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

Ac 214 8.2 s	Ac 215 0.17 s	Ac 216 0.44 ms	Ac 217 0.74 µs 69 ns	Ac 218 1.1 μs
a 7.215: 7.081 y 139: 244	α 7.600; 7.211 ε γ (396)	α 9.029; 9.105 γ 83; 854; 771	ly (850; 400; 382 α 10.54 α 9.65	α 9.205 9
Ra 213	Ra 214 2.46 s	Ra 215 1.67 ms	Ra 216 2.0 ns 0.18 µs	Ra 217 1.6 μs
1053, 6.731, 101;e <sup>rr</sup> 6.521 10.8466; 6.9110; 8.367 215;e <sup>r</sup>	α 7.137; 6.505 ε; g γ (642)	α 8.700; 7.879 γ 834; 540	344 a.9.551; 11.029 a.9.349	or 8.99
Fr 212 20.0 m	Fr 213 34.6 s	Fr 214 3.35 ms 5.0 ms	Fr 215 0.09 μs	Fr 216 0.70 μs
e 6.262; 6.384; 5.408; 5.340 y 1274; 227; 1185	α 6.775 ε	= 8.477; 8.547	α 9.36	a 9.01 9
Rn 211 14.6 h	Rn 212 24 m	Rn 213 19.5 ms	Rn 214	Rn 215 2.3 μs
α 5.789; 5.851 γ 674; 1363; 678; g	α 6.264 Υ	α 8.088; 7.252 γ 540	hy 182 hy 182 mi a 10.65 = 10.46 a 9.037	a 8.67 9
At 210 8.3 h	At 211 7.22 h	At 212	At 213 0.11 µs	At 214
ε; α 5.524; 5.442; 5.361 γ 1181; 245; 1483	α 5.867 γ (687) g	е 7.84; е 7.68; 7.90 7.62 үбЗ үбЗ е <sup>-</sup> е <sup>-</sup>	α 9.08	a 8.782 a 8.819 ; m a 8.877; g Y g Y
Po 209 102 a α 4.881	Po 210 138.38 d 15.30438 16031; o <0.0005	Po 211 252 s 0.516 s 	Po 212 45.1 s 17.1 ns 0.3 µs 11.05 ly 728	Po 213 4.2 μs
y (895; 261; 263)	+<0.030; σ <sub>6,02</sub> 0.002; σγ<0.1	Y 370, 1064	583 223 17 a 10.22 a 8.785	α 8.376 γ (779)
Bi 208 3.68 · 10 <sup>5</sup> a	Bi 209 100 1.9 · 10 <sup>10</sup> a	Bi 210 3.0-10 <sup>4</sup> s 5.013 d +4.948 d <sup>-1,2</sup> 4.908 +4.948	Bi 211 2.17 m α 6.6229; 6.2788	Bi 212 9m 25m 60.60 m 573 61.00 573 61.00 573 61.00 61
ς γ 2615	a 3.137 # 0.011 + 0.023 # <sub>0.0</sub> <3E/7	γ 268; 4.698 304 γ (305; # 0.054 268)	$\begin{array}{c} \gamma \ 351 \\ \alpha \rightarrow g; \ \beta^{-} \rightarrow g \end{array}$	y 101 101 1777. 1911. Jan 1838. 192 101 1
Pb 207 22.1	Pb 208 52.4	Pb 209 3.253 h	Pb 210 22.3 a	Pb 211 36.1 m
ır 0.61	or 0.00023 ora.u ≪8€∘6	6 <sup>+</sup> 0.6	p 0.02; 0.06 y 47; e <sup>-</sup> ; g a 3.72 a <0.5	0 <sup>™</sup> 1.4 γ 405; 832; 427



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.



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

First detailed study of <sup>211</sup>At at ISOLDE and the Stockholm cyclotron.



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  $B(E2;R \rightarrow R-2) = B_R$  in the two-particle nucleus.

1 2

Then the following relation can be obtained:

$$B(E2; j^3[I]J \to j^3[I']J') = \left(\sum_R g_j(J, I, J', I', R)\sqrt{B_R}\right)^{-1}$$

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

#### State dependent effective charges are needed in <sup>210</sup>Po.

$J_i^{\pi}$	$E_x$ (1	$E_x$ (MeV)		$B(E2; J_i \to J_f)(\mathrm{e}^2 \mathrm{fm}^4)$					
	Expt	SM	$J_f^{\pi}$	Expt	$SM1-gh^a$	$SM2-gh^b$	$\mathrm{SM}^b$		
$2^{+}_{1}$	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		

<sup>a</sup>With  $e_{\pi} = 1.51e$ . <sup>b</sup>With  $e_{\pi} = 1.09e$ . <sup>c</sup>From Ref. [36].

