(4)	3.3(4)	**3.15(30)**
$13/2_1^-$	2.6(3)	2.6(3)	**2.6(2)**
$11/2_1^-$	3.3(3)	3.1(3)	**3.2(2)**

The B(E2) values can be compared to the theoretical predictions.
KHP* with

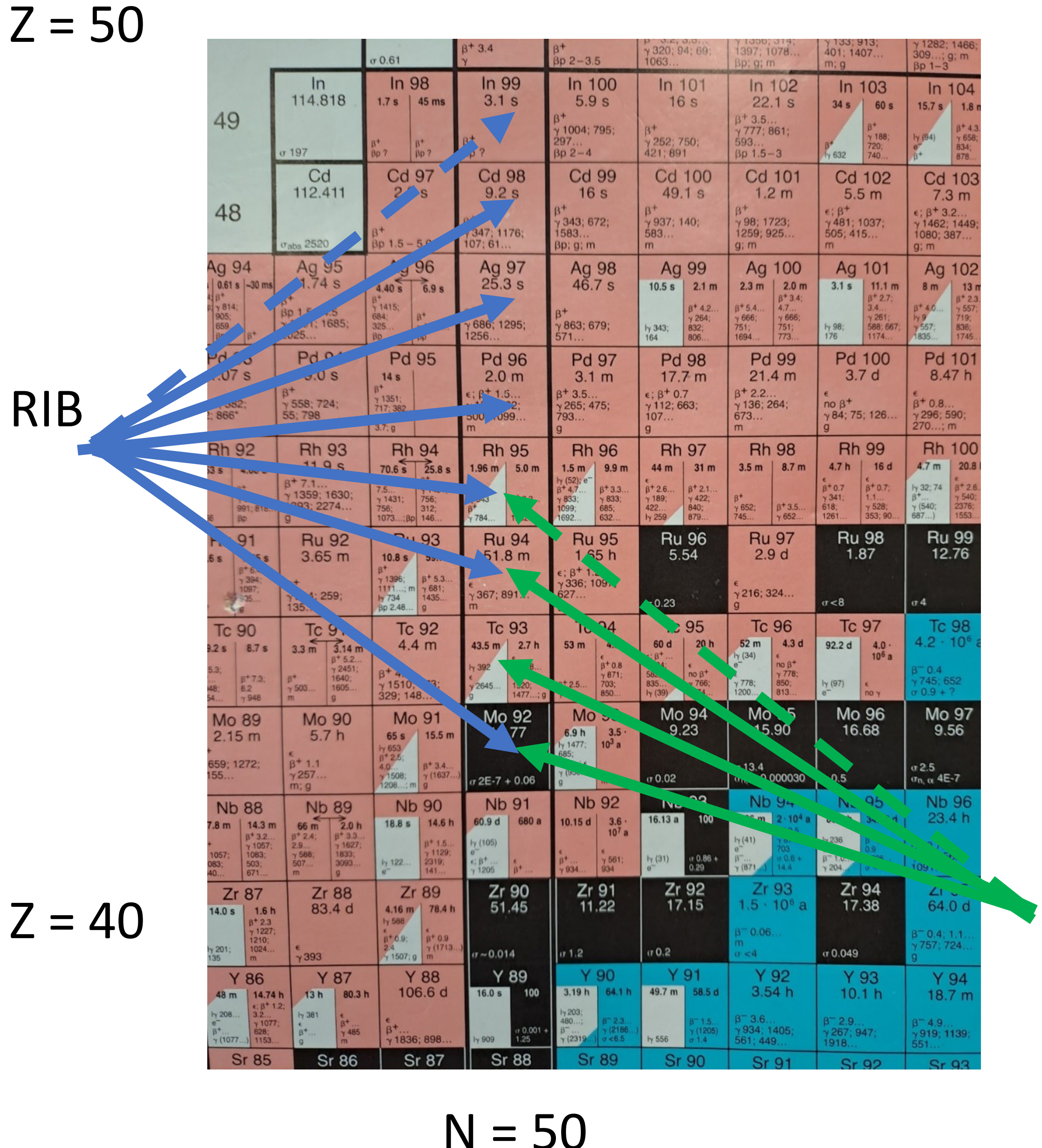
$$\langle 0h_{9/2}, 0h_{9/2} | \hat{V} | 0h_{9/2}, 1f_{7/2} \rangle_{J=2}$$

