Low-spin structure of ^{210}Bi
investigated in cold-neutron capture reaction on ^{209}Bi

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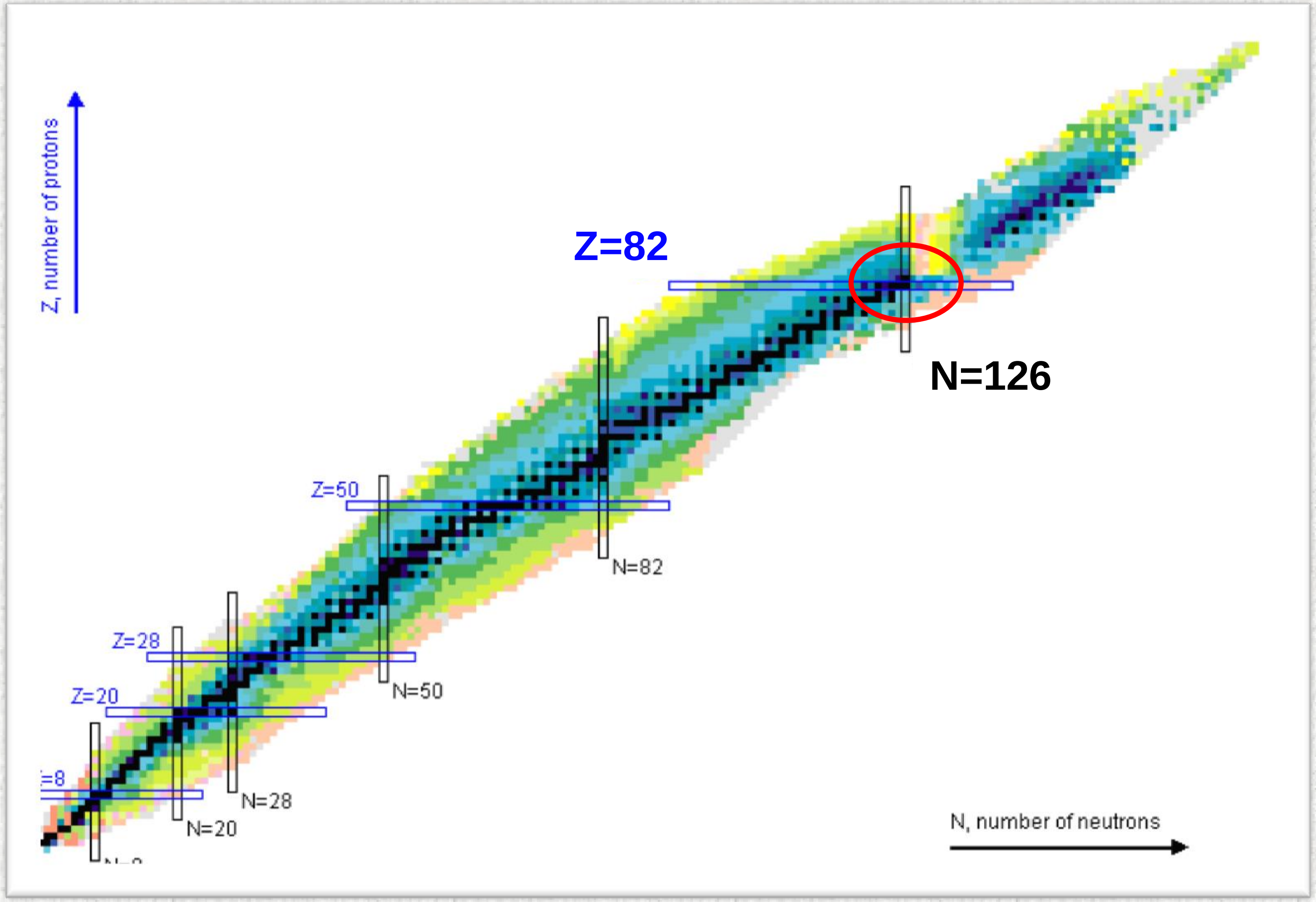
Physics motivation

- Why the ^{210}Bi nucleus is an ideal nucleus for testing the shell-model calculations?

- A rich ground for comparisons with theory, also states arising from coupling of proton and neutron particles excitations to the 3^- first excited state of octupole character in doubly-magic ^{208}Pb are also expected.

- The unknown multipolarity of the main transition feeding the ground state introduced rather large uncertainties in measurements of the capture cross section to the ground state in ^{210}Bi.

- The measured lifetimes may be compared to predictions of shell-model calculations.



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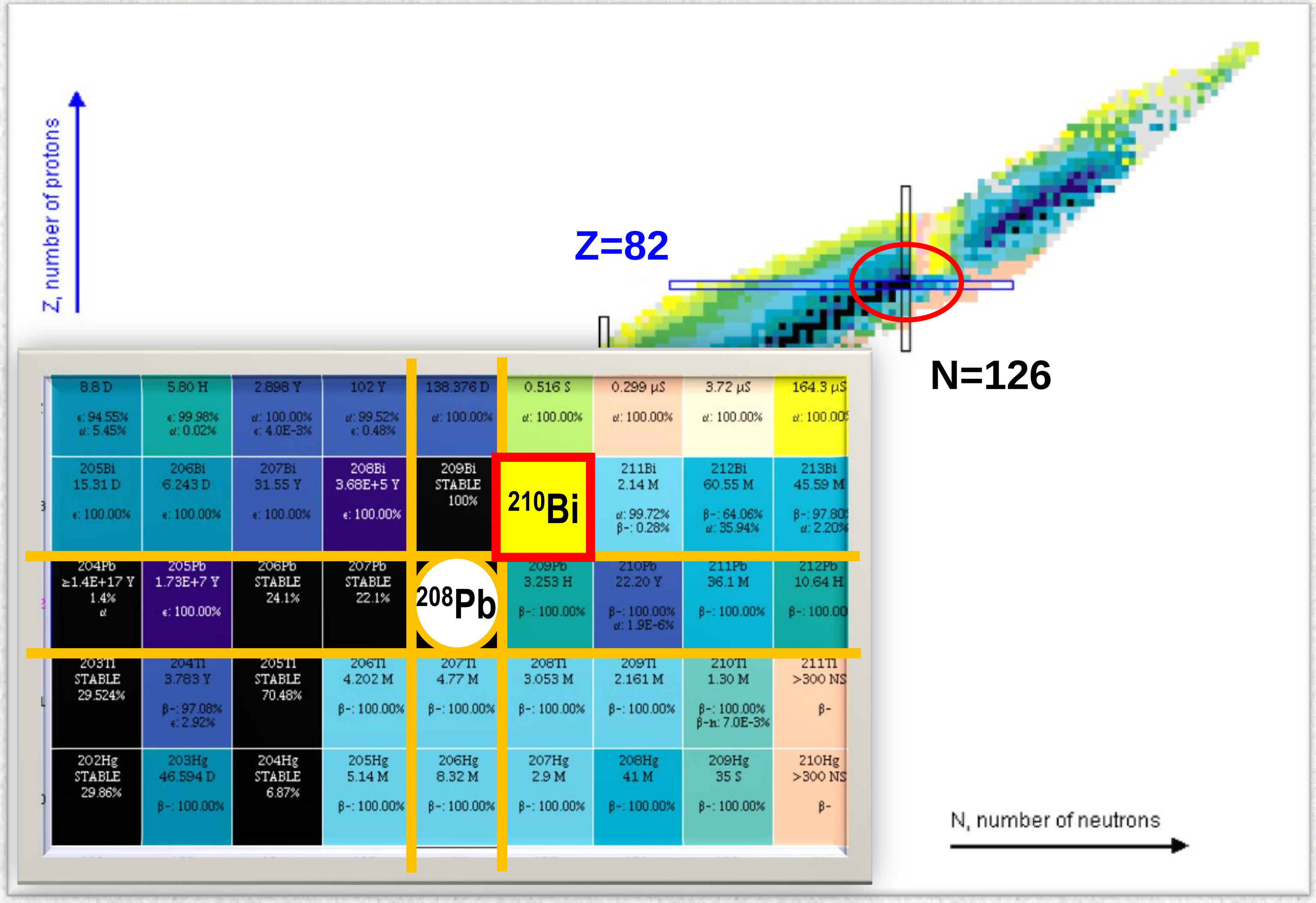

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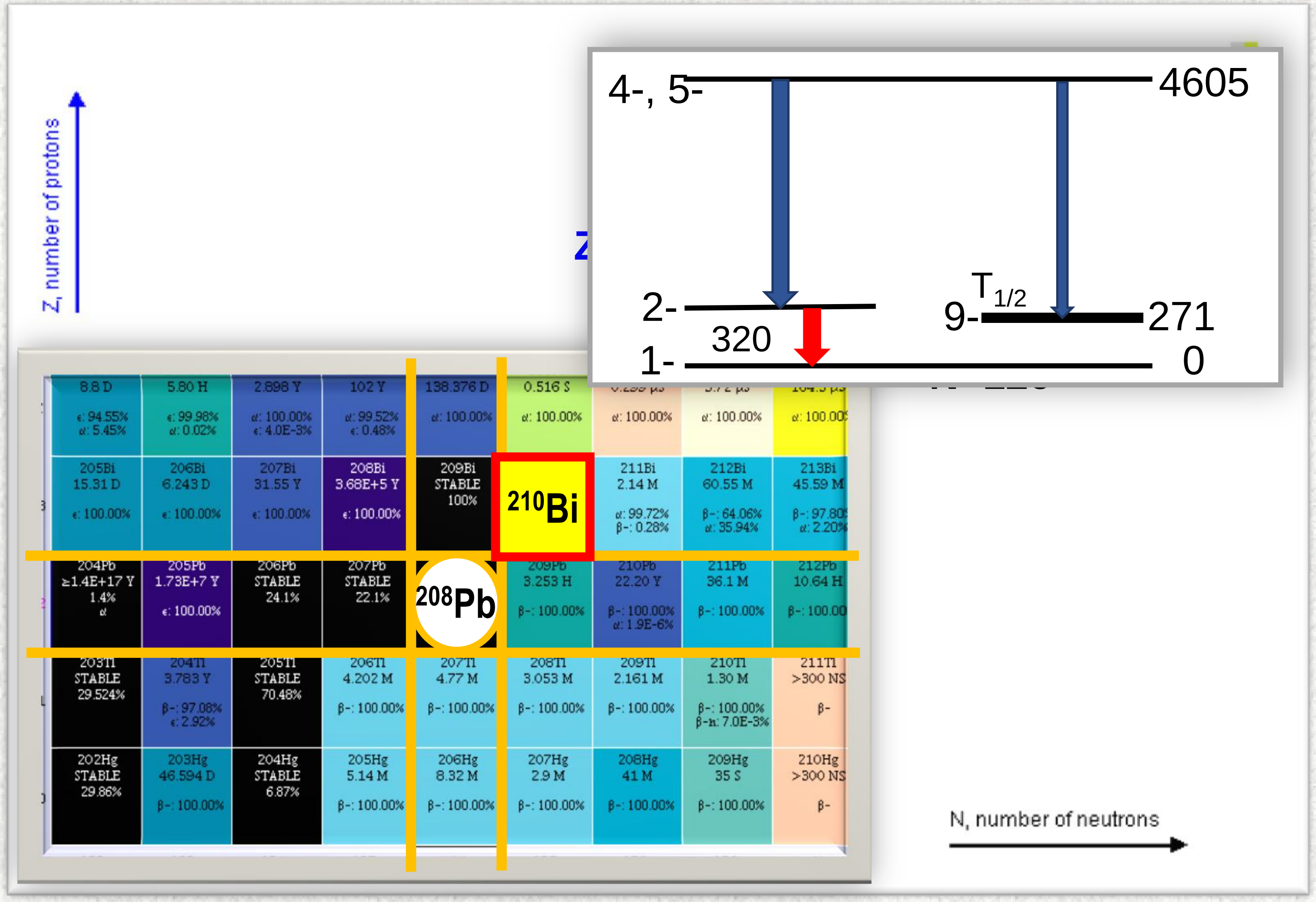
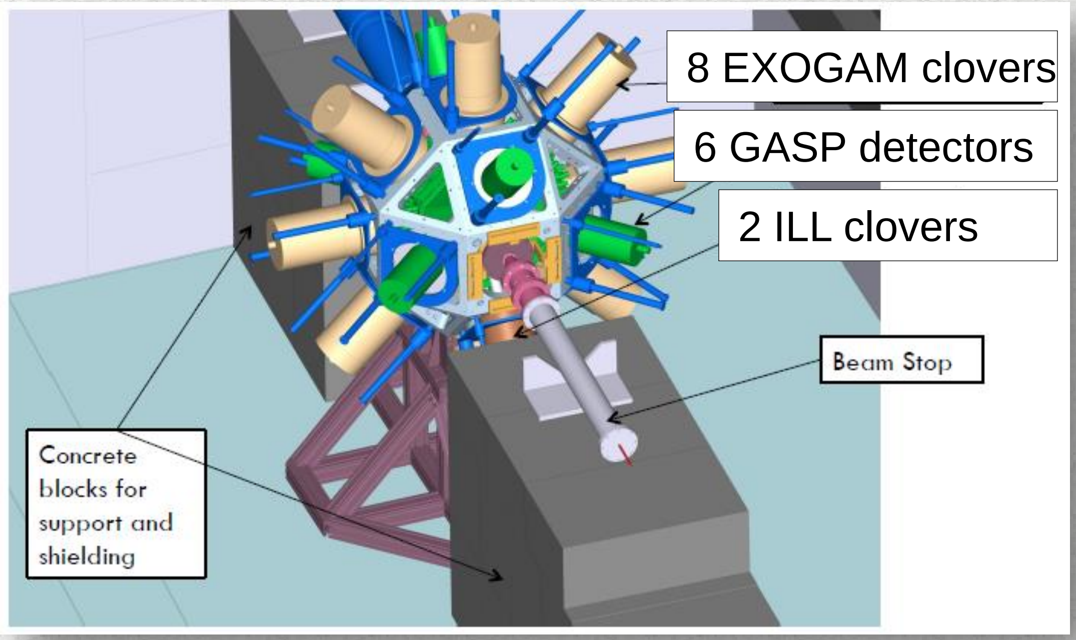
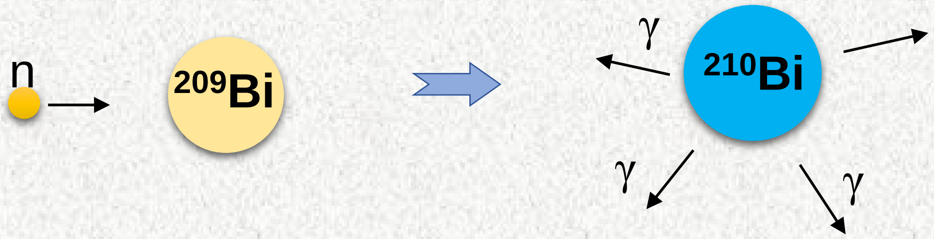


Experiment – ILL Grenoble (PF1B line)





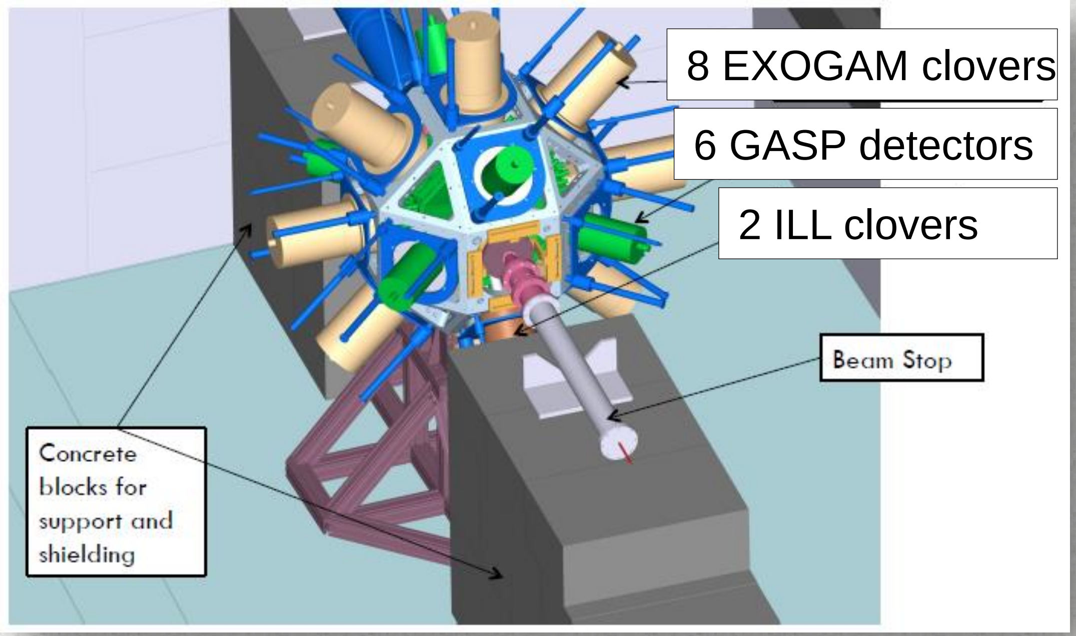
Cold neutron flux of $2{\cdot}10^{10}/(\mathrm{ns}\cdot\mathrm{cm}^2)$ from the ILL reactor with energy < 5 meV

