STUDY OF SHAPE COEXISTENCE AND COLLECTIVE PROPERTIES IN $^{94-96}$ZR ISOTOPES VIA COULOMB EXCITATION MEASUREMENTS

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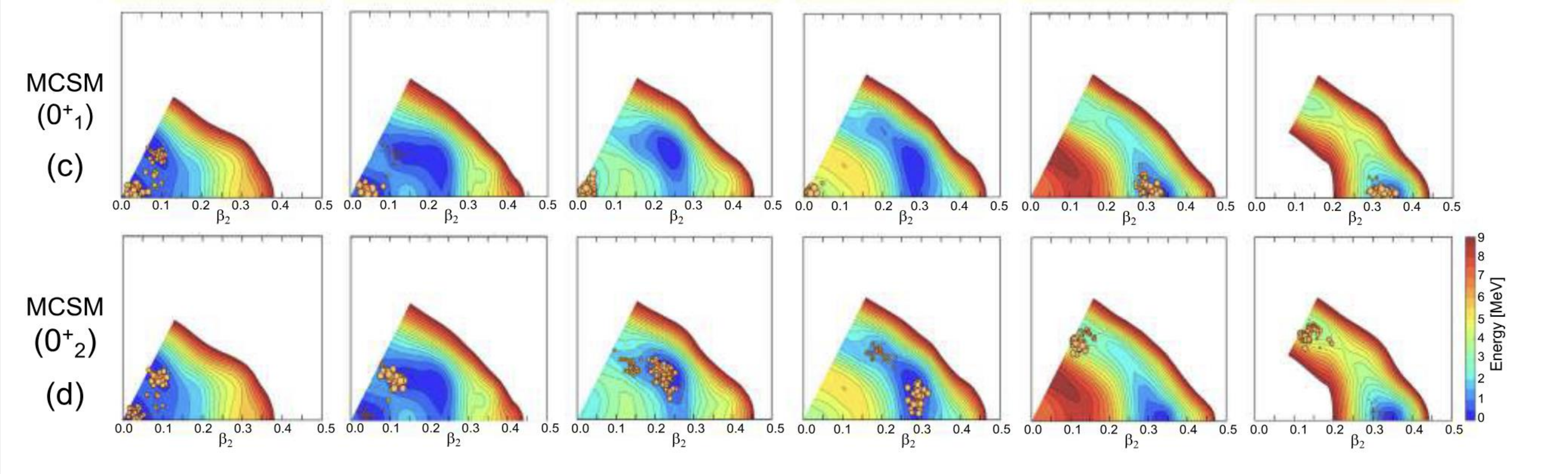
ZIRCONIUM ISOTOPES – NUCLEAR STRUCTURE