changed from -0.0235 to -0.2 MeV

$J_i^\pi \to J_f^\pi$	$B(E2; J_i^\pi \to J_f^\pi)$ [e^2fm^4] Expt[a]	single-j	KHP	KHP*
$2_1^+ \to 0_1^+$	136(21)[b]	136(21)	260	237
$4_1^+ \to 2_1^+$	331(13)	331(13)	331	336
$6_1^+ \to 4_1^+$	227(5)[c]	227(5)	227	226
$8_1^+ \to 6_1^+$	83(3)	83(3)	90	91
$3/2_1^- \to 5/2_1^-$	955(104)	678(9)	740	756
$3/2_1^- \to 7/2_1^-$	30(3)	—	$\boxed{0.7}$	24.5
$3/2_1^- \to 7/2_2^-$	133(13)	94(4)	130	115
$5/2_1^- \to 7/2_2^-$	—	83(10)	107	81.0
$5/2_1^- \to 9/2_1^-$	198^{+45}_{-31}[d]	195(12)	279	259
$7/2_1^- \to 9/2_1^-$	136^{+19}_{-19}[d]	—	$\boxed{14.7}$	128
$7/2_2^- \to 9/2_1^-$	400^{+43}_{-36}[d]	419(13)	459	314
$11/2_1^- \to 7/2_2^-$	—	95(6)	102	96.4
$11/2_1^- \to 9/2_1^-$	141^{+9}_{-8}[d]	149(7)	154	140
$11/2_1^- \to 13/2_1^-$	—	266(6)	252	248
$13/2_1^- \to 9/2_1^-$	226^{+19}_{-16}[d]	226(11)	291	273
$15/2_1^- \to 11/2_1^-$	127(22)	167(4)	169	169
$15/2_1^- \to 13/2_1^-$	28(6)	48(2)	50	50
$17/2_1^- \to 13/2_1^-$	300(20)[e]	306(6)	332	334
$17/2_1^- \to 15/2_1^-$	—	86(4)	82	81.7
$21/2_1^- \to 17/2_1^-$	198(7)	173(3)	191	190

d: EXP2
e: EXP1

3. Ongoing experiments on N = 50 isotones



After the success in the N = 126 isotones, it would be interesting to study similar isotones.

Candidates could be the N= 50 isotones above Z= 40 where the π(1g9/2) orbit gets filled. Also here the knowledge on lifetimes and B(E2) values is limited and often contradictory or unprecise.

The problem is to populate the isotones above ^{92}Mo using stable or radioactive ion beams.

Here we report on the stable beam experiments performed recently in Cologne.

^{92}Mo:

The main problem is the lifetime of the first 4^+ state is needed for the prediction of all other B(E2) values. Note B(E2) to first 2^+ known via Coulex.