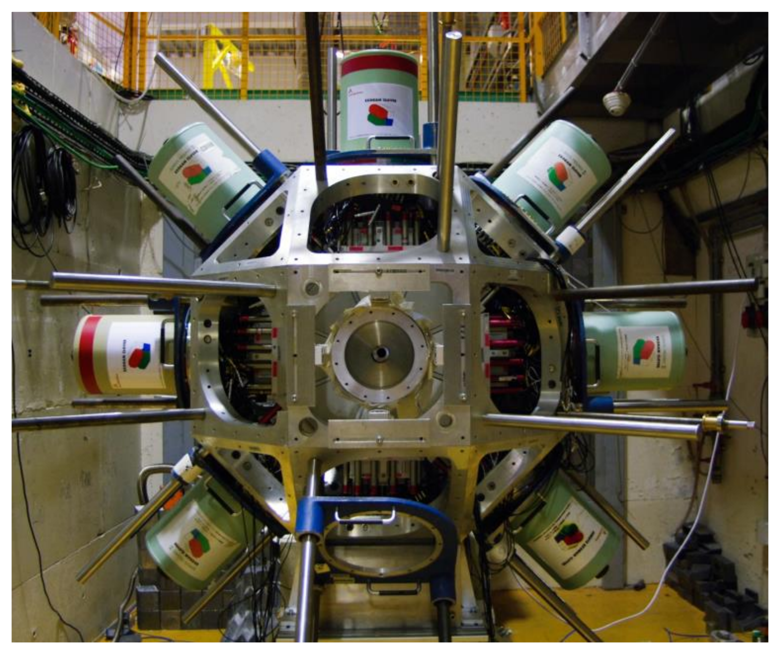
^{209}Bi solid target (3g)

Population of capture state in ^{210}Bi at binding energy of 4.6 MeV

16 Ge detectors of EXILL array: 8 of EXOGAM, 6 of GASP, and 2 from ILL collaboration – coincidence measurements of gamma rays

Experiment – ILL Grenoble (PF1B line)

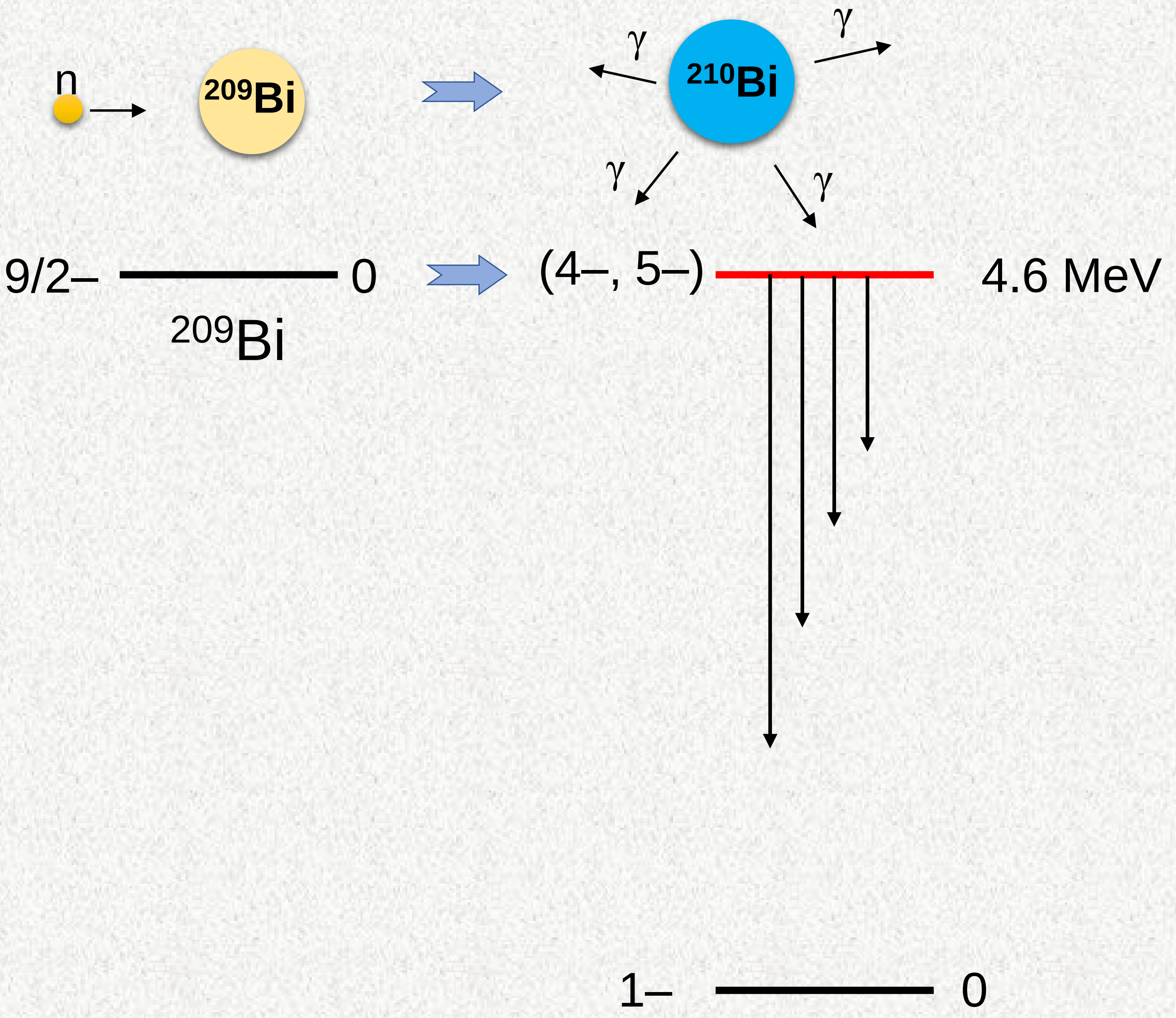




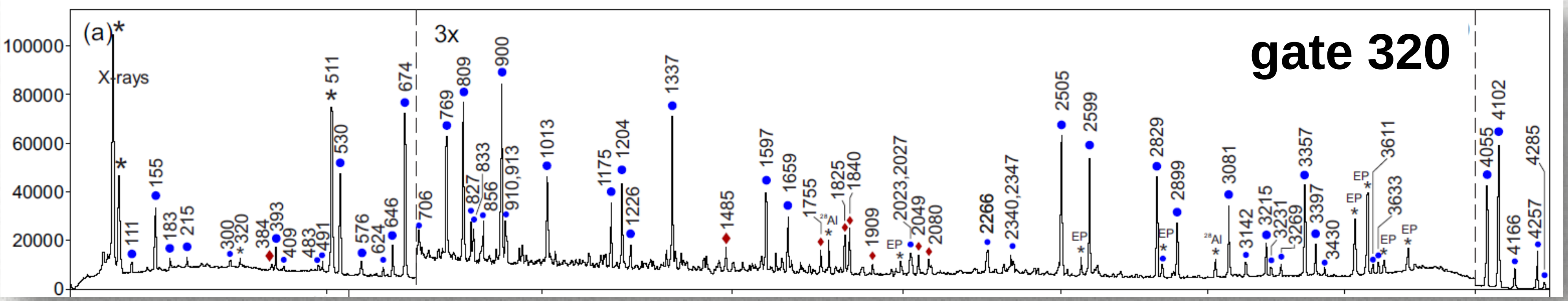
16 Ge detectors of EXILL array: 8 of EXOGAM, 6 of GASP, and 2 from ILL collaboration – coincidence measurements of gamma rays

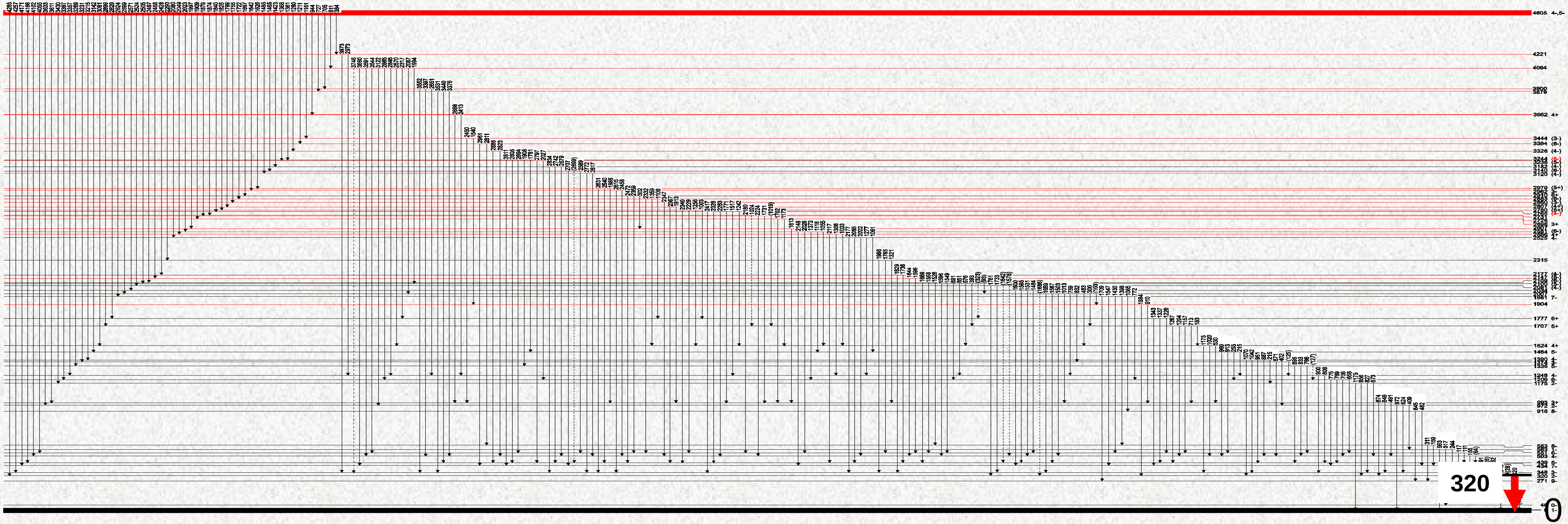
- 8 detectors of EXOGAM arranged into ring around the target at every 45° so angular correlation measurements could be performed
- Measurements of the lifetimes with FATIMA detectors

Experimental results: level scheme

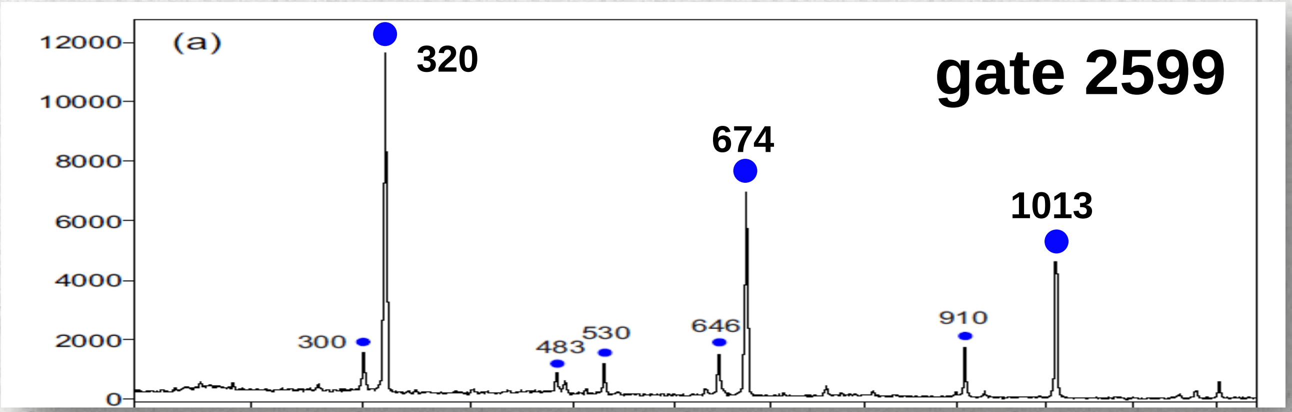


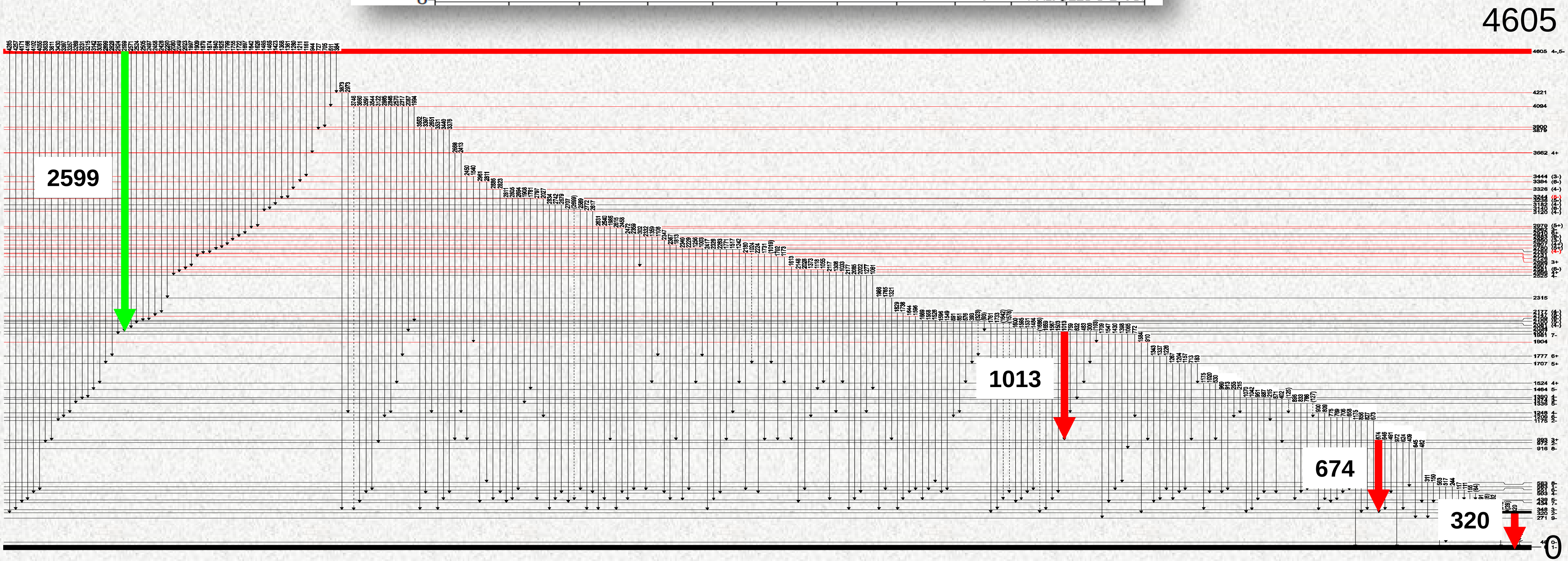
Capture state
at neutron binding energy


gate 320
(a)
X-rays
3x
100000
80000
60000
40000
20000
0
111
155
183
215
300
320
384
393
409
483
491
511
530
576
624
646
674
706
769
809
827
833
856
900
910,913
1013
1175
1204
1226
1337
1485
1597
1659
1755
1825
1840
1909
2023,2027
2049
2080
2266
2340,2347
2505
2599
2829
2899
3081
3142
3215
3231
3269
3357
3397
3430
3611
3633
4055
4102
4166
4257
4285
EP


4605
320
0

^{210}Bi


(a)
gate 2599
320
674
1013
300
483
530
646
910
12000
10000
8000
6000
4000
2000
0

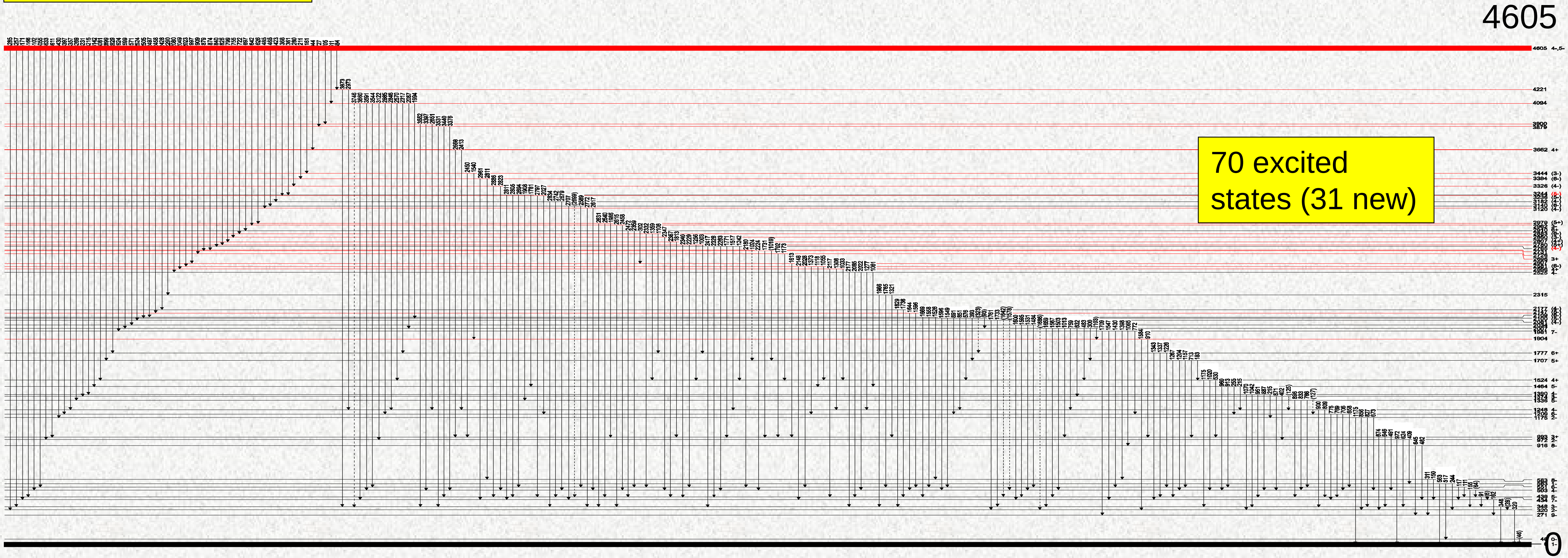

4605
2599
1013
674
320
0

^{210}Bi

Experimental results: level scheme

64 primary transitions (40 new)