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

# 2. Studies of 211-At

## **2.1 Fast timing results**

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



## **Triple coincidences and scheme**



## The 17/2<sup>-</sup> excited state



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

<sup>209</sup>Bi(<sup>16</sup>O, <sup>14</sup>C) <sup>211</sup>At two-proton transfer reaction with 84 MeV <sup>16</sup>O beam and <sup>14</sup>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<sup>2</sup> <sup>209</sup>Bi on 0.4 mg/cm<sup>2</sup> Mg backing. Stopper was 1.1 mg/cm<sup>2</sup> 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 (<sup>16</sup>O, <sup>14</sup>C) two-proton transfer reaction than in the (6Li,3n) fusion evaporation reaction.



 $\begin{array}{c}
689 & 714 \\
23/2 - 4 & 7 \\
511 & 599 \\
21/2 - 4 & 7 \\
511 & 599 \\
17/2 - 254 \\
13/2 - 254 \\
1067 \\
9/2 - 4 \\
9/2 - 4 \\
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#### Results for forwards ring:



	Lifetime [ps]	
Forward	Backward	Adopted
	RDDS	
15.5(10)	14.5(10)	15.0(7)
5.4(10)		5.4(10)
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

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



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

	ing th	a now life	atimac						
US	ing th	e new me	eumes		B(E2; J	$J_{\rm i}^{\pi} \to J_{\rm f}^{\pi}) \ [e^2 {\rm fm}^4]$	']		
State	$E_{\text{feeder}}$ $E_{\text{feeder}}$ $E_{\text{feeder}}$	decay HPGe gate	$\tau$ (expt.) $\tau$ (	lit.) $J_{\mathrm{i}}^{\pi} \rightarrow J_{\mathrm{f}}^{\pi}$	Expt <sup>a</sup>	single-j	KHP	KHP*	
J <sup>n</sup>	(keV) (k	(kev)	(ps) (p	$2_1^+ \rightarrow 0_1^+$	136(21) <sup>b</sup>	136(21)	260	237	•
13/2 <sup>-</sup> 17/2 <sup>-</sup>	254 1 599 2	067 511 254 1067	$\leq 7 \leq 2140(140) \leq 2140(140)$	$4_{100}^{+} \rightarrow 2_{1}^{+}$	331(13)	331(13)	331	336	
23/2-	689 5	511 254 and 1067	56(5) <	$6_1^+ \to 4_1^+$	227(5) <sup>c</sup>	227(5)	227	226	
		Lifotimo [ps]		$8^+_1 \rightarrow 6^+_1$	83(3)	83(3)	90	91	
	Forward	Backward	Adopted	$3/2^1 \to 5/2^1$	955(104)	678(9)	740	756	e
State $7/2_1^-$	15.5(10)	RDDS 14.5(10)	15.0(7)	$3/2^1 \to 7/2^1$	30(3)		0.7	24.5	•
$5/2^{-}_{1}$	5.4(10)		5.4(10)	$3/2^1 \to 7/2^2$	133(13)	94(4)	130	115	
$13/2_1$	180(50)	DSAM	220(80)	$5/2^1 \to 7/2^2$		83(10)	107	81.0	
$7/2_2^-$ $13/2_1^-$	3.0(4) 2.6(3)	3.3(4) 2.6(3)	3.15(30) 2.6(2)	$5/2^1  o 9/2^1$	$198^{+45}_{-31}$	195(12)	279	259	
$11/2_1^-$	3.3(3)	3.1(3)	3.2(2)	$7/2^1  o 9/2^1$	$136^{+19d}_{-19}$		14.7	128	
The	B(F2)	) values c	an he	$7/2^2  o 9/2^1$	$400^{+43d}_{-36}$	419(13)	459	314	·
inc				$11/2^1 \to 7/2^2$		95(6)	102	96.4	е. С
compared to the			$11/2^1 \to 9/2^1$	$141^{+9d}_{-8}$	149(7)	154	140		
theoretical predictions			$11/2^1 \to 13/2^1$		266(6)	252	248		
				$13/2^1 \to 9/2^1$	$226^{+19d}_{-16}$	226(11)	291	273	
KHF	<sup>o</sup> * wit	h		$15/2^1  ightarrow 11/2^1$	127(22)	167(4)	169	169	
$h_{0}$	$2.0h_{\odot}$	$\sqrt{2} \hat{V} 0h_{0}/2$	$1 f_{7/2}$	$15/2^1 \to 13/2^1$	28(6)	48(2)	50	50	d: EX
$(J_{j})_{2}^{(j)}, (J_{j})_{2}^{(j)}, (J_{j})_{2}$			$=2$ $17/2^1 \rightarrow 13/2^1$	$300(20)^{e}$	306(6)	332	334	e: EX	
cha	nged	from -0.C	1235	$17/2^1 \rightarrow 15/2^1$		86(4)	82	81.7	- -
to -	0.2 M	eV		$21/2^1 \to 17/2^1$	198(7)	173(3)	191	190	