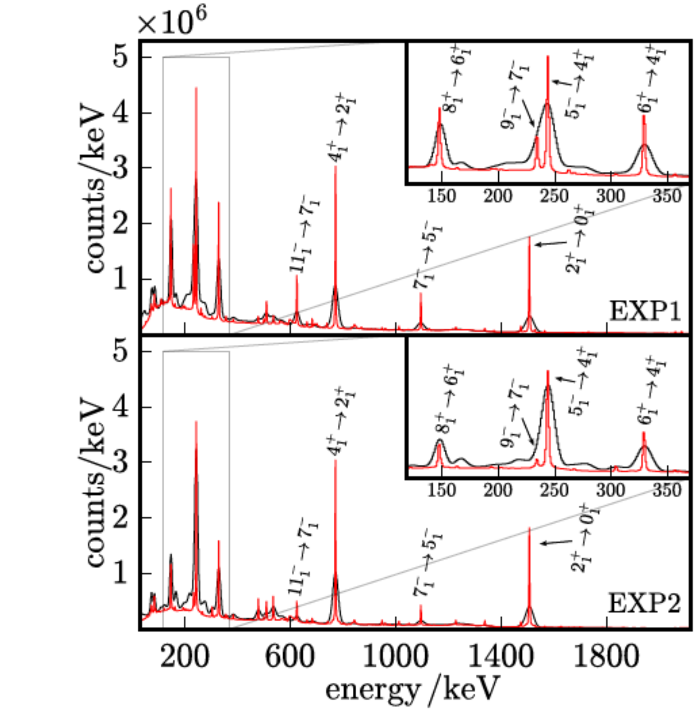
Recently, the lifetime of the 2^+ and 4^+ states was measured for the first time as 0.8(4) ps and 35.5(24) or 36.6(13) depending on the analysis method of a recoil distance experiment at GANIL. *R. M. Pérez-Vidal et al. Phys. Rev. Lett. 129 (2022) 112501.*

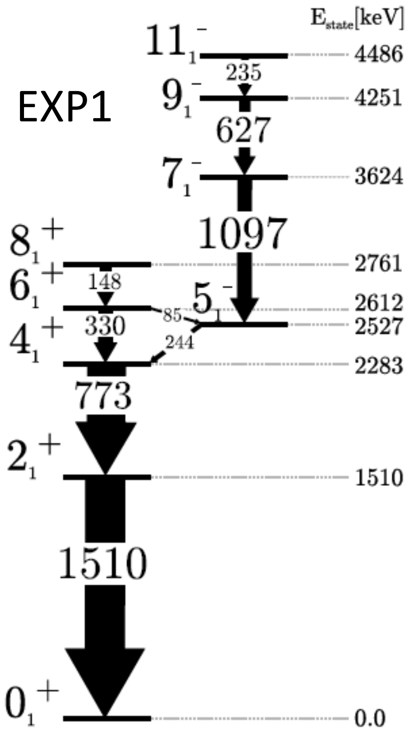
To clarify the situation and reduce the statistical and systematic error two fusion evaporation reactions were used at the 10MV Tandem accelerator in Cologne.

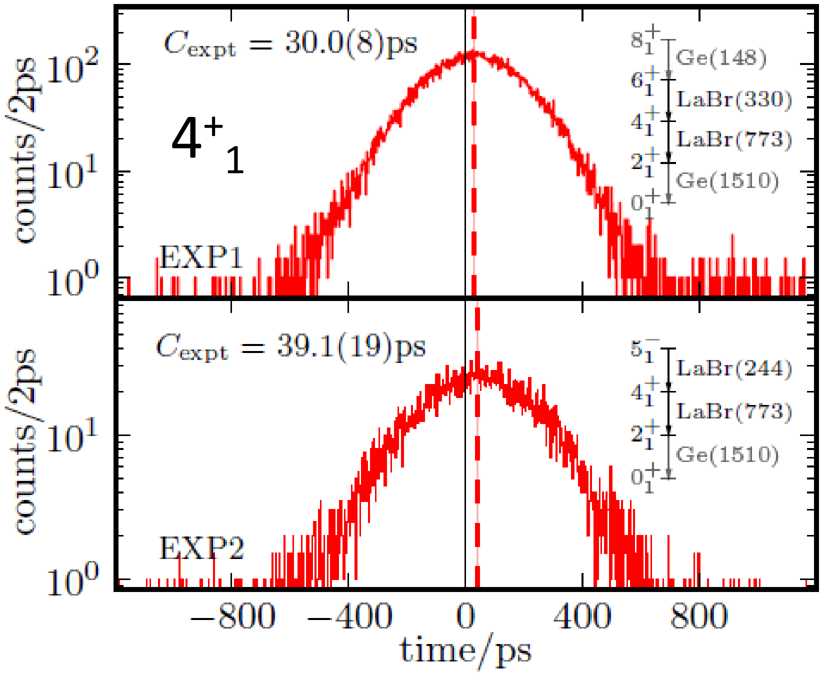
EXP1: ^{90}Zr(α,2n) ^{92}Mo @ 27 MeV on a 5.3mg cm^{-2} 97.62% enriched target.