Population of neutron capture state at 4605.2(1) keV

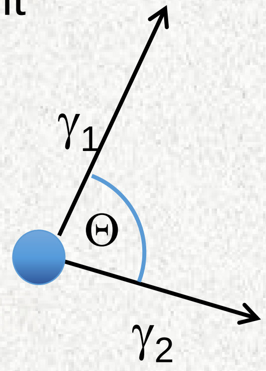


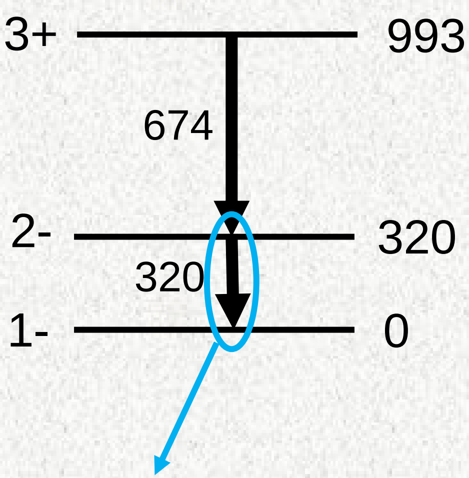
70 excited states (31 new)

^{210}Bi

Angular correlations of γ rays from ^{210}Bi

The angular correlation function for a pair of coincident γ rays connecting the nuclear states with spins $J_i \rightarrow J \rightarrow J_f$ is usually expressed as:





$$W(\Theta) = 1 + A_2 P_2(\cos \Theta) + A_4 P_4(\cos \Theta)$$

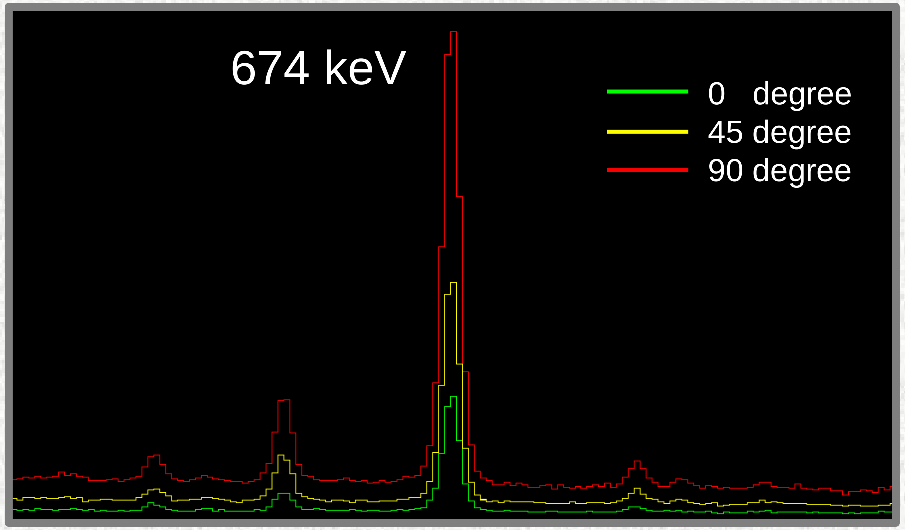
Θ – the angle between the direction of emission of two γ rays

$P_n(\cos \Theta)$ – Legendre polynomials

$A_n = q_n A(1) A(2)$ – the coefficients which depend on the attenuation factor q_n as well as on the multipolarities of 1 and 2 γ rays and the spins of involved nuclear states

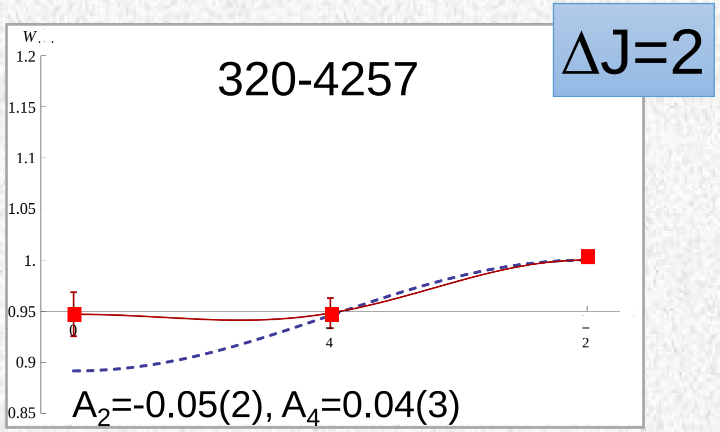
$q_2 = 0.86(2)$

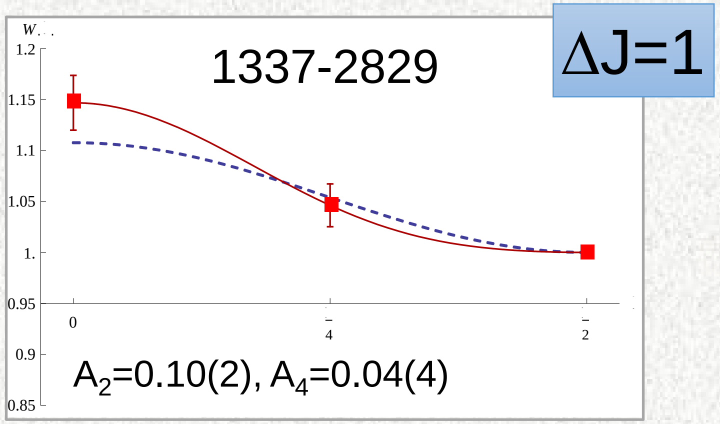
$q_4 = 0.60(3)$

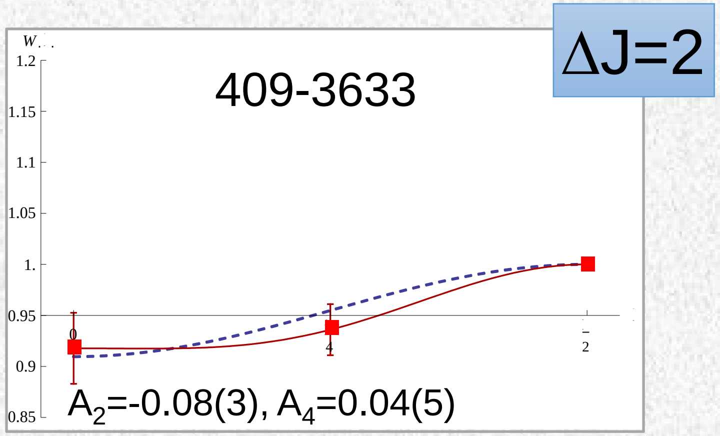


Normalization: number of pairs of the detectors, efficiency → W(Θ)
norm0 = 0.495(5) (4 combinations)
norm45 = 2.020(12) (16 combinations)
norm90 = 1 (8 combinations)

Spin-parity number of the capture state

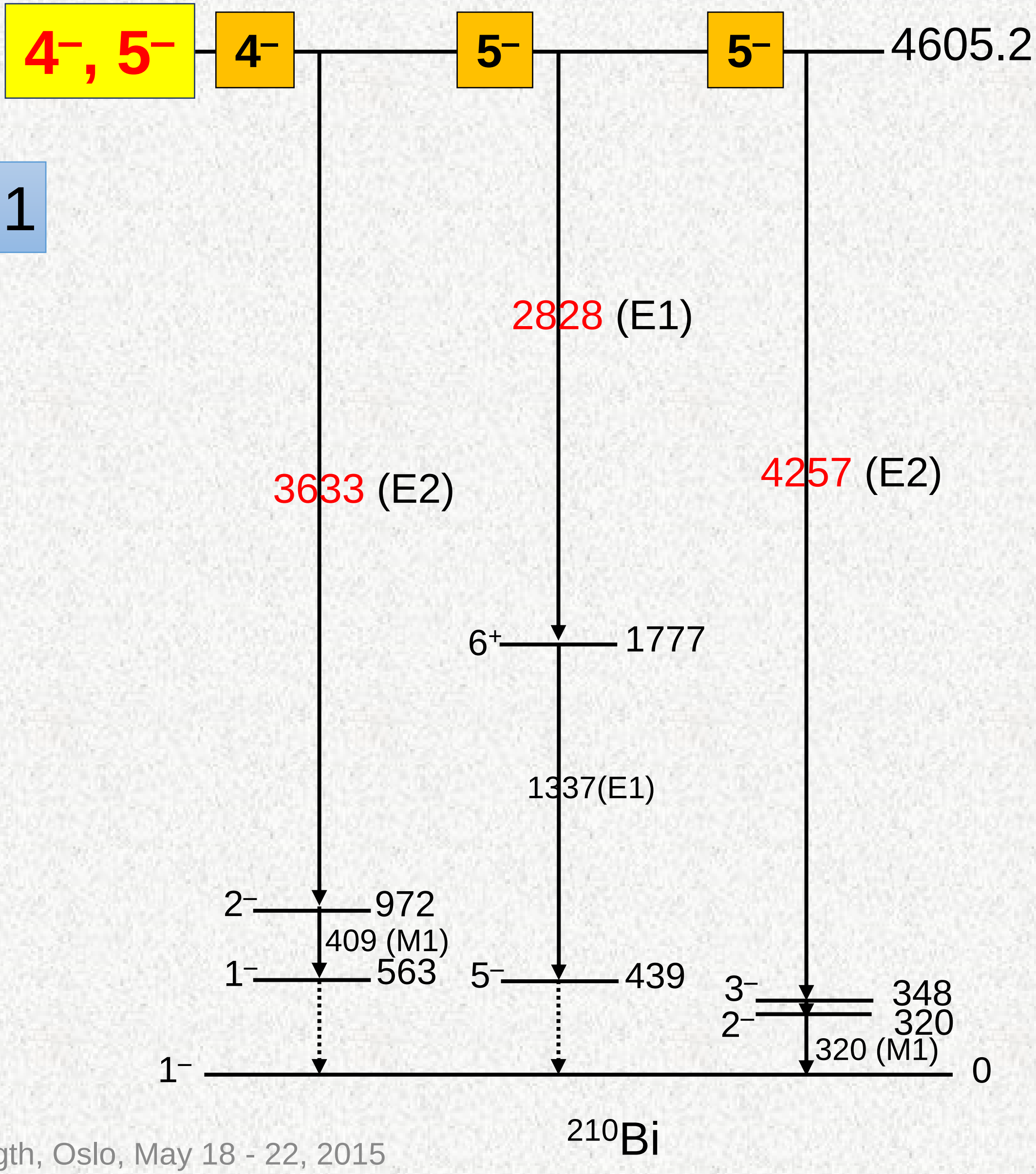






experiment

theory



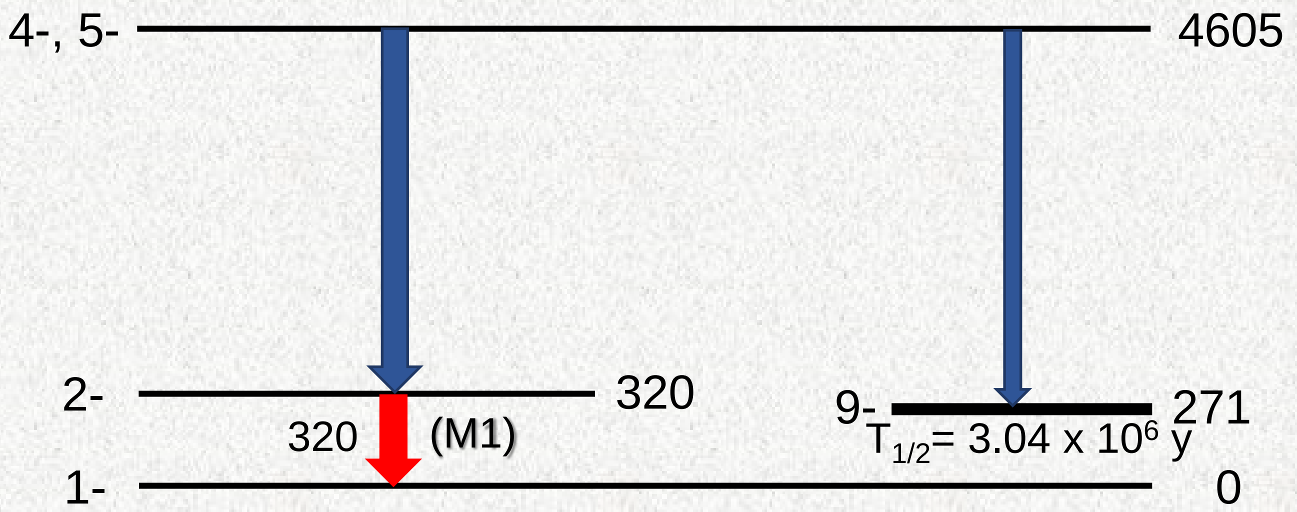
Multipolarity of the main transition leading to the ground state

Not confirmed experimentally M1 multipolarity of 320-keV line

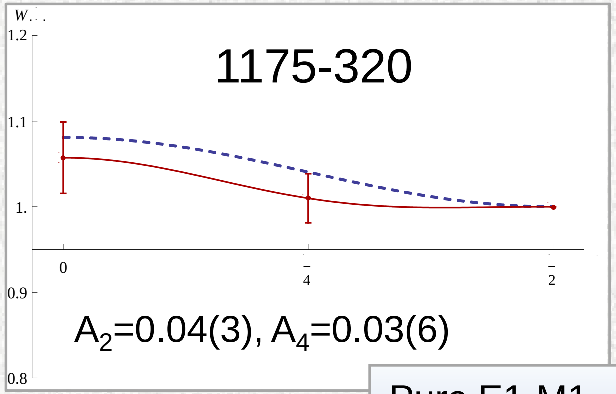
A. Borella et al., Nucl. Phys. A 850, 1 (2011)

Thermal capture cross section for the $^{209}Bi(n,\gamma)^{210}Bi$ reaction to the ground state [mb]		
100% M1	50% M1 +50 % E2	100% E2
21.5(0.9)	**19.3(0.8)**	**17.2(0.7)**

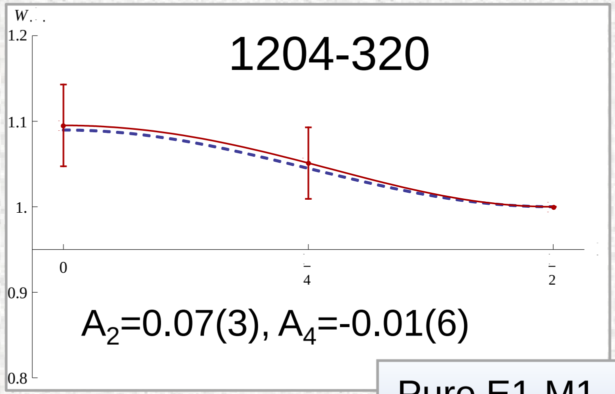
A. Borella et al., AIP Conf. Proc. 769, 648 (2005)