^{92}Zr ^{94}Zr ^{96}Zr ^{98}Zr ^{100}Zr ^{102}Zr



Type II shell evolution

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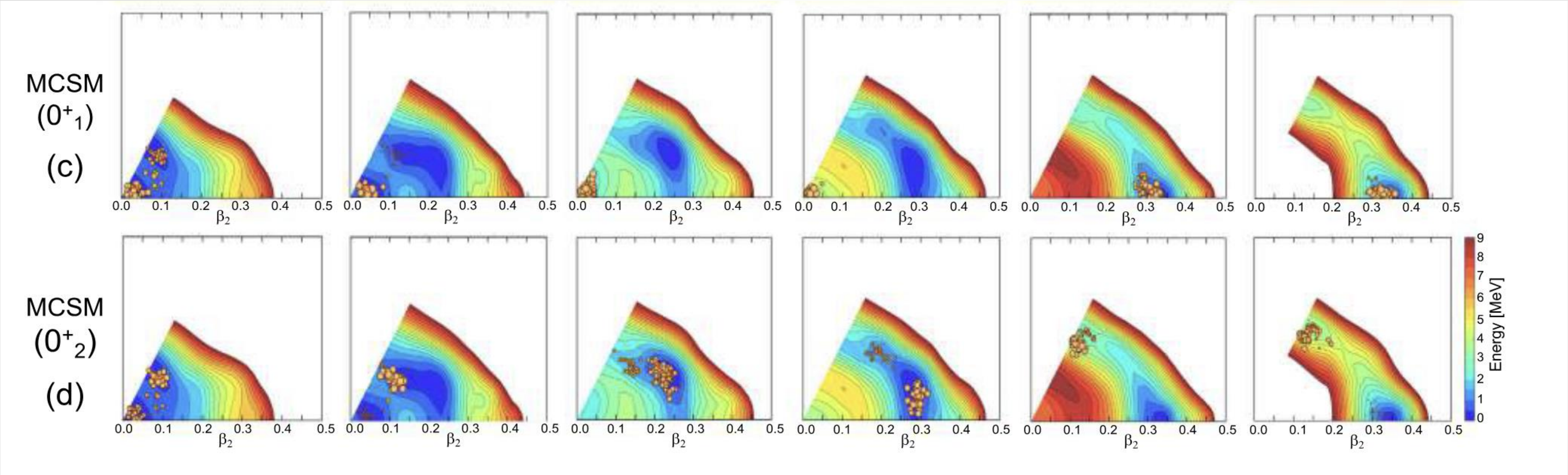

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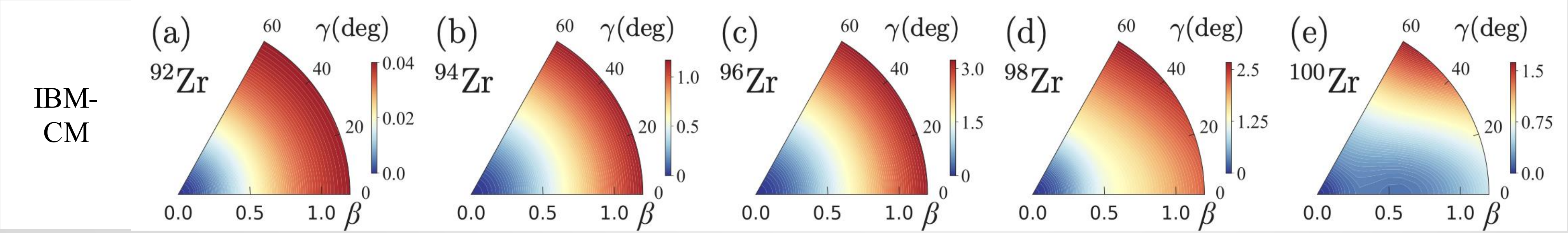
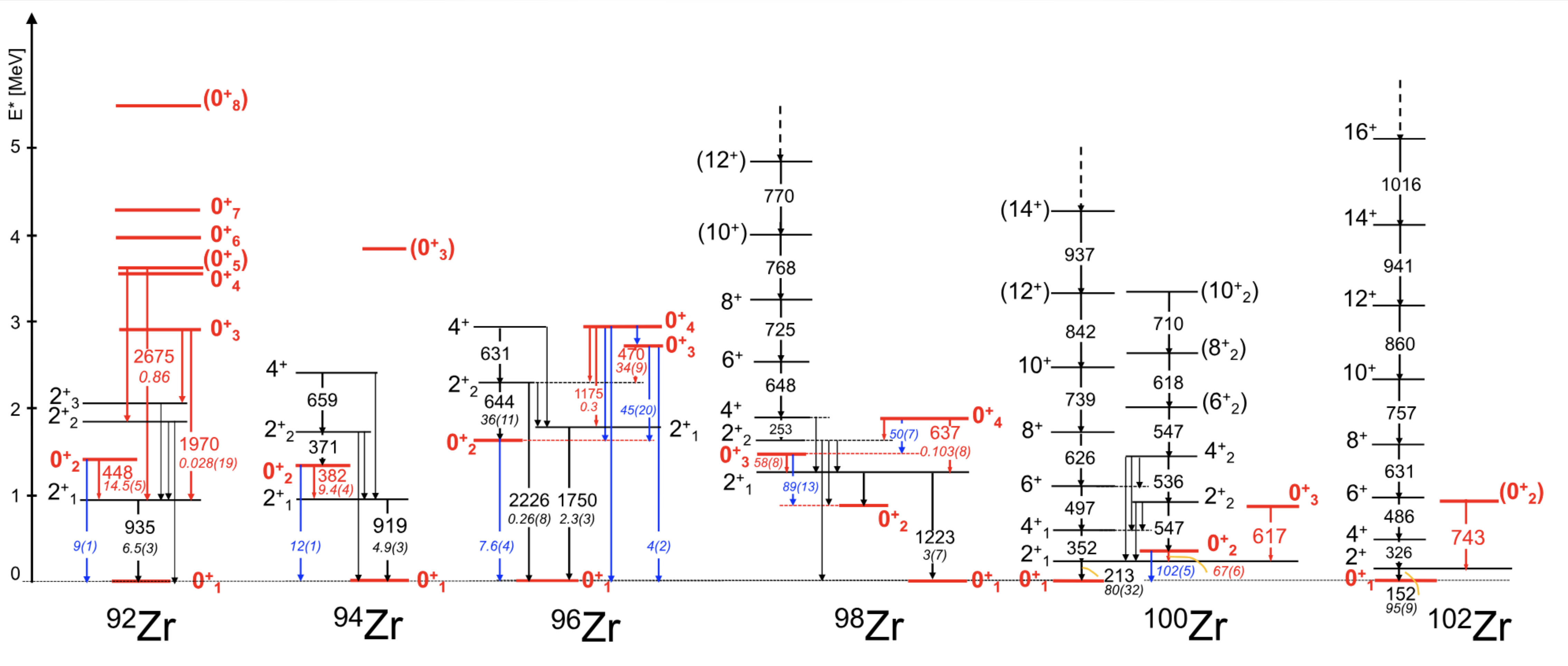