## **3. Ongoing experiments on N = 50 isotones**

Z = 50

In 98 In 99 In 100 In In 10 In 102 In 103 114.818 3.1 s 5.9 s 17s | 45 m 16 s 22.1 s 49 1004: 795 252; 750 Cd Cd 97 Cd 98 Cd 99 Cd 100 Cd 101 Cd 102 112.411 16 s 49.1 s 1.2 m 7.3 n 48 343; 672; 937; 140; 98; 1723 Ag 94 Ag 97 25.3 s Ag 98 46.7 s Ag 99 Ag 100 Ag 101 10.5 s 2.1 m 2.3 m | 2.0 m 3.1 s 863; 679; Pd 98 Pd 96 Pd 97 Pd 99 Pd 100 2.0 m 3.1 m 17.7 m 21.4 m 3.7 d RIB 3<sup>+</sup> 3.5... 265; 475; ε; β<sup>+</sup> 0.7 γ 112; 663; 3<sup>+</sup> 2.2... y 136; 264; ο β<sup>+</sup> 84: 75: 126 Rh 94 Rh 97 Rh 98 Rh 99 Rh 95 Rh 96 1.5 m | 8.7 m Ru 94 Ru 95 Ru 96 Ru 97 Ru 98 Ru 99 Ru 92 5.54 2.9 d 1.87 12.76 3.65 m 1,65 h 51.8 m 10.8 s 16: 324 Tc 96 Tc 97 Tc 92 Tc 93 4.4 m 92.2 d Mo 91 Mo 96 Mo 97 Mo 90 Mo 89 9.56 9.23 2.15 m 5.7 h Nb 92 Nb 90 Nb 91 Nb 89 0.15 d 3.6 18.8 s | 14.6 Zr 92 Zr 94 Zr 90 Zr 91 11.22 Zr 87 Zr 88 Zr 89 64.0 d Z = 4083.4 d 1.16 m 4.0 s Y 89 Y 92 Y 91 Y 86 Y 87 Y 88 Y 93 Y 94 106.6 d 3.19 h 49.7 m 18.7 r 48 m 13 h 80.3 h 16.0 s

N = 50

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  $\pi(1g9/2)$  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 <sup>92</sup>Mo using stable or radioactive ion beams.

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

## <sup>92</sup>Mo:

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

Recently, the lifetime of the 2<sup>+</sup> and 4<sup>+</sup> 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( $\alpha$ ,2n)  ${}^{92}$ Mo @ 27 MeV on a 5.3mg cm<sup>-2</sup> 97.62% enriched target.

EXP2: <sup>93</sup>Nb(p,2n) <sup>92</sup>Mo @ 18 MeV on a 5.4mg cm<sup>-2</sup> 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 <sup>152</sup>Gd. L. Knafla et al. NIM A 1052 (2023), 168279.





Exp1:  $\tau = 22.5(11)$  ps Exp2:  $\tau = 23(2)$  ps

$J_i^{\pi_i} \to J_f^{\pi_f}$	$ au_{ m EXP1} \  m ps$	$ au_{\mathrm{EXP2}}$ ps	$ au_{ m adopted} \ { m ps}$	Multipolarity	$\begin{array}{c} \mathbf{B}(\sigma\lambda;J_i^{\pi_i}\to J_f^{\pi_f})\\ \text{adopted} \end{array}$	$\begin{array}{c} \mathbf{B}(\sigma\lambda;J_i^{\pi_i}\to J_f^{\pi_f})\\ \text{literature} \end{array}$
$2^+_1 \rightarrow 0^+_1$	$\leq 3$	$\leq 8$	$\leq 3$	E2	$\geq 35 \text{ e}^2 \text{fm}^4$	$207(12) e^{2} fm^{4} a$
$4^+_1 \rightarrow 2^+_1$	22.5(11)	23(2) <sup>d</sup>	22.5(11)	$\mathbf{E2}$	$132^{+7}_{-6} e^2 fm^4$	$84.3(14) e^2 fm^{4 b}$
$\begin{array}{c} 6^+_1 \rightarrow 4^+_1 \\ \rightarrow 5^1 \end{array}$	2200(20)	2220(70)	2200(20)	E2 E1	81(2) $e^{2} fm^{4}$ 5.3(6) ×10 <sup>-5</sup> $e fm^{2}$	80(3) $e^{2} fm^{4} a$ 5.3(7) ×10 <sup>-5</sup> $e fm^{2} a$
$8^+_1 \rightarrow 6^+_1$	$310(3) \times 10^{3}$ f	-	$310(3) \times 10^3$	$\mathbf{E2}$	$28.6(3) e^2 fm^4$	$32(1) e^2 fm^4 a$
$5^1 \rightarrow 4^+_1$	2270(30)	2250(60)	<mark>2270(30)</mark>	E1 <sup>e</sup> M2 <sup>e</sup>	$ \begin{split} &\geq 1.88(3) \times 10^{-5} \ \mathrm{efm^2} \\ &\leq 93 \ \mu \mathrm{N^2 fm^4} \end{split} $	$\begin{array}{l} 1.91(5) \times 10^{-5} \ {\rm efm^{2\ a}} \\ \leq 98 \ \mu {\rm N^2 fm^{4\ a}} \end{array}$
$7^1 \rightarrow 5^1$	$\leq 5$	$\leq 7$	$\leq 5$	$\mathbf{E2}$	$\geq 101 \text{ e}^2 \text{fm}^4$	-
$9^1 \rightarrow 7^1$	37(11)	29(7)	<i>33(7)</i> °	E2	$255^{+69}_{-45} e^2 fm^4$	-