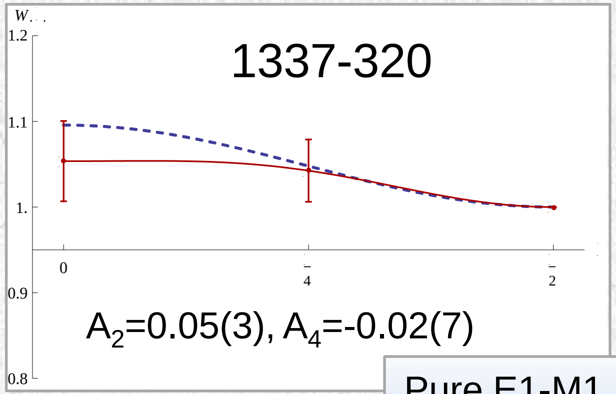
Multipolarity of the 320-keV line



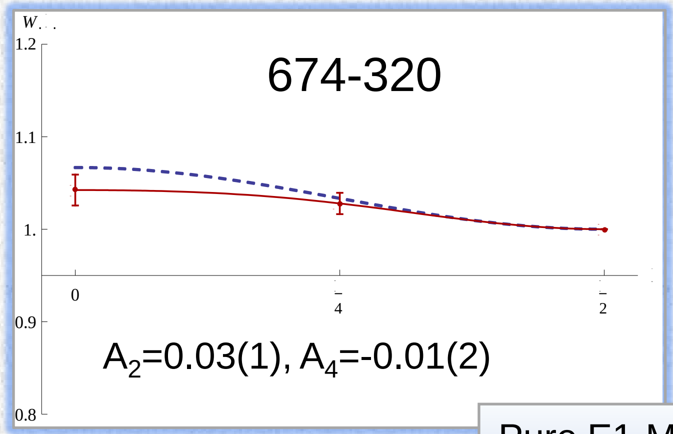
Pure E1-M1
A_2=0.06, A_4=0.00



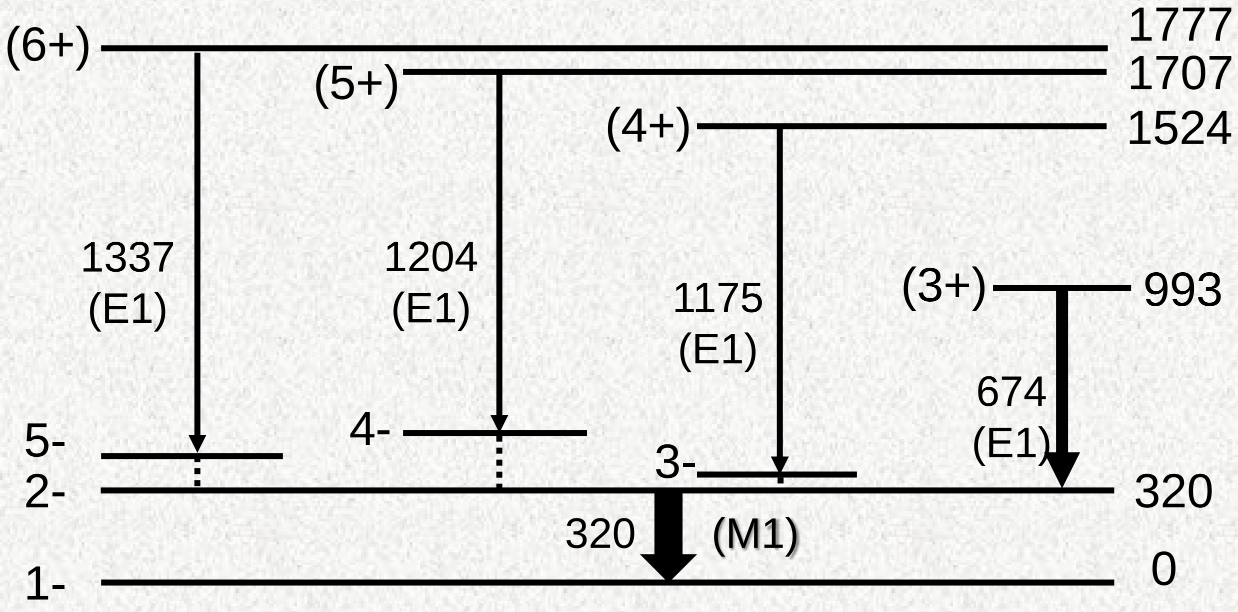
Pure E1-M1
A_2=0.07, A_4=0.00

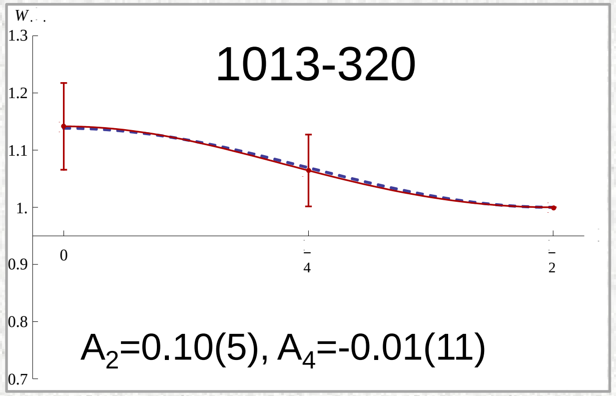


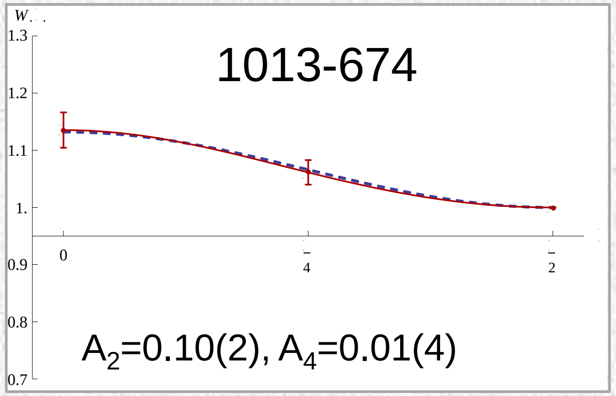
Pure E1-M1
A_2=0.07, A_4=0.00



Pure E1-M1
A_2=0.05, A_4=0.00







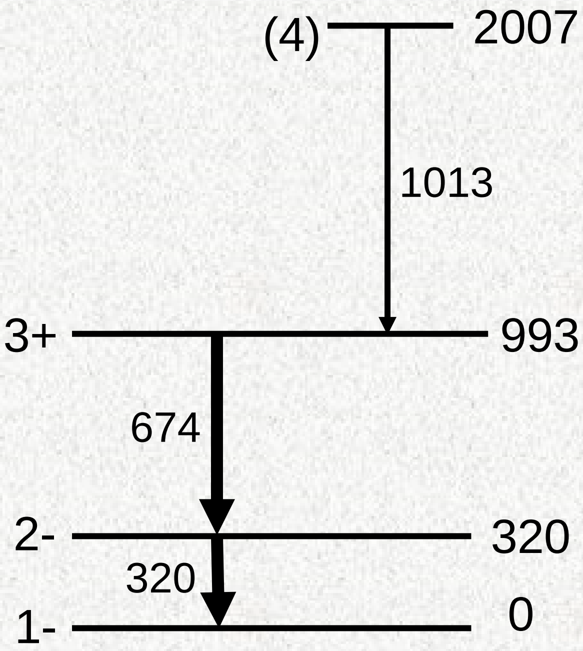
$\boxed{\delta_{320}=0.04}$

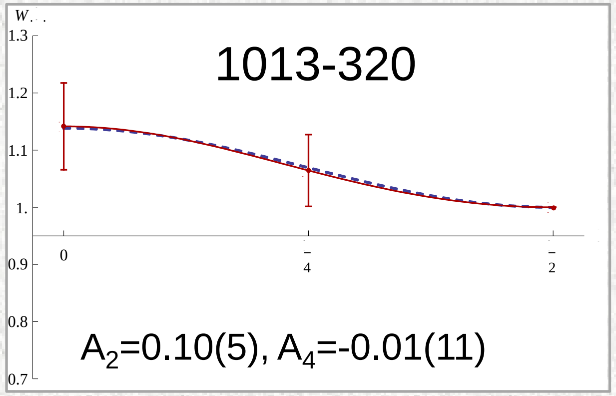
δ_{1013}=-0.105(100)

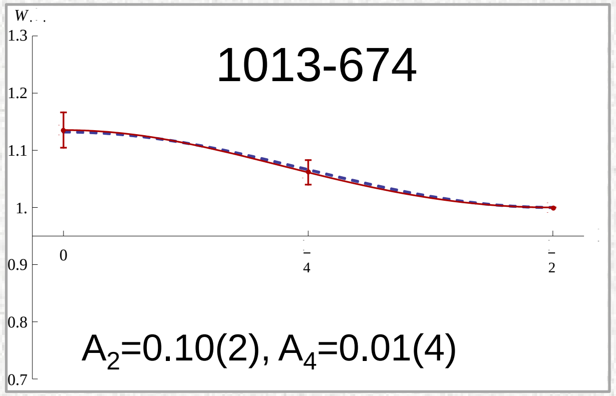
$\boxed{\delta_{674}=0.01}$

δ_{1013}=-0.105(40)

$$\chi^2=\left(\frac{A_{2\_exp}-A_2(\delta_1,\delta_2)}{\Delta A_{2\_exp}}\right)^2+\left(\frac{A_{4\_exp}-A_4(\delta_1,\delta_2)}{\Delta A_{4\_exp}}\right)^2$$

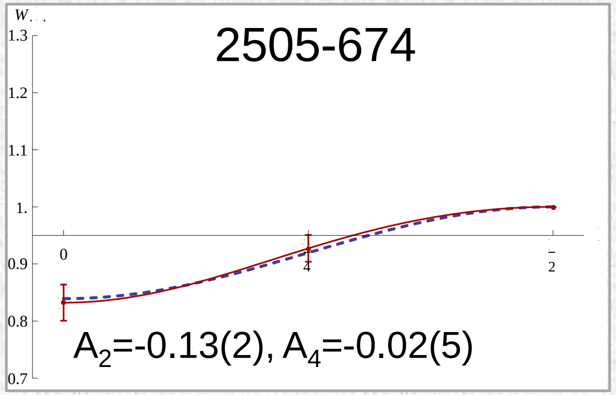


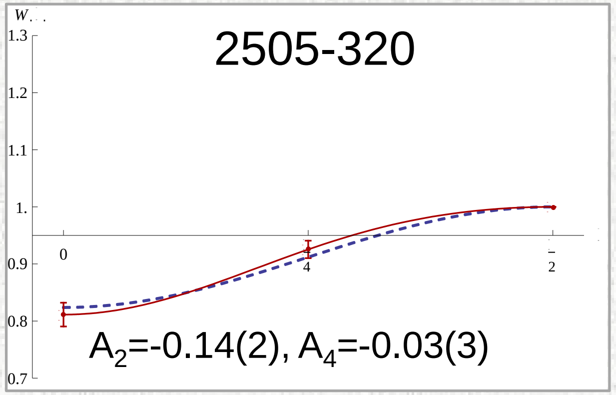




δ_{1013}=-0.105

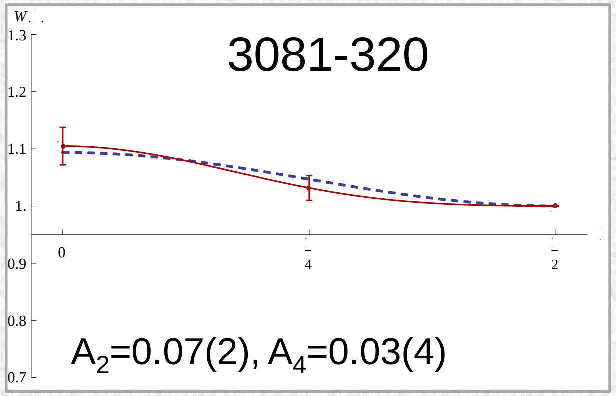
δ_{674}=0.01(3)
δ_{320}=0.04(8)

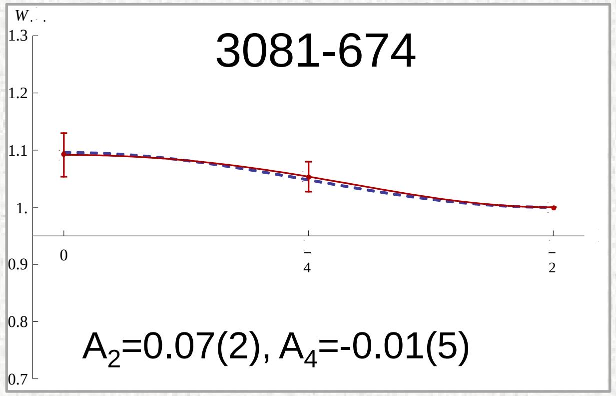




δ_{2505}=0.055

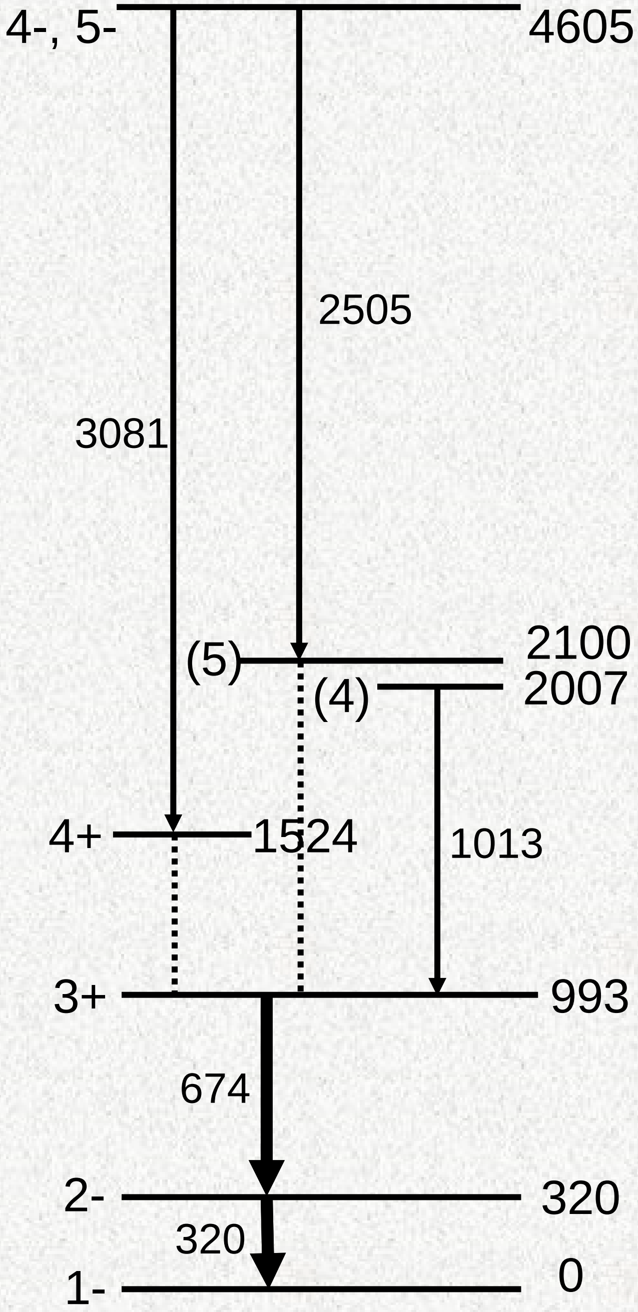
δ_{674}=0.015(29)
δ_{320}=0.036(20)



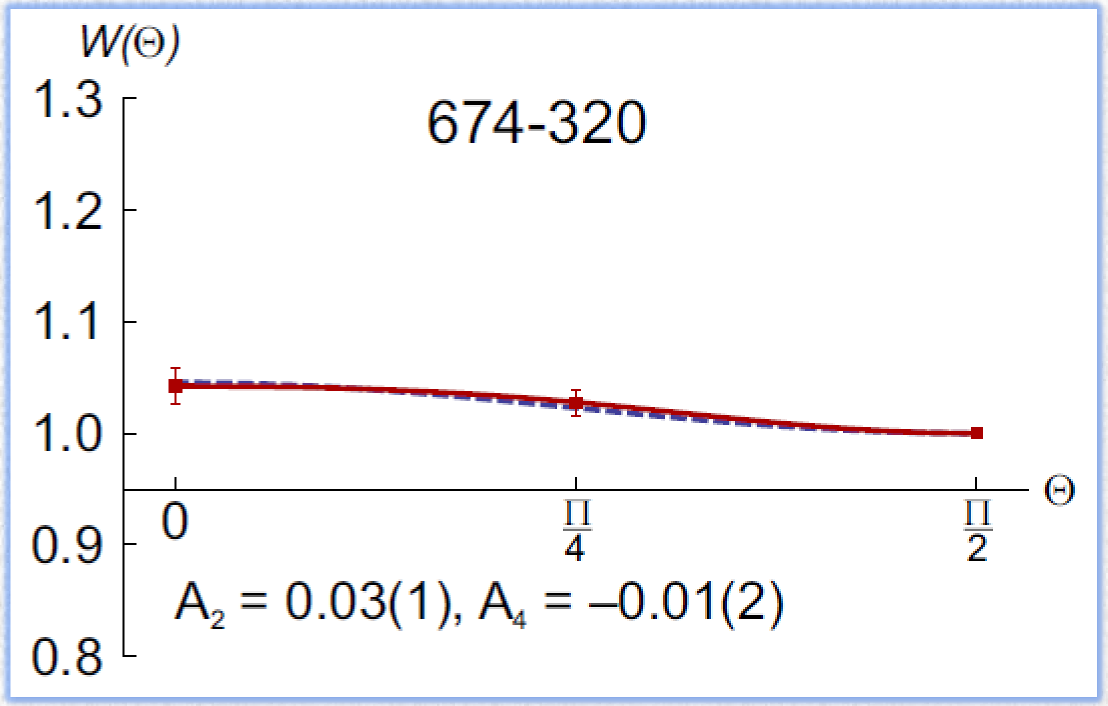


δ_{3081}=-0.037

δ_{674}=0.009(56)
δ_{320}=0.05(5)



Multipolarity of 320-keV transition



δ_{674}=0.01(3)

δ_{320}=0.04(3)

$$\delta^2 = \frac{I_{L'}}{I_L}$$

$$I(L) = \frac{1}{\delta^2 + 1}$$

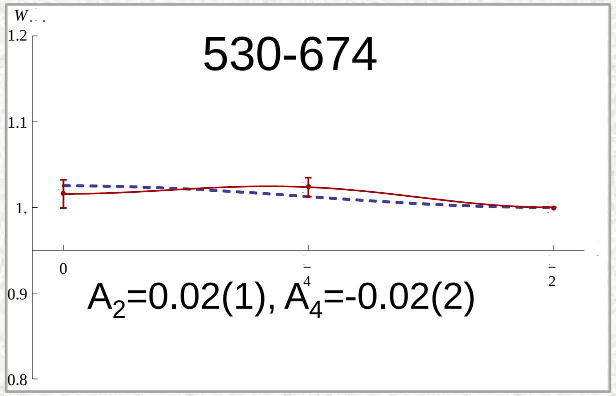
$$I(L') = \frac{\delta^2}{\delta^2 + 1}$$