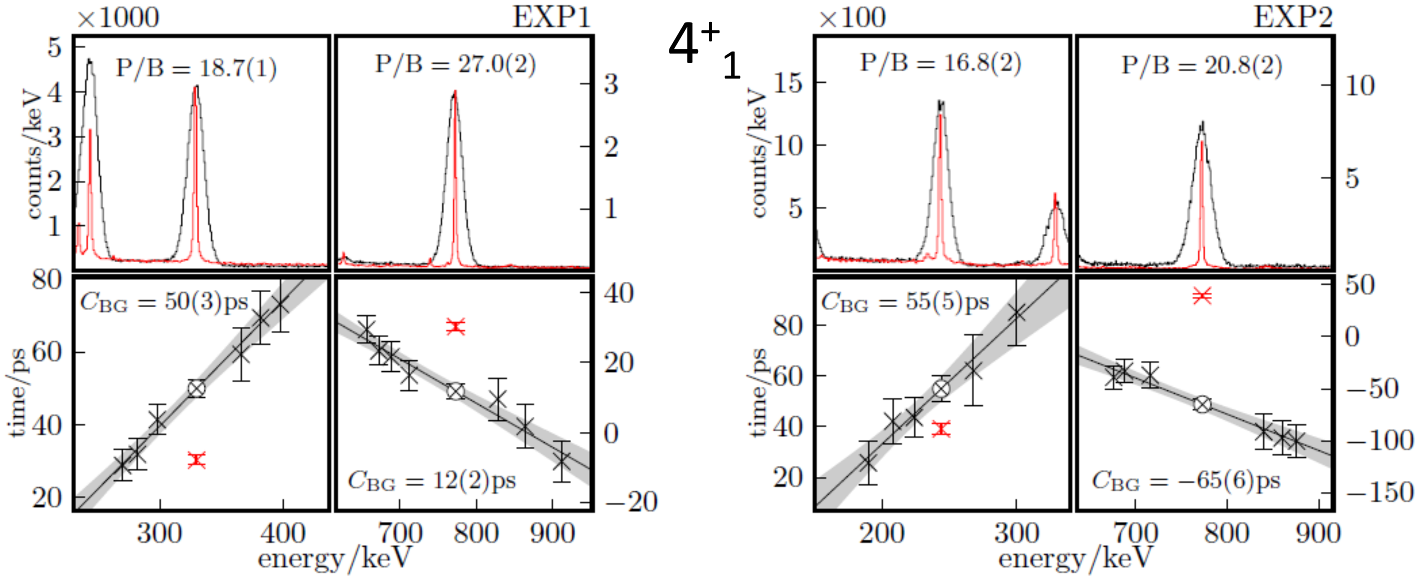
EXP2: ^{93}Nb(p,2n) ^{92}Mo @ 18 MeV on a 5.4mg cm^{-2} monoisotopic target.

New:
Completely digital acquisition system (CAEN 500MHz digitisers) with digital CFD algorithm to reach timestamps with ps resolution. *A. Harter et al. NIM A 1053 (2023) 168279.*
Symmetrized Analysis. *J. M. Régis et al. NIM A 897 (2018) 3.*
Remeasurement of PRD relevant lifetime in ^{152}Gd. *L. Knafla et al. NIM A 1052 (2023), 168279.*









Exp1: τ = 22.5(11) ps

Exp2: τ = 23(2) ps

TABLE I. Summary of the measured mean lifetimes of the states $J_i^{\pi_i}$ and the respective reduced transition probabilities