Intertwined QPT

ZIRCONIUM ISOTOPES – EXPERIMENTAL VALUES



S. Leoni et al. Progress in Particle and Nuclear Physics 139 (2024) 104119

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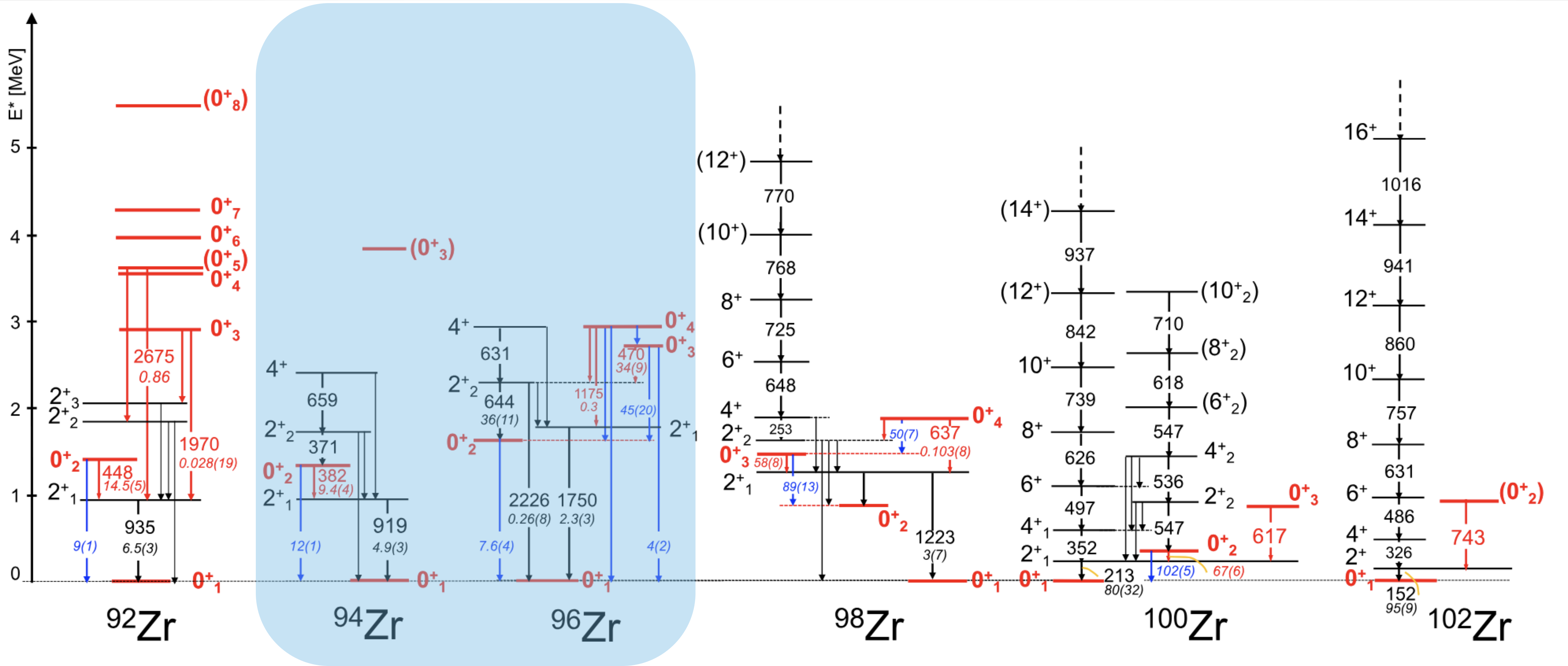