674 keV: 99.99% E1 + 0.01% M2

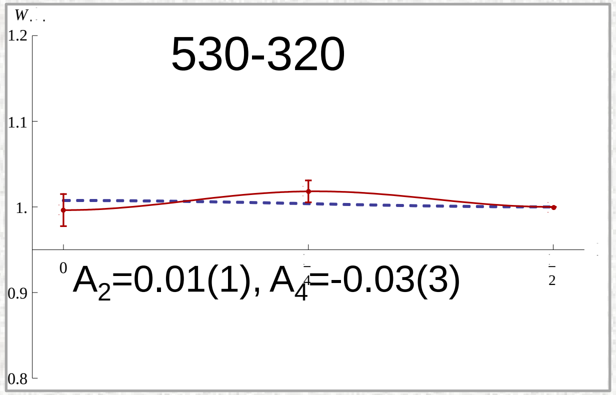
320 keV: 99.84% M1 + 0.16% E2

Decays to:
3+, 4-, 3-

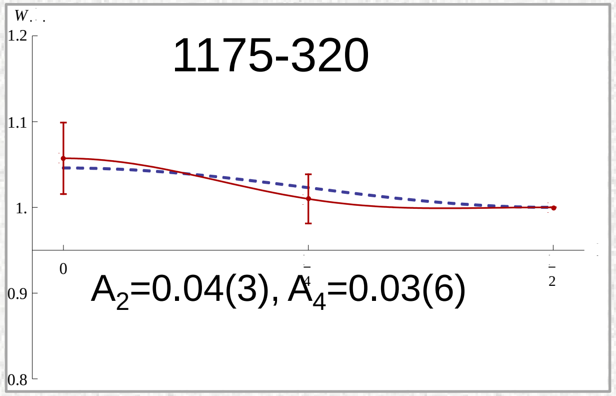
Spin-parity values: state at 1524 keV



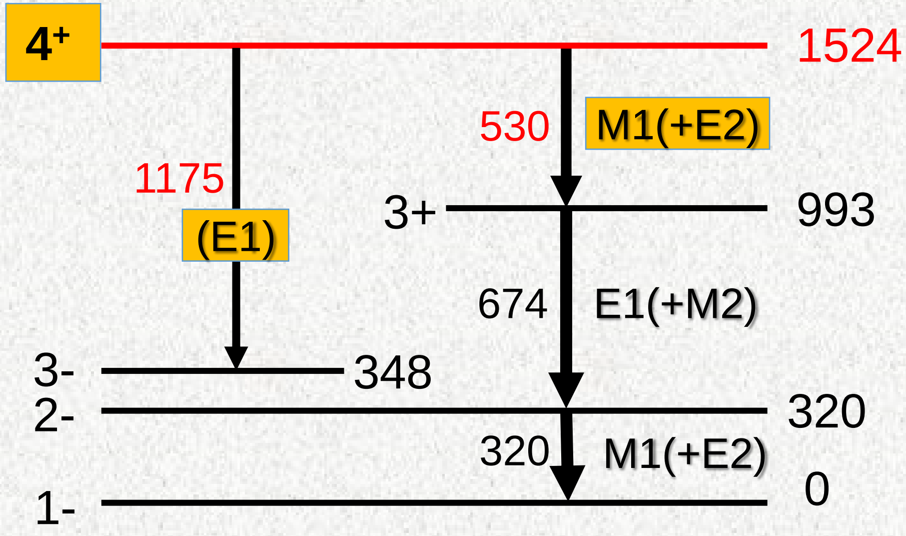
δ_{530}=0.06(2)



δ_{530}=0.09(3)

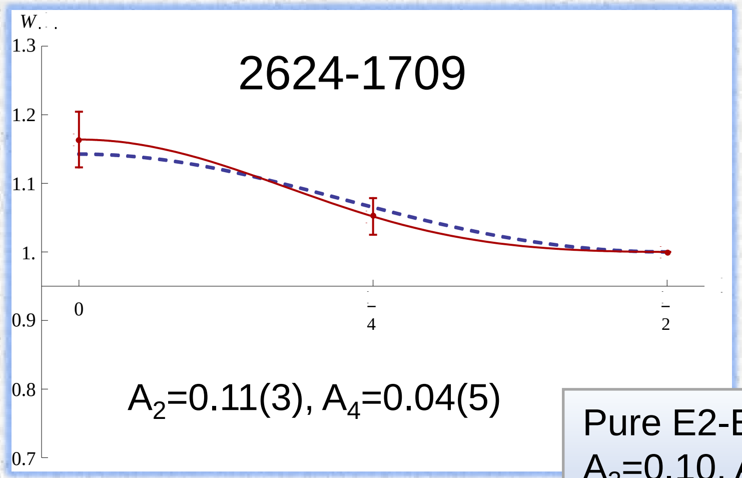


δ_{1175}=0.03(5)

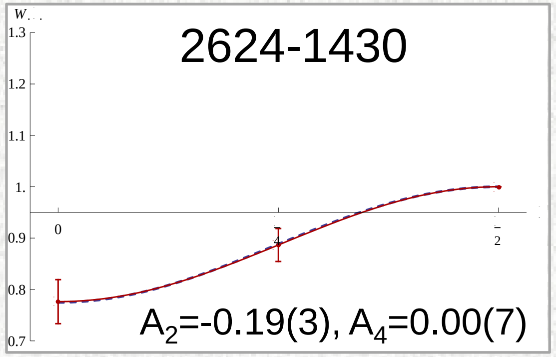


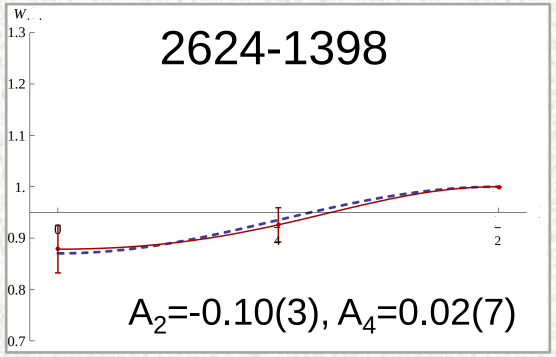
Decays to:
(6-), 8-, 8-, 6-, 7-, 9-

State at 1981 keV



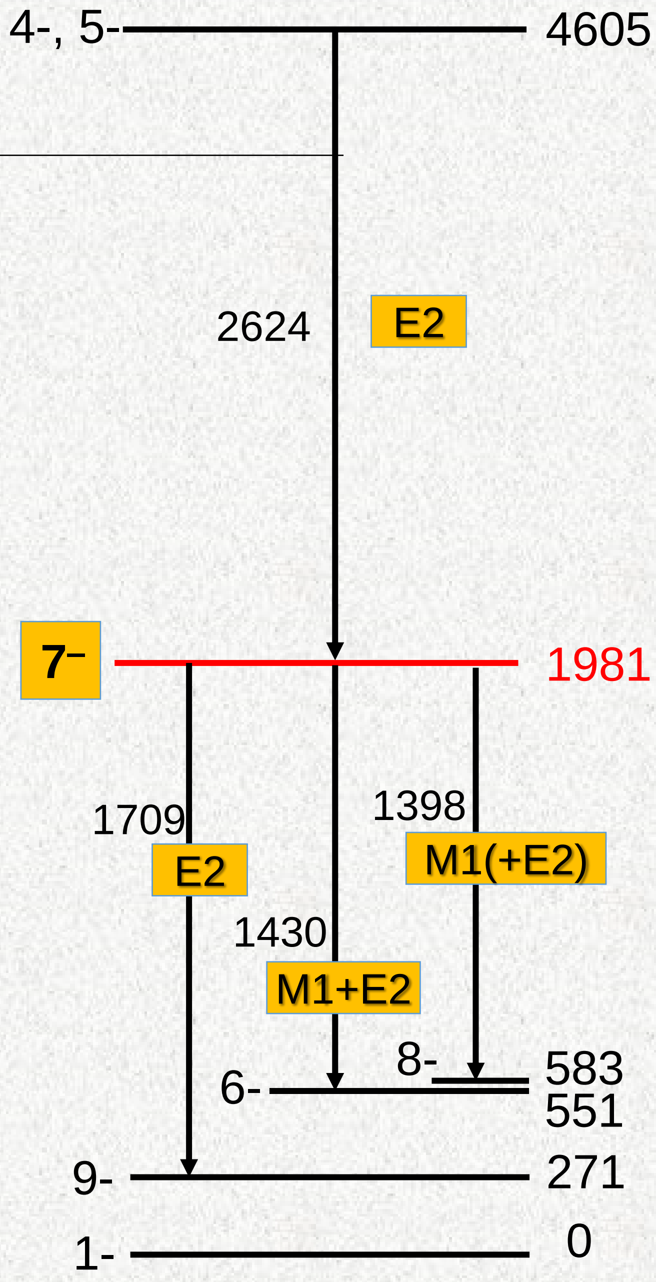
Pure E2-E2
A_2=0.10, A_4=0.01





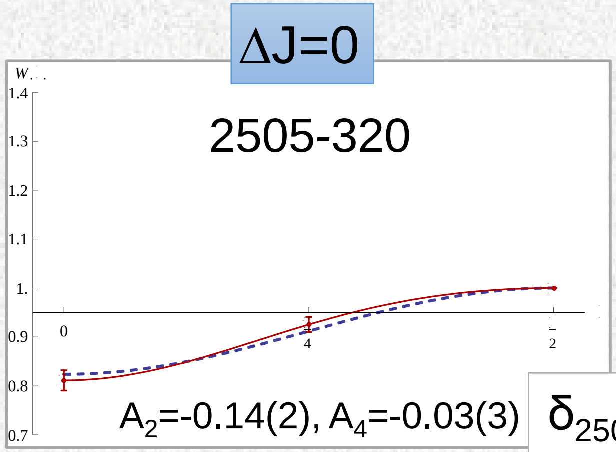
δ_{1430}=-0.11(5)

δ_{1398}=0.05(5)

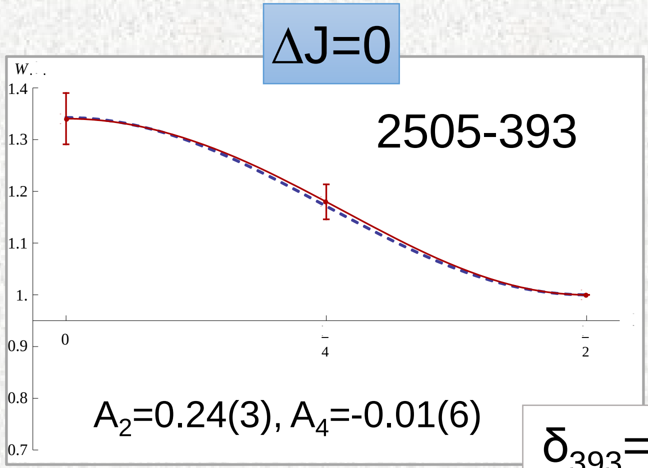


Decays to:
(6+), (5+), (4+), (4-), (6-), 6-, 4-

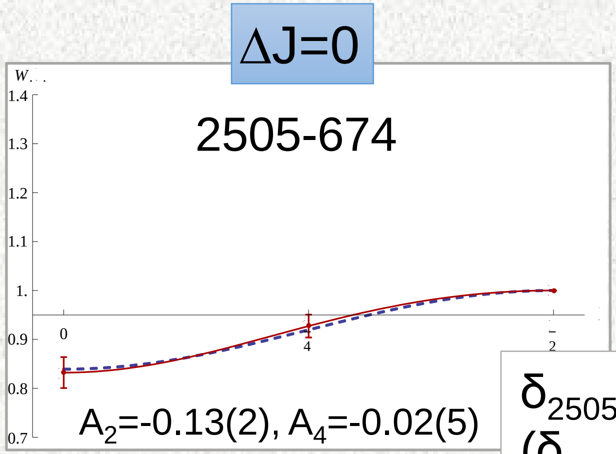
State at 2100 keV



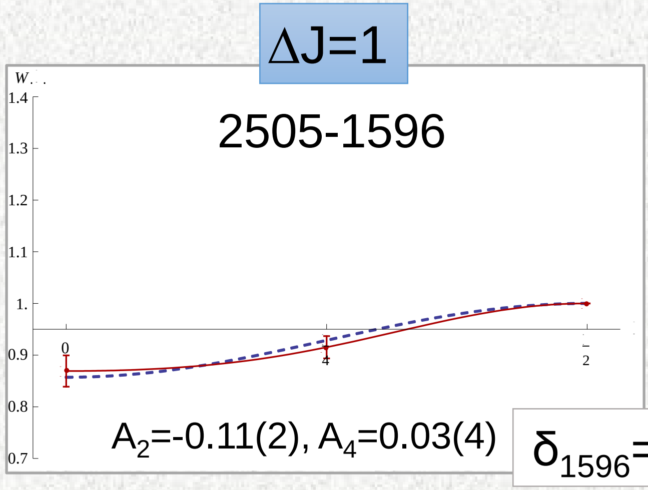
δ_{2505}=0.04(8)
(δ_{2505}=-0.82(12))



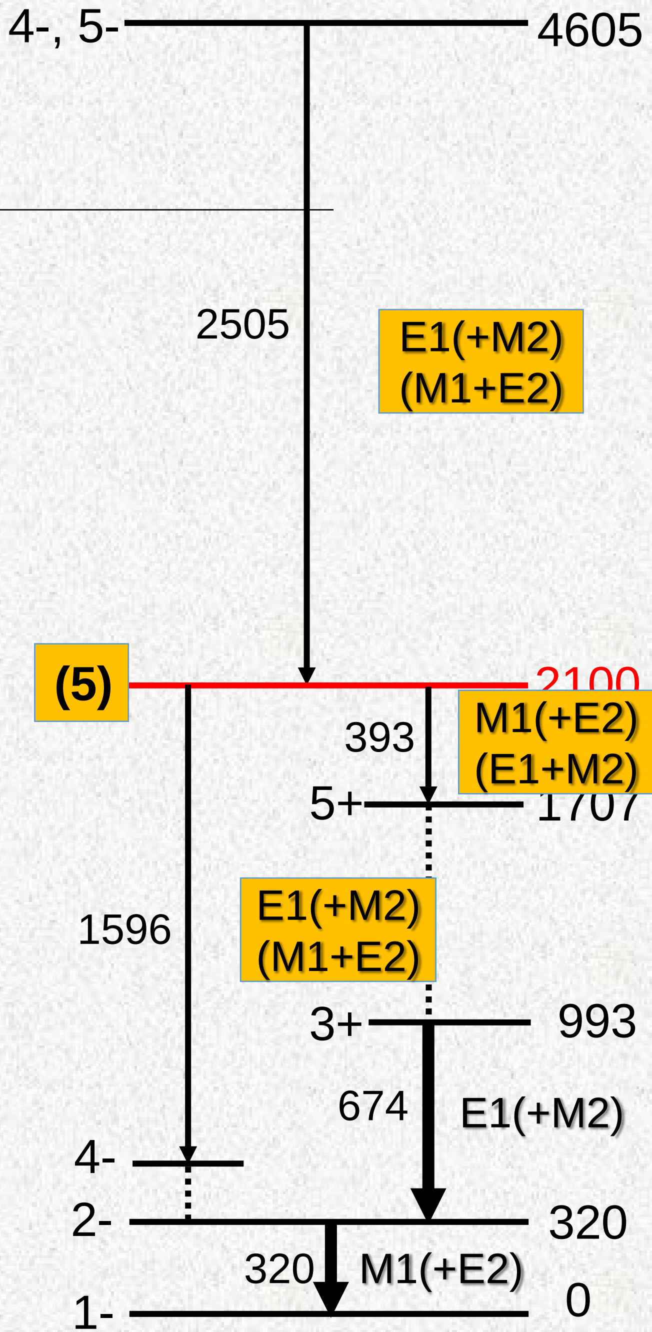
δ_{393}=-0.3(3)



δ_{2505}=0.07(12)
(δ_{2505}=-0.88(19))

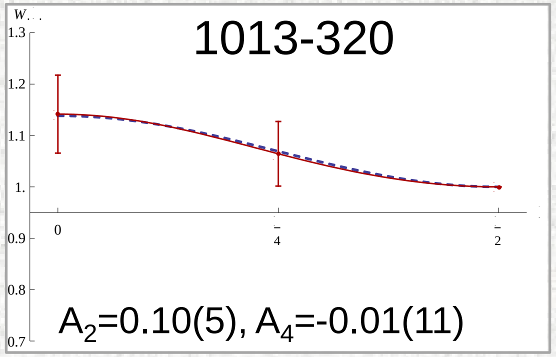


δ_{1596}=0.01(3)

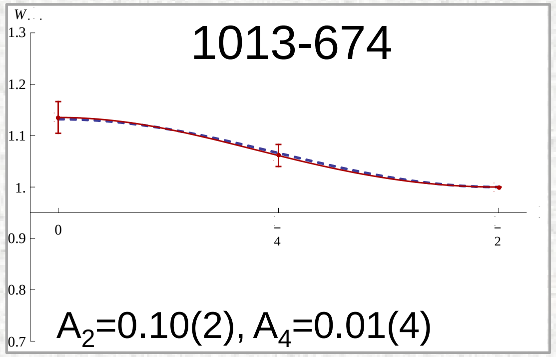


Decays to:
5+, 4+, 3-, 4-, 3+, 4-, 5-, 3-, 2-

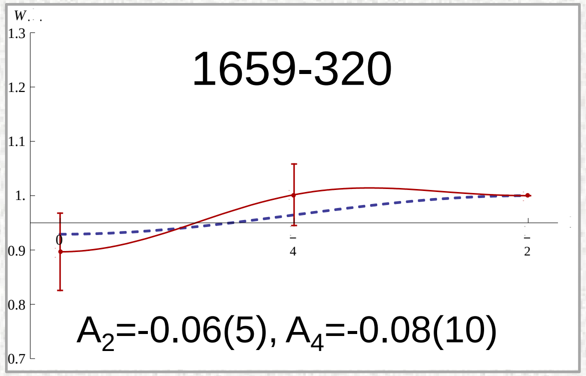
State at 2007 keV



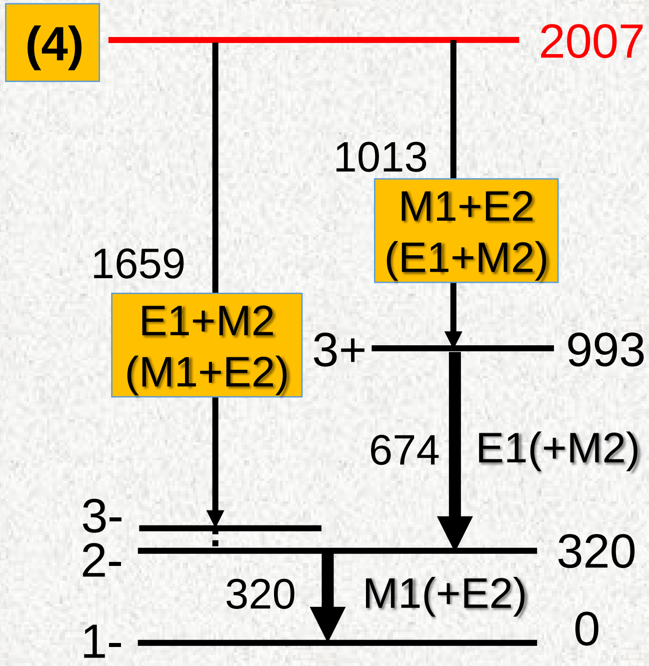
δ_{1013}=-0.11(9)