$J_i^{\pi_i} \rightarrow J_f^{\pi_f}$	τ_{EXP1} ps	τ_{EXP2} ps	τ_{adopted} ps	Multipolarity	$B(\sigma\lambda; J_i^{\pi_i} \rightarrow J_f^{\pi_f})$ adopted	$B(\sigma\lambda; J_i^{\pi_i} \rightarrow J_f^{\pi_f})$ literature
$2_1^+ \rightarrow 0_1^+$	≤ 3	≤ 8	≤ 3	E2	≥ 35 e^2fm^4	207(12) e^2fm^4 [a]
$4_1^+ \rightarrow 2_1^+$	22.5(11)	23(2) [d]	22.5(11)	E2	132^{+7}_{-6} e^2fm^4	84.3(14) e^2fm^4 [b]
$6_1^+ \rightarrow 4_1^+$	2200(20)	2220(70)	2200(20)	E2	81(2) e^2fm^4	80(3) e^2fm^4 [a]
$\rightarrow 5_1^-$				E1	5.3(6) $\times 10^{-5}$ e fm^2	5.3(7) $\times 10^{-5}$ e fm^2 [a]
$8_1^+ \rightarrow 6_1^+$	310(3)$\times 10^3$ [f]	-	310(3)$\times 10^3$	E2	28.6(3) e^2fm^4	32(1) e^2fm^4 [a]
$5_1^- \rightarrow 4_1^+$	2270(30)	2250(60)	2270(30)	E1 [e]	$\geq 1.88(3)\times 10^{-5}$ e fm^2	1.91(5)$\times 10^{-5}$ e fm^2 [a]
				M2 [e]	≤ 93 μN^2fm^4	≤ 98 μN^2fm^4 [a]
$7_1^- \rightarrow 5_1^-$	≤ 5	≤ 7	≤ 5	E2	≥ 101 e^2fm^4	-
$9_1^- \rightarrow 7_1^-$	37(11)	29(7)	33(7) [c]	E2	255^{+69}_{-45} e^2fm^4	-

[a] From Refs.[25–33]
[b] From Ref. [5]
[c] Averaged value from EXP1 and EXP2 calculated using a Monte-Carlo method
[d] Averaged value from feeder-decay cascades 244-773 and 330-773 calculated using a monte-carlo method
[e] Mixing ratio $\delta \leq 0.05$ from Ref. [34]
[f] Determined using Ge-LaBr timing

M. Ley,* L. Knafla, A. Esmaylzadeh, A. Harter, J.-M. Regis, A. Blazhev, C. Fransen, J. Jolie and P. Van Isacker, to be subm. to PRC

^{93}Tc:

Very few absolute transition rates are known in this three valence proton nucleus:

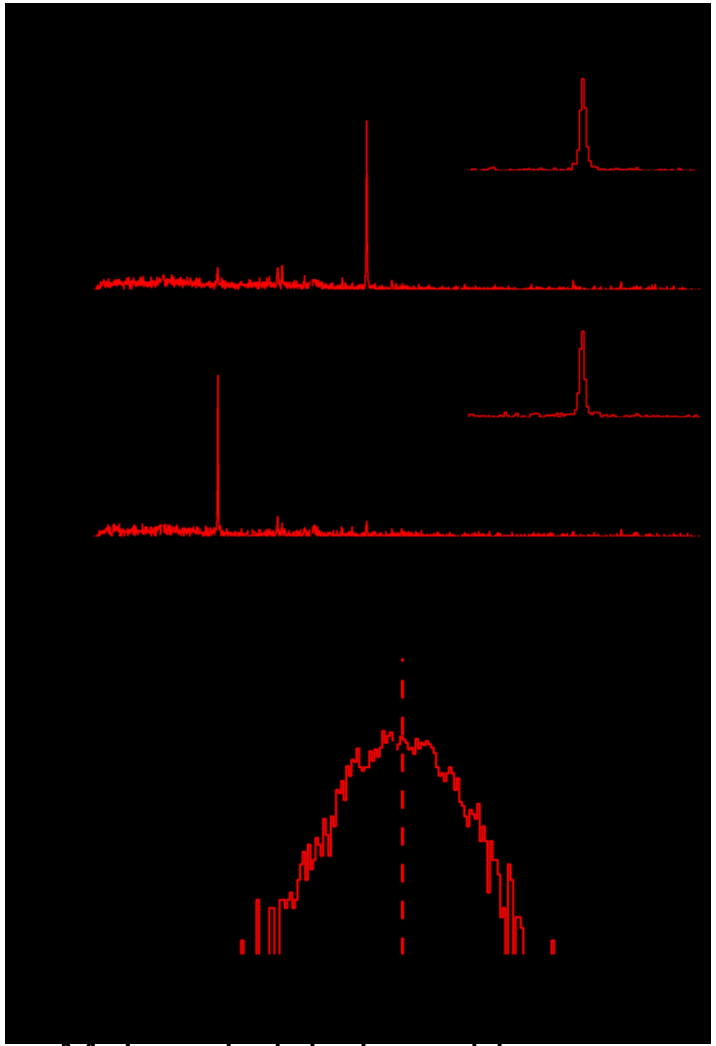
the B(E2; $17/2_1^+ \rightarrow 13/2_1^+$)= 88(18) e^2fm^4 and the B(E2; $21/2_1^+ \rightarrow 17/2_1^+$)= 73(5) e^2fm^4