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

<sup>a</sup> From Refs.[25–33]

<sup>b</sup> From Ref. [5]

<sup>c</sup> Averaged value from EXP1 and EXP2 calculated using a Monte-Carlo method

<sup>d</sup> Averaged value from feeder-decay cascades 244-773 and 330-773 calculated using a monte-carlo method

<sup>e</sup> Mixing ratio  $\delta \leq 0.05$  from Ref. [34]

<sup>f</sup> 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

## <sup>93</sup>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<sup>2</sup>fm<sup>4</sup> and the B(E2;  $21/2_1^+ \rightarrow 17/2_1^+$ ) = 73(5) e<sup>2</sup>fm<sup>4</sup>

A fast timing experiment was performed in Cologne using the <sup>90</sup>Zr(<sup>6</sup>Li, 3n)<sup>93</sup>Tc @ 31MeV reaction on a : 5.3mg/cm<sup>2</sup> <sup>90</sup>Zr (98% enriched) target.

Results (preliminary!):

$E_{state}$ [keV	V]	state $J^{\pi}$	$ au =  au_{ m expt.} \ [ m ps]$	$]$ $ au_{ m lit.} [ m ps]$	
1434		$(13/2)^+$	< 4	$<14$ $\times 10^{3}$ $^1$	
1516	1516 (11/		< 4	-	
2185	2185		29(4)	$39(7)$ $^{1}$	
transition	$\mathrm{E}_{\gamma}$	multipolarity	B(E2) expt. $[e^2fm^4]$	B(E2) single particle $[e^2 fm^4]$	
$13/2^+_1 \to 9/2^+_1$	1434	E2	> 34	164(6)	
$11/2^+_1 \to 9/2^+_1$	1516	E2	> 24	86(3)	
$17/2^+_1 \rightarrow 13/2^+_1$	750	E2	$118^{+19}_{-14}$	114(3)	
$21/2_1^+ \to 17/2_1^+$	350	${ m E2}$	73(5) <sup>1</sup>	60(1)	

<sup>1</sup> Nuclear Data Sheets Update for A = 93



## <sup>94</sup>Ru (preliminary):

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

 $\tau$  = 32(11) ps <sup>1</sup>

 $\tau$  = 87(8) ps <sup>2</sup>

Fast Timing experiment at Cologne Tandem <sup>92</sup>Mo(<sup>4</sup>He, 2n)<sup>94</sup>Ru @ 28MeV on 5.5mg/cm<sup>2</sup> <sup>92</sup>Mo (98% enriched)

yielded:  $\tau = 66(2) \text{ ps}$  or B(E2; 4+ $\rightarrow$  2+)= 50(2) e<sup>2</sup>fm<sup>4</sup> single-j prediction: B(E2; 4+ $\rightarrow$  2+)= 7.7(7) e<sup>2</sup>fm<sup>4</sup>

<sup>1</sup> B. Das et al. Phys. Rev. C 105, L031304 (2022) Fast Timing
 <sup>2</sup> 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 <sup>211</sup>At were measured in three different experiments.

Excellent agreement with the single-j predictions for the B(E2) values in <sup>211</sup>At was obtained when using the ones in <sup>210</sup>Po as input.

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

A fast timing experiment in <sup>93</sup>Tc yields promising results but more B(E2) values are needed.

The B(E2;  $4^+ \rightarrow 2^+$ ) in <sup>94</sup>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