δ_{1013}=-0.10(4)

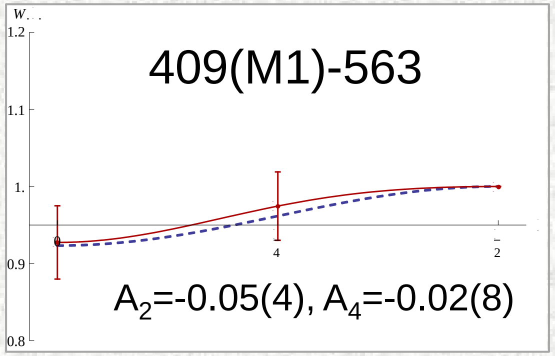


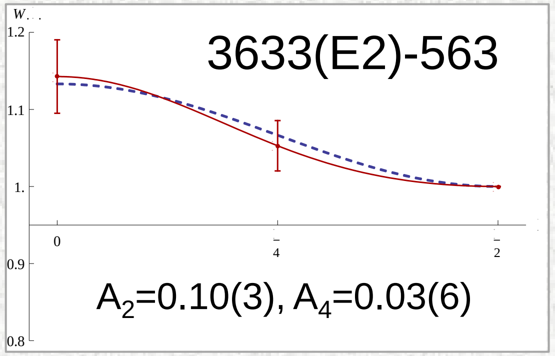
δ_{1659}=0.23(14)



Fed from: BE
Decays to: 1-, 3-, 1-

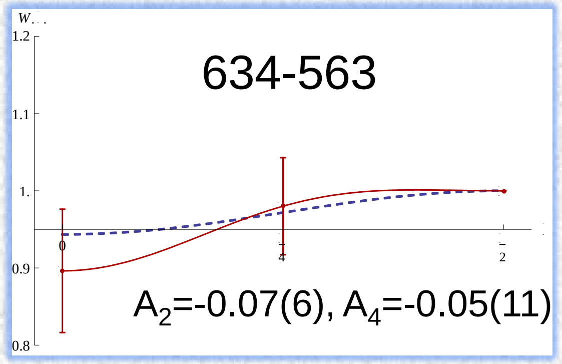
State at 1197 keV





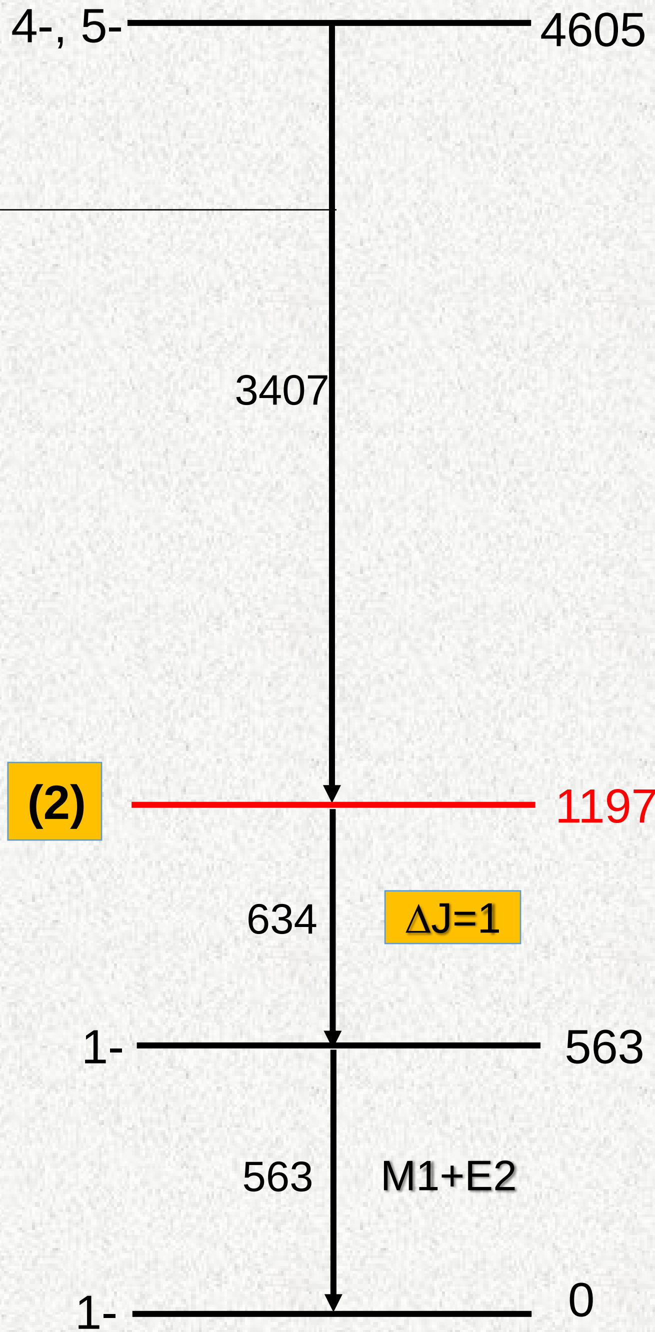
(δ_{409} = 0)
δ_{563}=0.25(30)

δ_{563}=0.10(8)



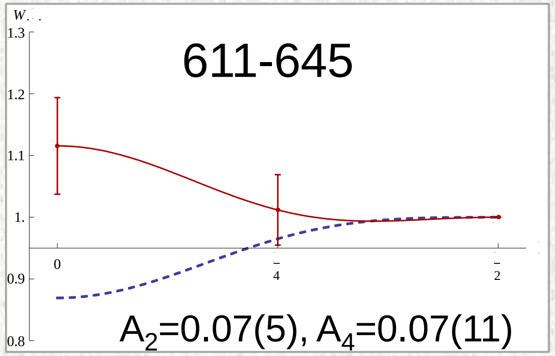
Theory ΔJ=1-(M1+E2)
δ_{563}=0.18(16)

A_2=-0.04
A_4=0.00

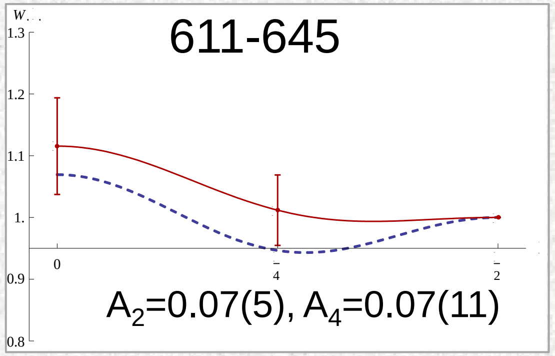


Fed from: BE, (6-), (6-), (6-)
Decays to: 8-, 8-, 6-

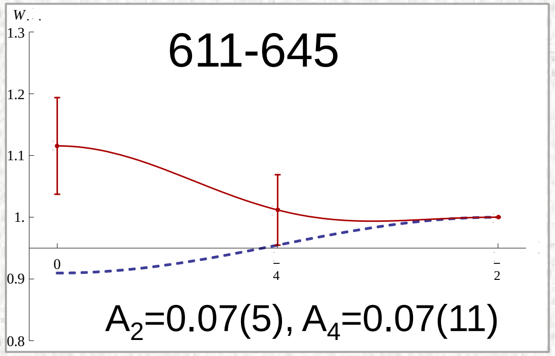
State at 1527 keV



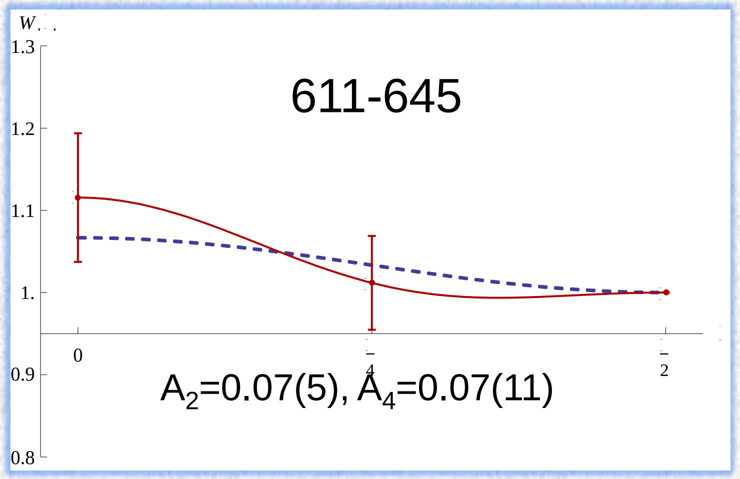
Theory ΔJ=2 (6 → 8) E2
ΔJ=2 (8 → 9) E2
A_2=-0.09
A_4=0.00



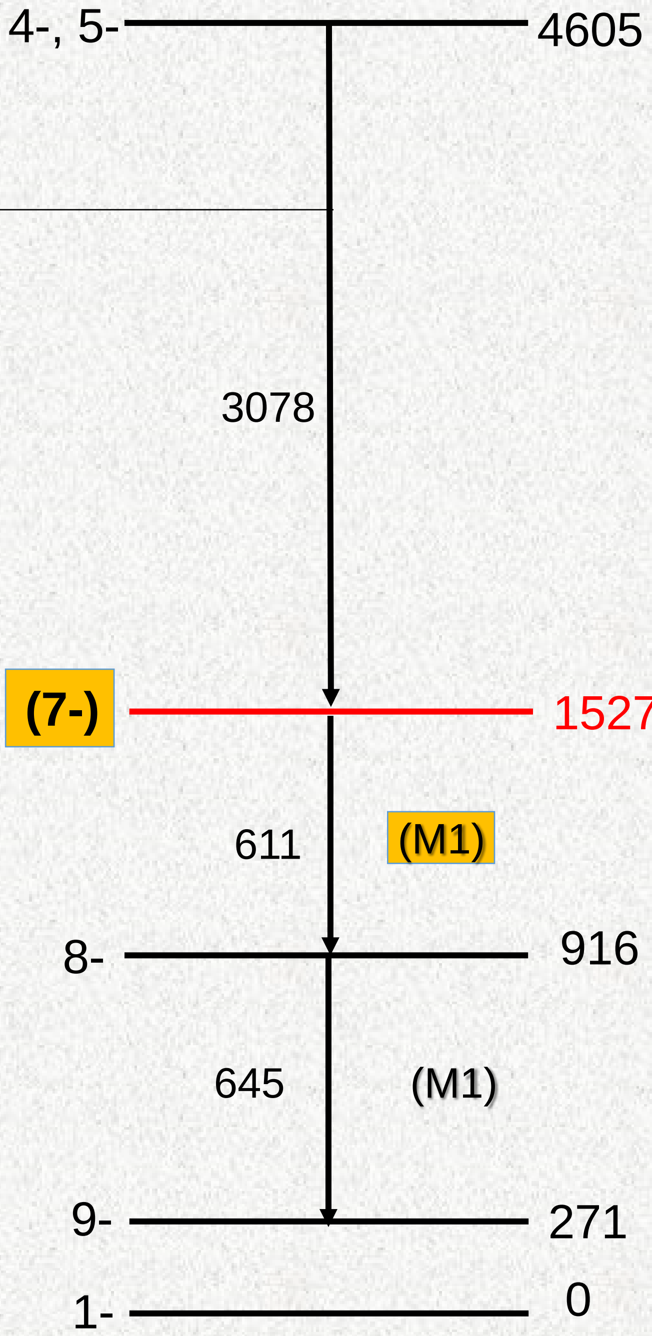
Theory ΔJ=2 (7 → 8) E2
ΔJ=2 (8 → 9) E2
A_2=0.01
A_4=0.14



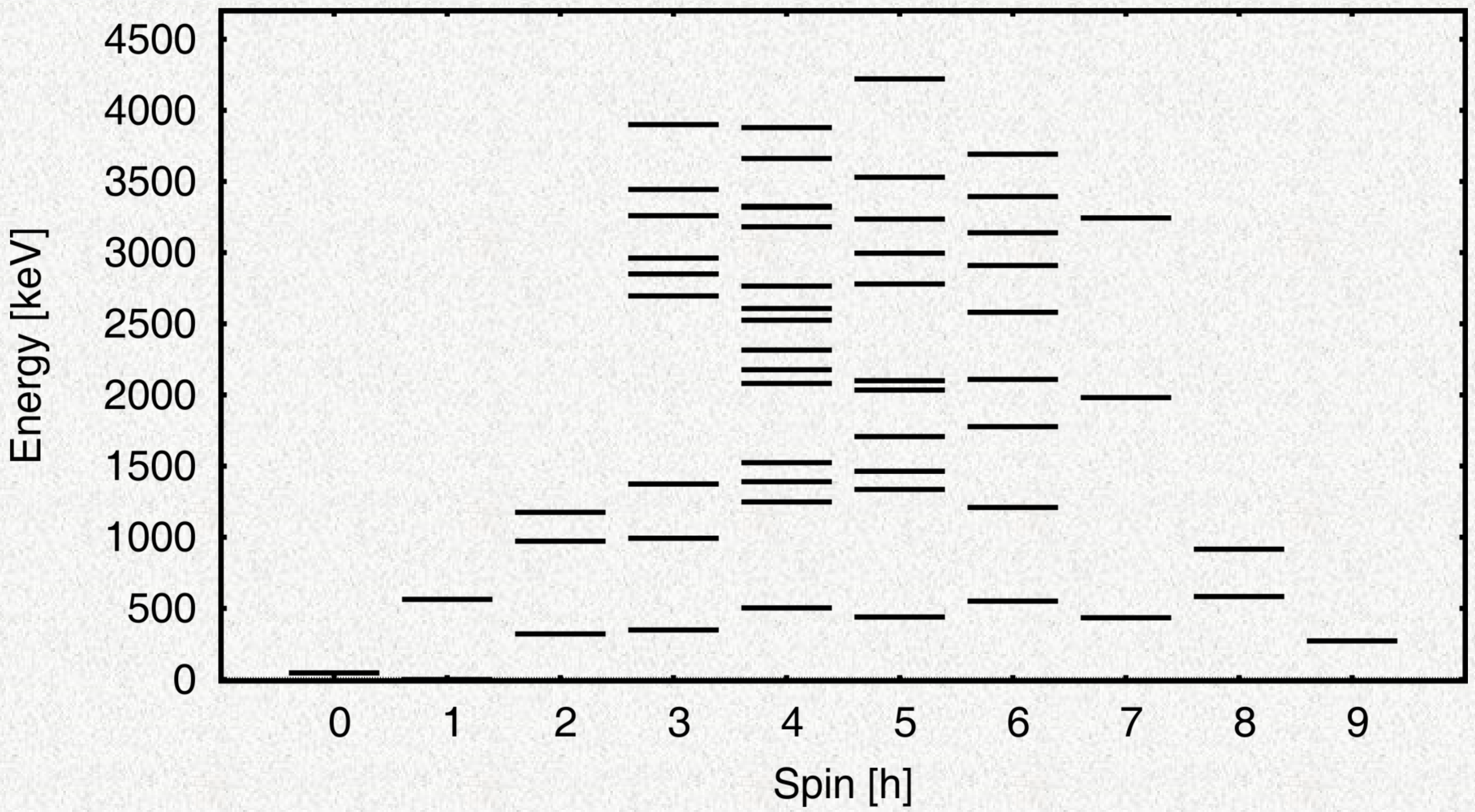
Theory ΔJ=2 (6 → 8) E2
ΔJ=1 (8 → 9) M1
A_2=-0.07
A_4=0.00