A fast timing experiment was performed in Cologne using the ^{90}Zr(^{6}Li, 3n)^{93}Tc @ 31MeV reaction on a : 5.3mg/cm² ^{90}Zr (98% enriched) target.

Results (preliminary!):

E_{state} [keV]	state J^π	$\tau_{expt.}$ [ps]	$\tau_{lit.}$ [ps]
1434	$(13/2)^+$	< 4	$< 14 \times 10^3$ [1]
1516	$(11/2)^+$	< 4	-
2185	$(17/2)^+$	29(4)	39(7) [1]

transition	E_γ	multipolarity	B(E2) expt. [e^2fm^4]	B(E2) single particle [e^2fm^4]
$13/2_1^+ \rightarrow 9/2_1^+$	1434	E2	> 34	164(6)
$11/2_1^+ \rightarrow 9/2_1^+$	1516	E2	> 24	86(3)
$17/2_1^+ \rightarrow 13/2_1^+$	750	E2	118^{+19}_{-14}	114(3)
$21/2_1^+ \rightarrow 17/2_1^+$	350	E2	73(5) [1]	60(1)



M. Ley et al. to be publ.

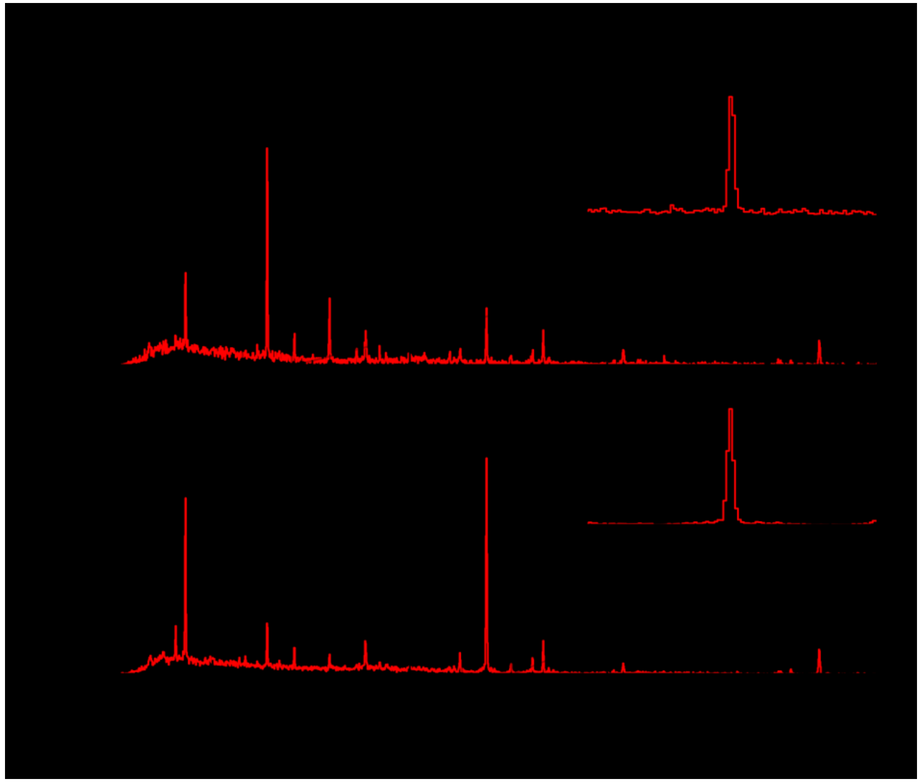
- [1] Nuclear Data Sheets Update for A = 93