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^{94}ZR – COULEX EXPERIMENT @LNL

- Beam : ^{94}Zr 370 MeV 0.1 pnA
- Target : self-supporting ^{208}Pb 1mg/cm^2

25 HPGe Compton-suppressed detectors

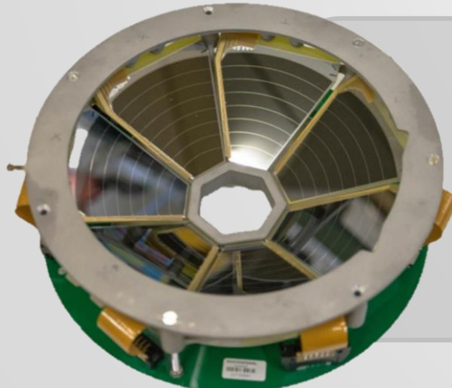
FWHM @1332 keV ~ 0.2%

Efficiency @1332 keV ~ 2%

six 3"x3" LaBr3:Ce

FWHM @1332 keV ~ 2%

Efficiency @1332 keV ~ 4%

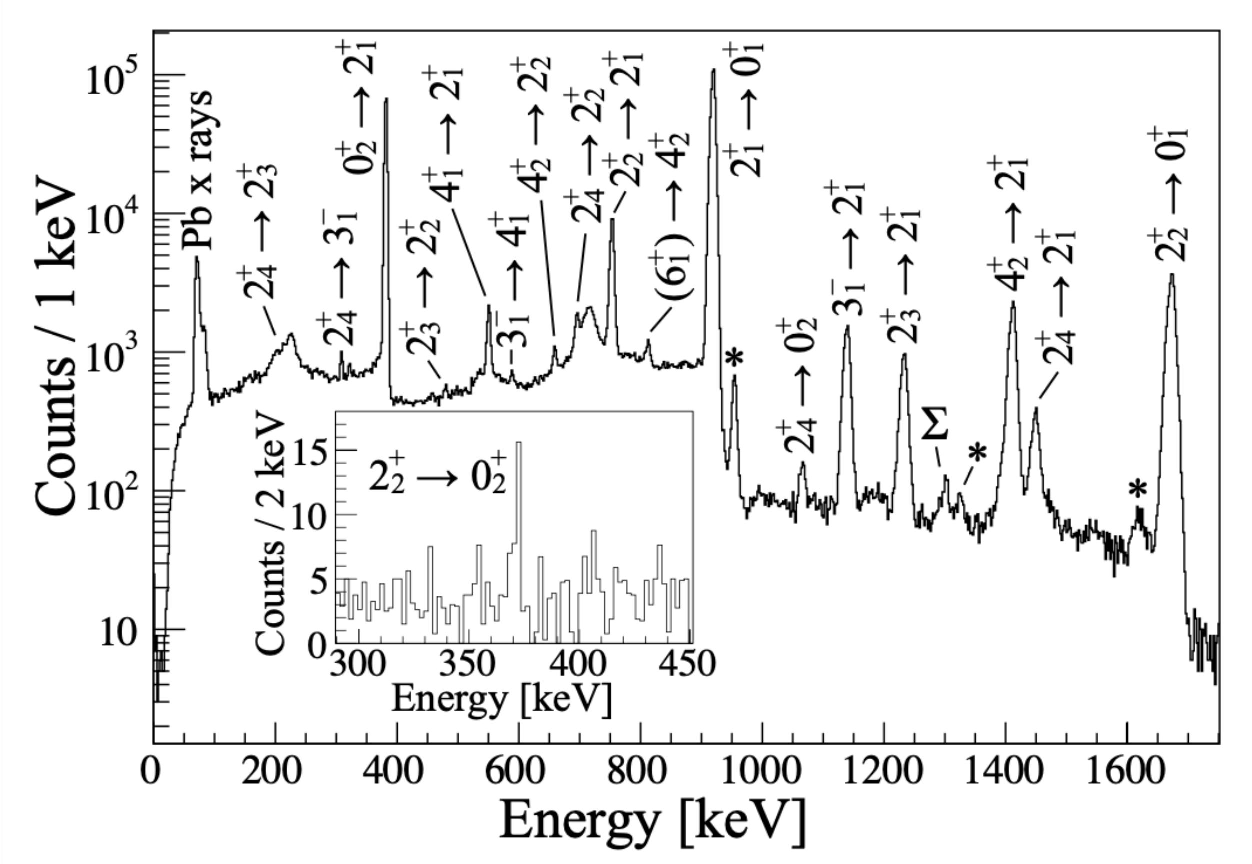


SPIDER modular array of Si detectors segmented into 8 annular strips (junction side).

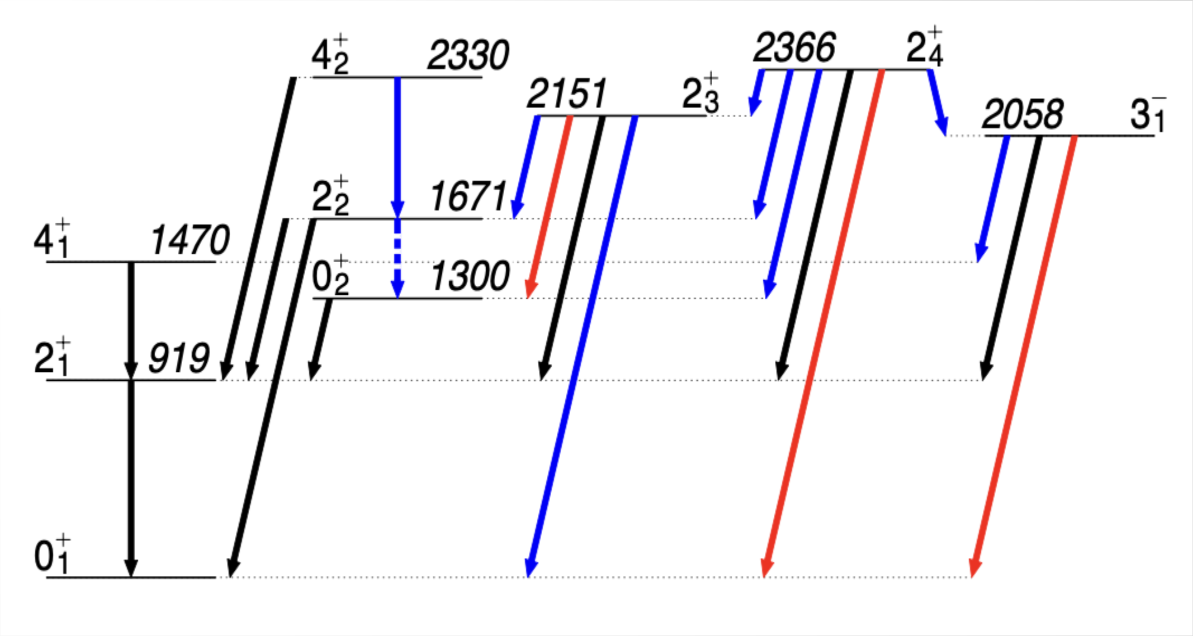
Θ_{Lab} = 126° - 162°(detection of backscattered ^{94}Zr ions)