Theory ΔJ=1 (7 → 8) M1
ΔJ=1 (8 → 9) M1
A_2=0.05
A_4=0.00

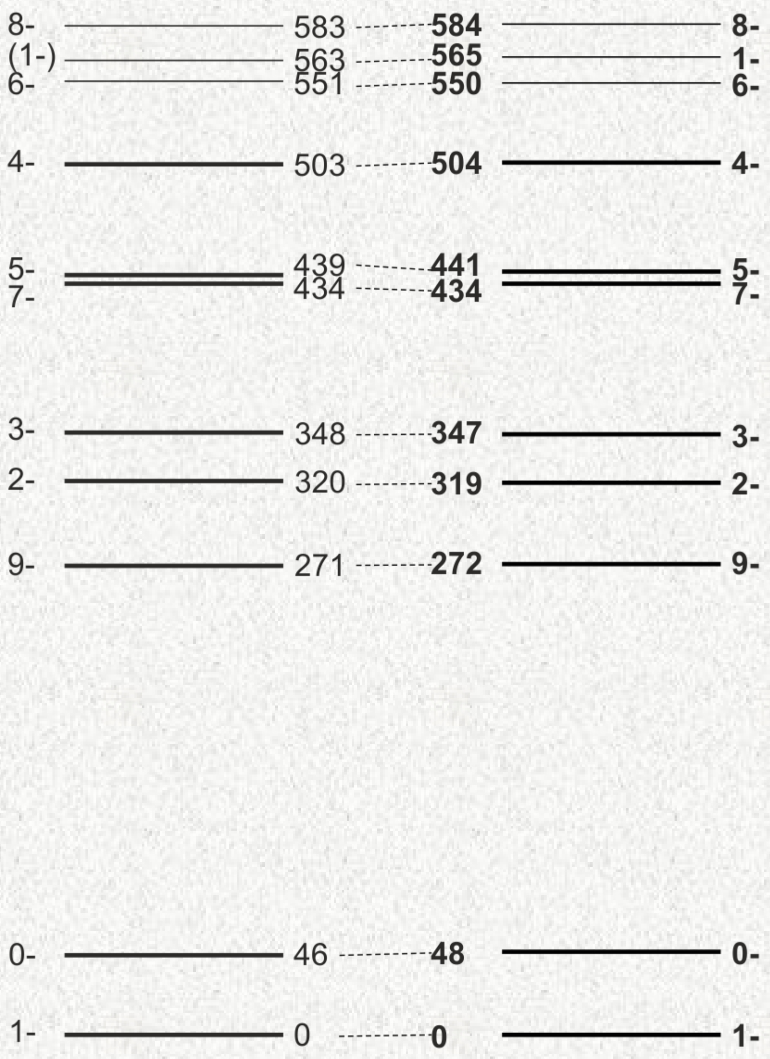


Spin distribution from $^{209}Bi(n,\gamma)^{210}Bi$ reaction (experimental results: shell-model states)

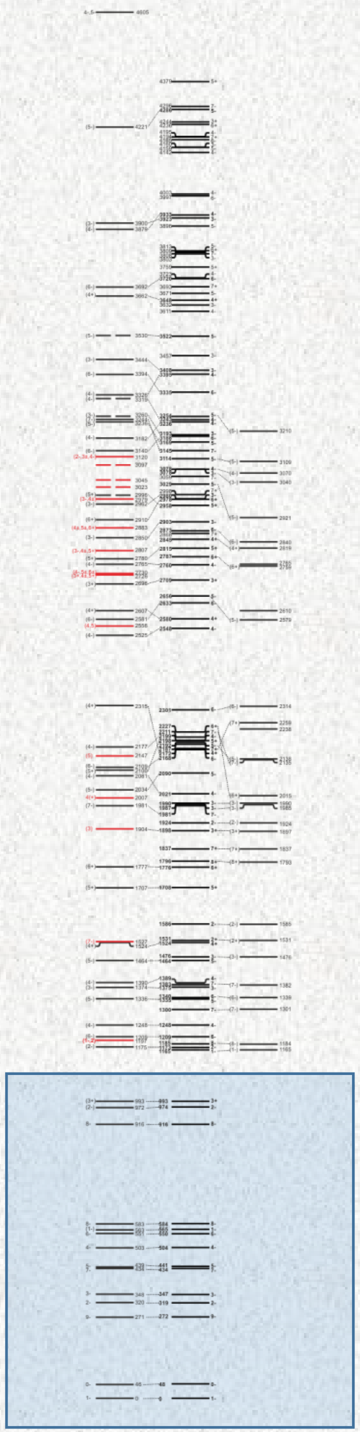


Comparison with shell-model calculations

Firmly known states used to fit TBME of p-n interaction
E. K. Warburton, B. A. Brown, Phys. Rev. C 43, 602 (1991)



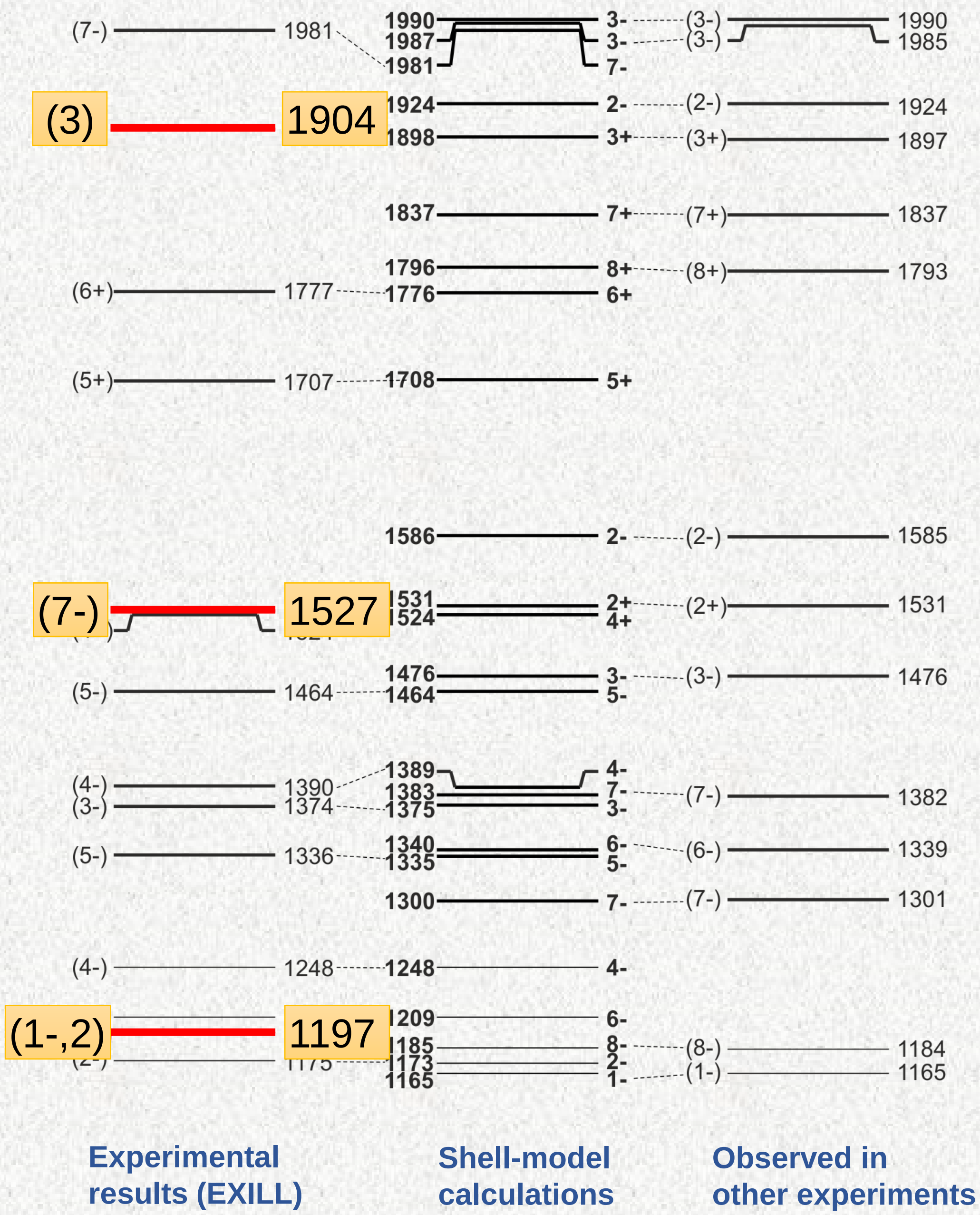
Experimental results (EXILL) **Shell-model calculations**

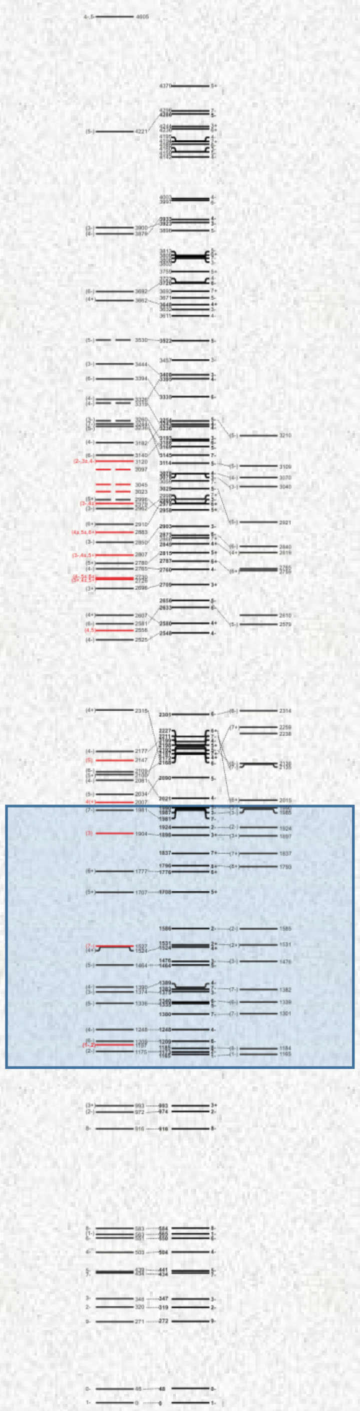


Comparison with shell-model calculations

Firmly known states used to fit TBME of p-n interaction
E. K. Warburton, B. A. Brown, Phys. Rev. C 43, 602 (1991)

Three states below 2 MeV without theoretical counterparts

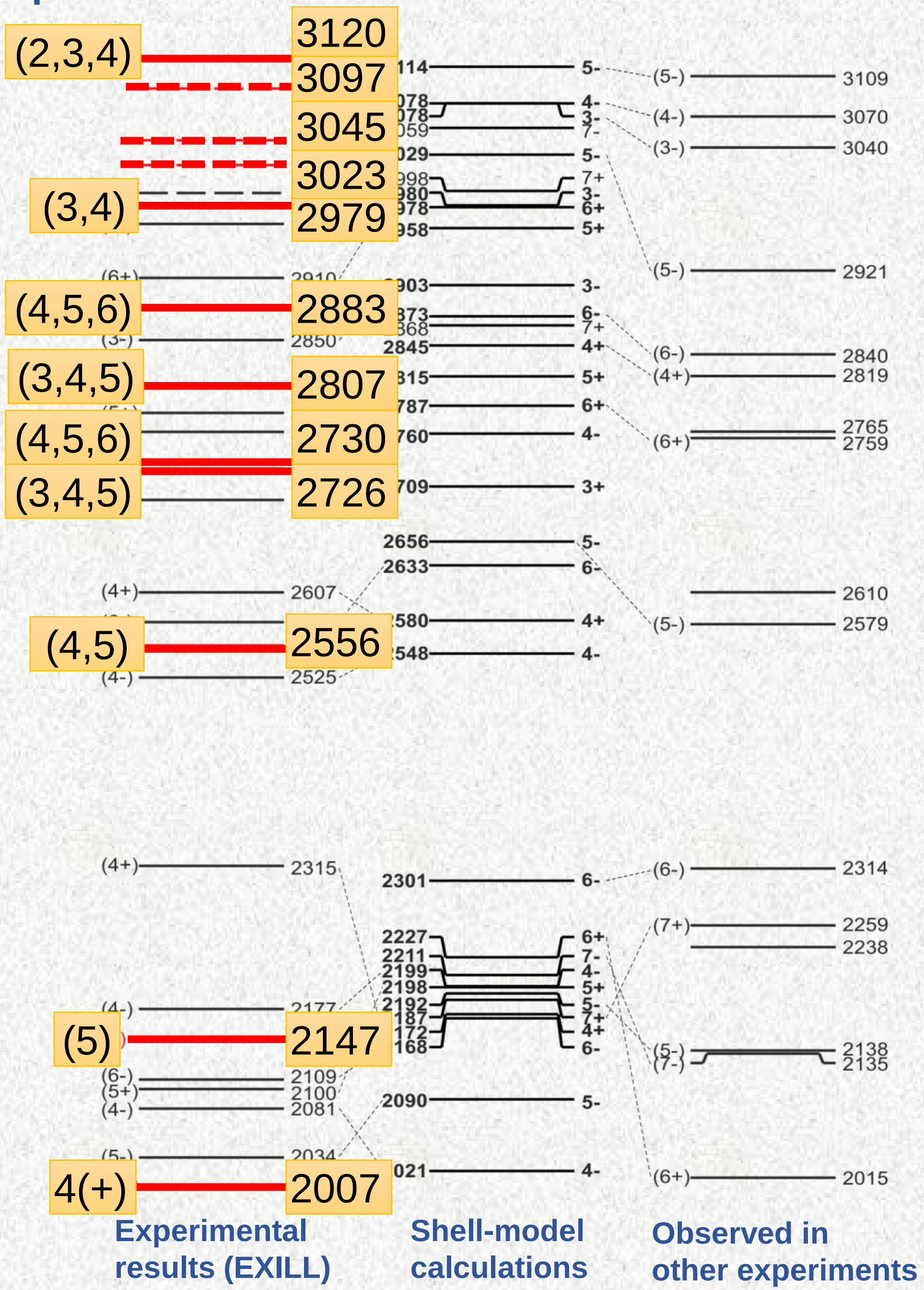




Comparison with shell-model calculations

3- —— **2.6 MeV**

208Pb

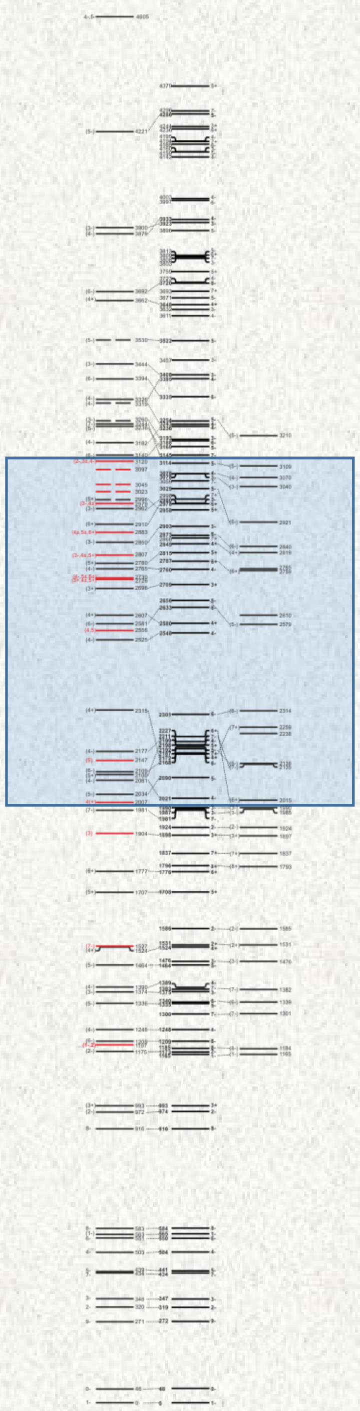


$3^- \times (\pi h_{9/2} \nu g_{9/2})$

3- × 0- → 3+

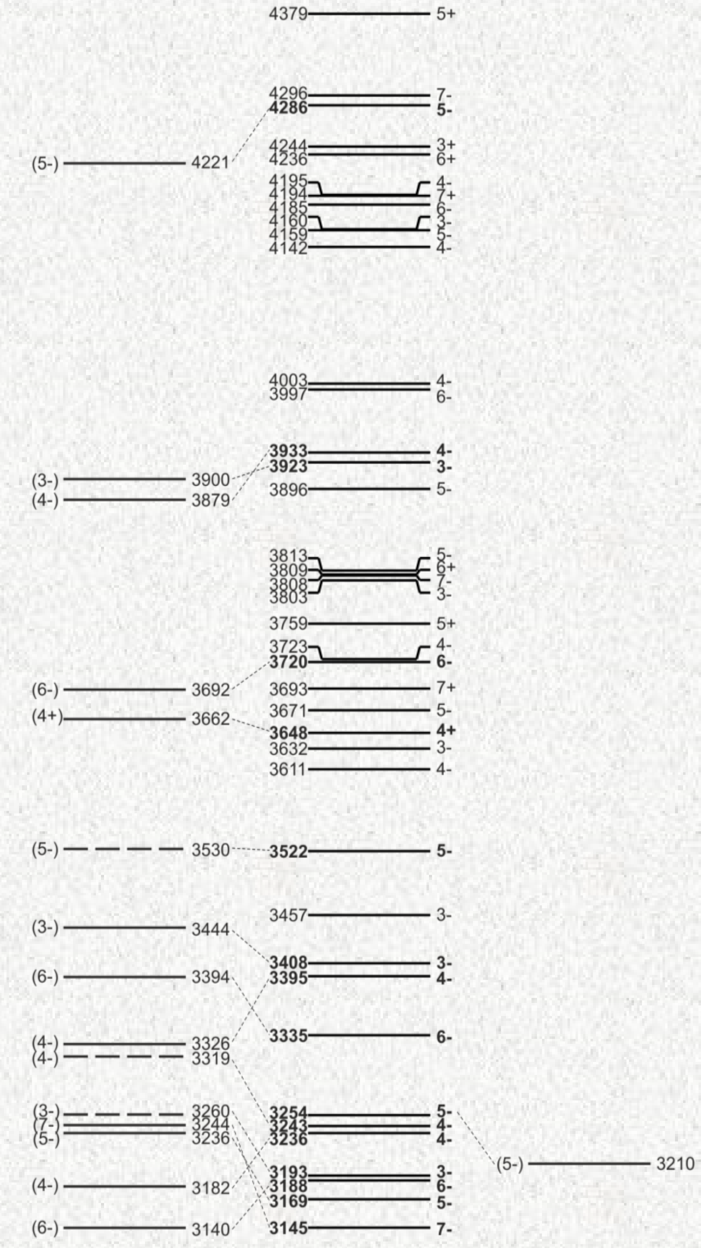
3- × 1- → 2+, 3+, 4+

3- × 9- → 6+, 7+, 8+, (9+, 10+, 11+, 12+)