^{94}Ru (preliminary):

Also here the main problem is the lifetime of the first 4^+ state. Two recent RIB experiments at FAIR Phase 0 and GANIL yielded contradictory results:

τ = 32(11) ps [1]

τ = 87(8) ps [2]



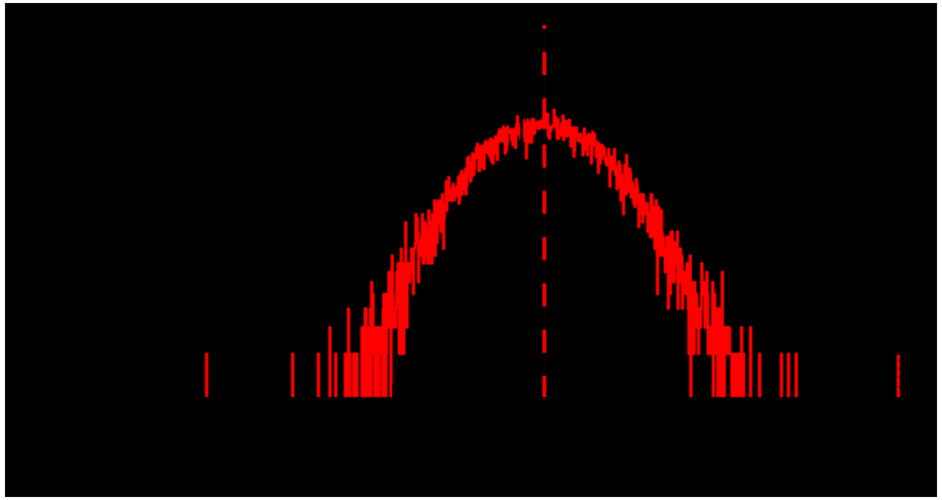
Fast Timing experiment at Cologne Tandem

^{92}Mo(^{4}He, 2n)^{94}Ru @ 28MeV on 5.5mg/cm²

^{92}Mo (98% enriched)

yielded: τ = 66(2) ps or $B(E2; 4^+ \rightarrow 2^+) = 50(2)\ e^2fm^4$

single-j prediction: $B(E2; 4^+ \rightarrow 2^+) = 7.7(7)\ e^2fm^4$



[1] B. Das et al. Phys. Rev. C 105, L031304 (2022) Fast Timing

[2] R. M. Pérez-Vidal et al. Phys. Rev. Let. 129, 112501 (2022) RDDM

M. Ley et al. to be publ.

5. Conclusions

Nine lifetimes in ^{211}At were measured in three different experiments.

Excellent agreement with the single-j predictions for the B(E2) values in ^{211}At was obtained when using the ones in ^{210}Po as input.

In order to perform the same for the N= 50 isotones, precise lifetimes in ^{92}Mo were determined to serve as input for the calculations with more than two protons.

A fast timing experiment in ^{93}Tc yields promising results but more B(E2) values are needed.

The B(E2; $4^+ \rightarrow 2^+$) in ^{94}Ru was measured to solve contradictory results from RIB experiments, but it still disagrees with the single-j predictions.

Much more stable and RIB experiments are needed.

THANKS FOR YOUR ATTENTION