^{94}ZR – COULEX EXPERIMENT @LNL - RESULTS

γ -particle spectrum



Level scheme



^{94}ZR – COULEX EXPERIMENT @LNL – GOSIA ANALYSIS

Using known spectroscopic data (lifetime, mixing and branching ratios):

- **16 B(E2) extracted**
  $B(E3; 3_1^- \rightarrow 0_1^+) = 33(3)$ W.u.

$J_i \rightarrow J_f$	$\langle J_f \| E2 \| J_i \rangle$ [eb]	$B(E2; J_i \rightarrow J_f)$ [W.u.]	
	Exp.	Exp.	IBM-CM
$2_1^+ \longrightarrow 0_1^+$	$+0.250(7)^{ab}$	$4.8(2)^{b}$	2.7
$0_2^+ \longrightarrow 2_1^+$	$+0.155(4)^{a}$	9.5(5)	9.3
$4_1^+ \longrightarrow 2_1^+$	$+0.141(4)^{a}$	0.87(5)	—[c]
$2_2^+ \longrightarrow 0_2^+$	$+0.484(12)^{a}$	18.5(9)	20.2
$2_2^+ \longrightarrow 2_1^+$	+0.03(3)	< 0.3	1.49
$2_2^+ \longrightarrow 0_1^+$	+0.221(6)	3.9(2)	0.82
$4_2^+ \longrightarrow 2_2^+$	$+0.96(3)^{a}$	40(3)	26.6
$4_2^+ \longrightarrow 2_1^+$	+0.607(16)	16.1(9)	2.1
$2_3^+ \longrightarrow 2_2^+$	$+0.249^{+0.019}_{-0.040}$	$4.9^{+0.7}_{-1.6}$	17.3
$2_3^+ \longrightarrow 0_2^+$	$< 0.13^{d}$	< 1.3	0.07
$2_3^+ \longrightarrow 2_1^+$	$+0.290^{+0.014\,a}_{-0.012}$	$6.6^{+0.6}_{-0.5}$	1.2
$2_3^+ \longrightarrow 0_1^+$	$-0.0182^{+0.0016}_{-0.0020}$	$0.026^{+0.005}_{-0.006}$	0.001
$2_4^+ \longrightarrow 2_3^+$	$-0.02^{+0.06}_{-0.03}$	< 0.2	2.44
$2_4^+ \longrightarrow 2_2^+$	$\pm 0.073^{+0.030}_{-0.018}$	$0.4^{+0.3}_{-0.2}$	0.1
$2_4^+ \longrightarrow 0_2^+$	$\pm 0.177^{+0.010}_{-0.005}$	$2.47^{+0.30}_{-0.14}$	0.06
$2_4^+ \longrightarrow 2_1^+$	$+0.092^{+0.006\,a}_{-0.004}$	$0.67^{+0.09}_{-0.06}$	0.001
$2_4^+ \longrightarrow 0_1^+$	$-0.001^{+0.003}_{-0.006}$	$< 4 \cdot 10^{-3}$	$3 \cdot 10^{-4}$

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- **$Q_s(2_1)$, $Q_s(2_2)$**

J_i	$\langle J_i \| E2 \| J_i \rangle$ [eb]	$Q_s(J_i)$ [eb]	
	Exp.	Exp.	IBM-CM
2_1^+	$+0.131^{+0.013}_{-0.030}$	$+0.099^{+0.010}_{-0.025}$	$+0.066$
2_2^+	$+0.37(4)$	$+0.28(3)$	$+0.31$