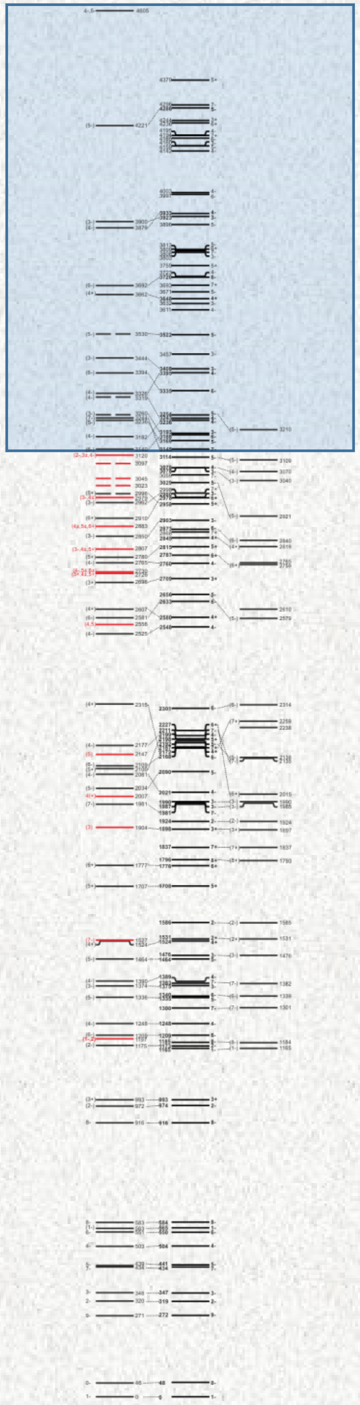


Comparison with shell-model calculations

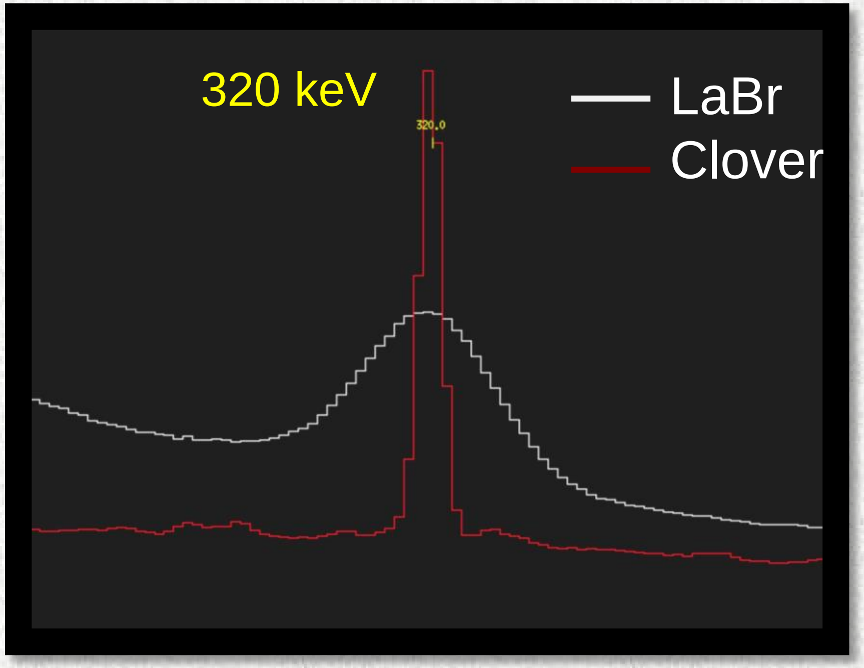
Higher part of the level scheme: states arising from the valence particles excitations.

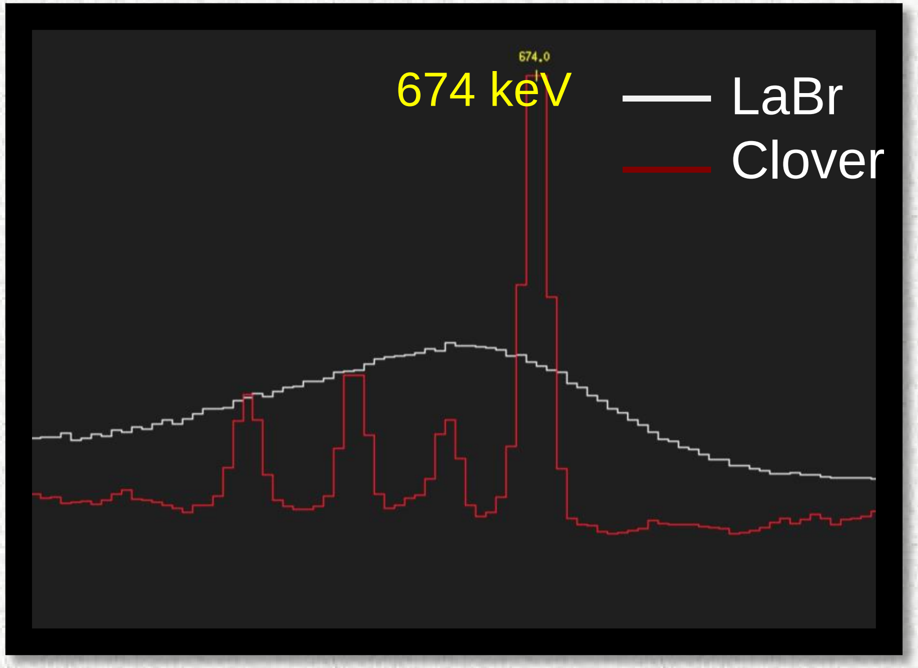


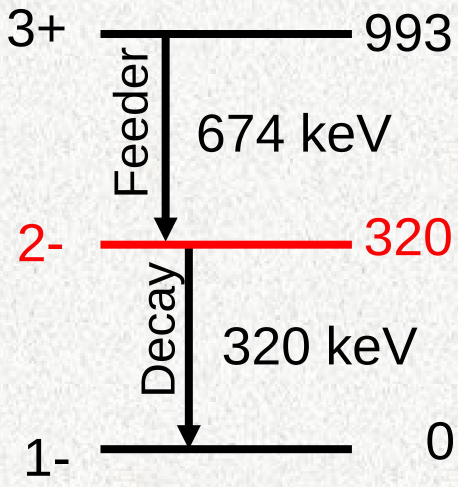
Experimental results (EXILL) **Shell-model calculations** **Observed in other experiments**



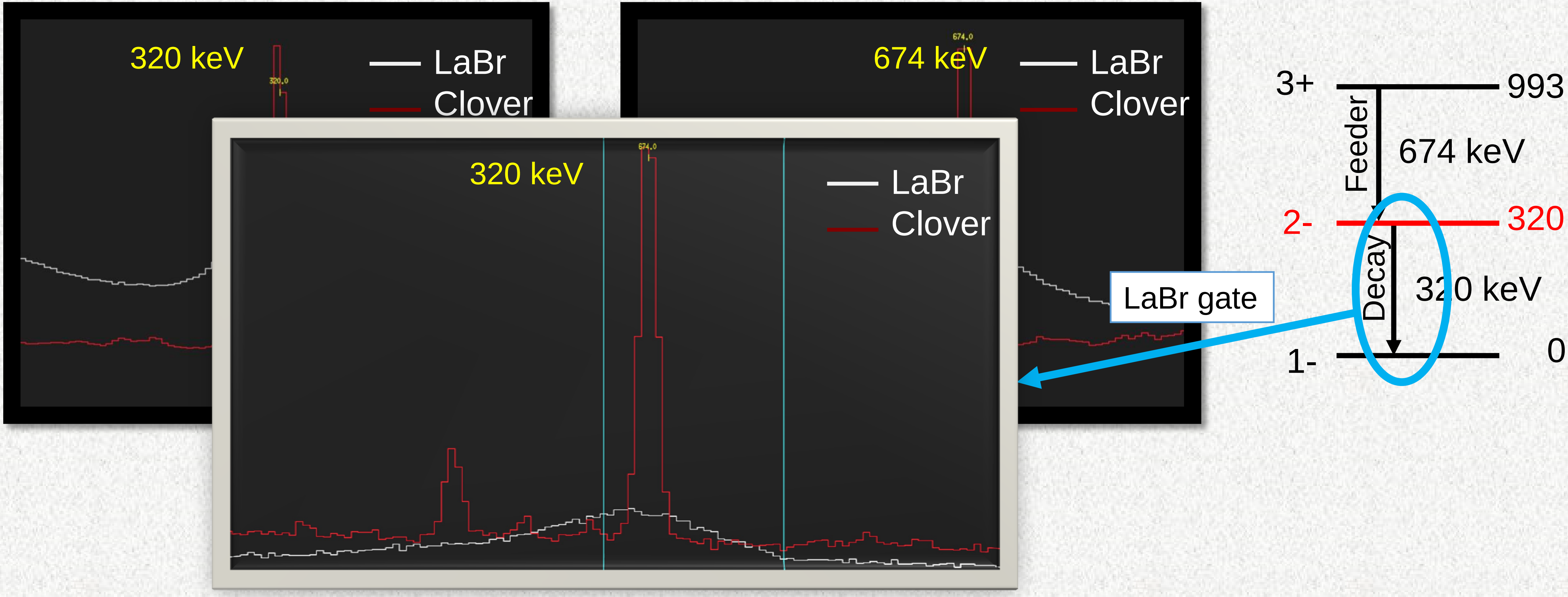
Measurements of the lifetimes of excited states in ^{210}Bi



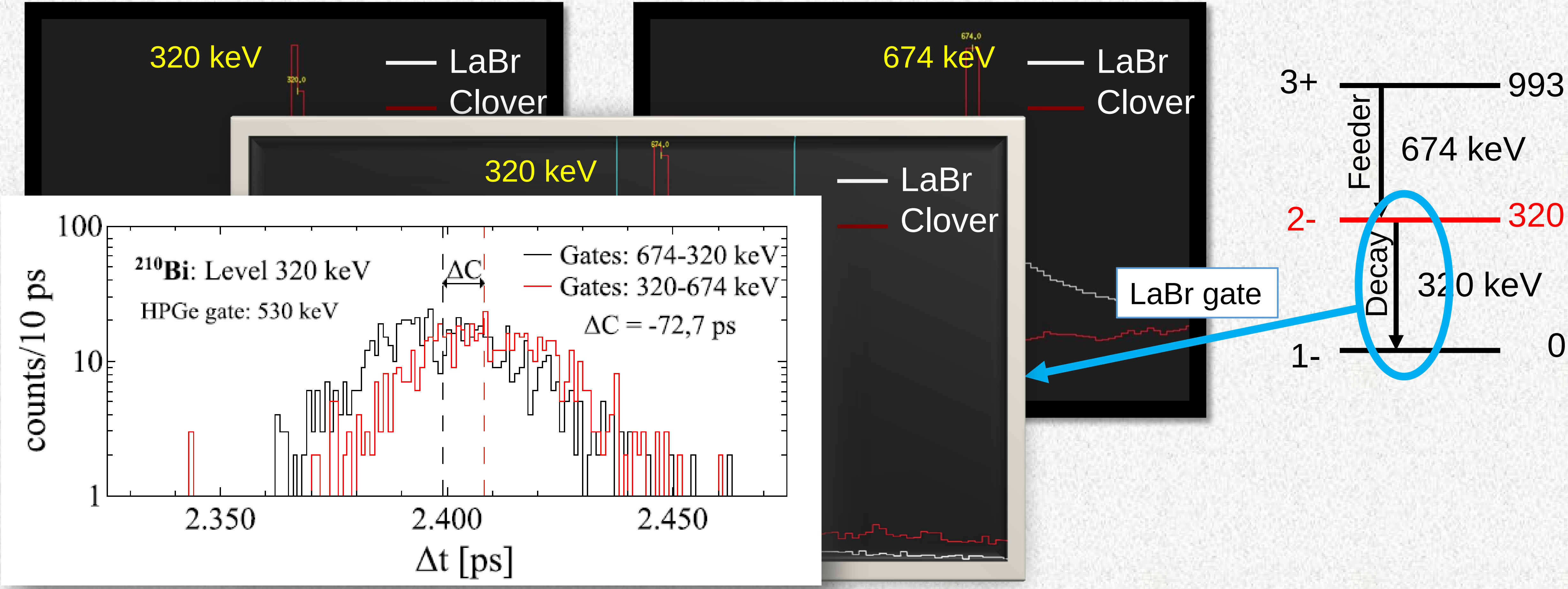




Measurements of the lifetimes of excited states in ^{210}Bi



Measurements of the lifetimes of excited states in ^{210}Bi



Measurements of the lifetimes of excited states in ^{210}Bi

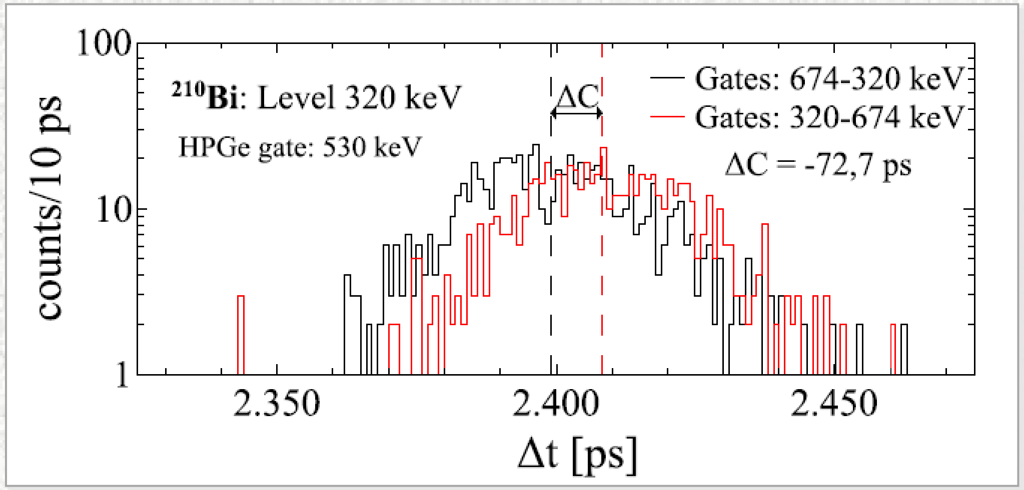
$$\tau = \frac{1}{2}\left[\frac{\Delta C - \Delta C_{compton}}{\pi} + \Delta C - PRD\right]$$

ΔC = 22 ps
$\Delta C_{compton}$ = 106.8 ps
PRD (E_{feeder} – E_{decay}) = -83.4 ps
π = 0.8

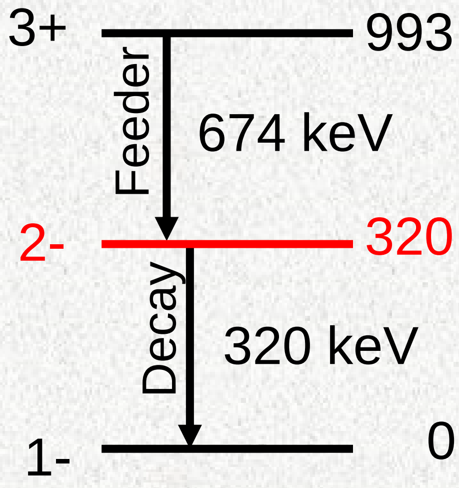
τ = 2(9) ps

τ_{lit} = 7.5(14) ps

Phys Rev. C 12, 1547(1975)



With this method the lower limit is 10 ps



Measurements of the lifetimes of excited states in ^{210}Bi

- 2–, 320 keV

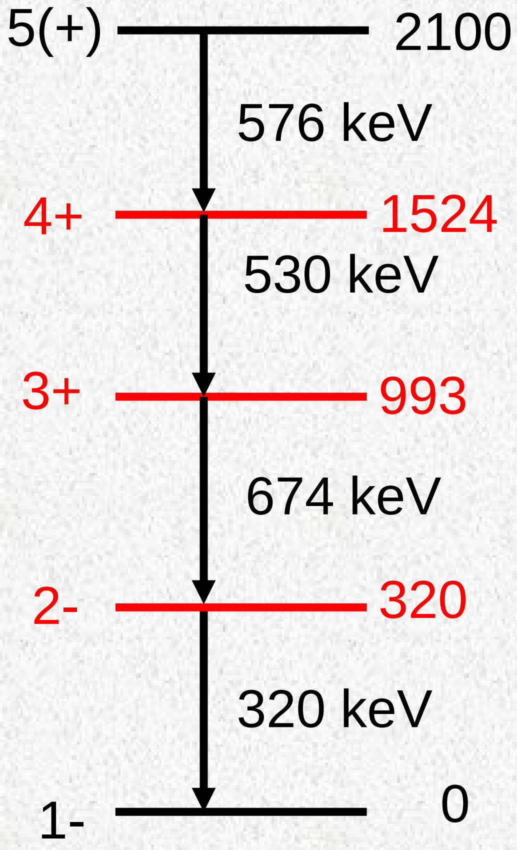
  τ = 2(9) ps

- 3+, 993 keV

  τ < 40 ps

- 4+, 1524 keV

  τ = 31(16) ps



S. Lodetti, MS Thesis, Milano (2015)

Summary

- The level structure of ^{210}Bi investigated in cold neutron capture on ^{209}Bi was compared to shell model calculations – some of the states must come from the core excitations.
- The analysis of angular correlations allowed to confirm almost pure M1 character of the main transition leading to the ground state.
- The results of present analysis of ^{210}Bi structure will serve as an excellent testing ground for the future calculataions.

Thank you for your attention!