^{94}ZR – COULEX EXPERIMENT @LNL – GOSIA ANALYSIS

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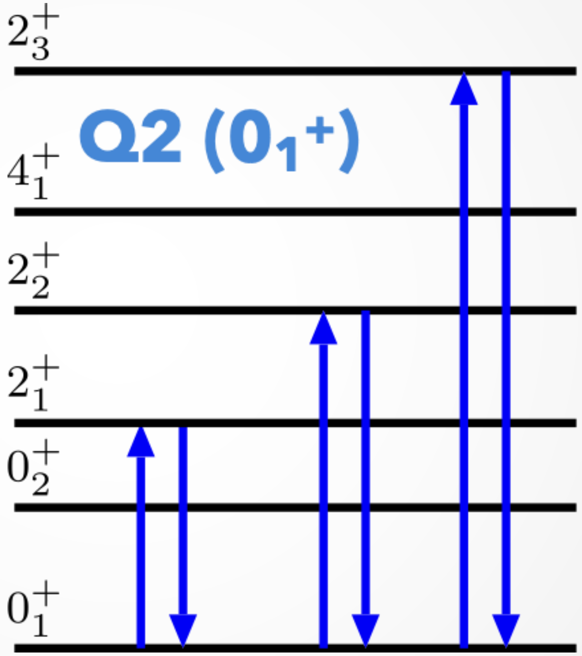
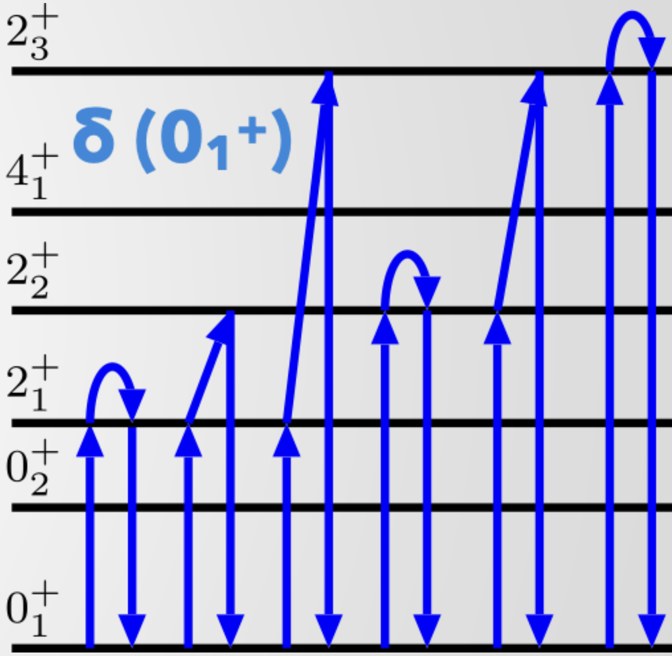
  $B(E3; 3_1^- \rightarrow 0_1^+) = 33(3)$ W.u.
- **$Q_s(2_1)$, $Q_s(2_2)$**
- **Deformation parameters ($\langle Q^2 \rangle$, $\langle \delta \rangle$) for the 0_1 and 0_2 states using quadrupole sum rules**
  Extracted also the $\langle Q^4 \rangle$ value related to the softness in deformation
  $\sigma(Q^2) = (\langle Q^4 \rangle - (\langle Q^2 \rangle)^2)^{1/2}$





J_i	$\langle Q^2 \rangle$ [e^2b^2]		$\sigma(Q^2)$ [e^2b^2]		$\langle \cos(3\delta) \rangle$	
	Exp.	Th.	Exp.	Th.	Exp.	Th.
0_1^+	0.112(4)	0.046	0.143(4)	0.094	−0.37(7)	−0.72
0_2^+	0.305(12)	0.308	0.14(3)	0.153	−0.8(2)	−0.4

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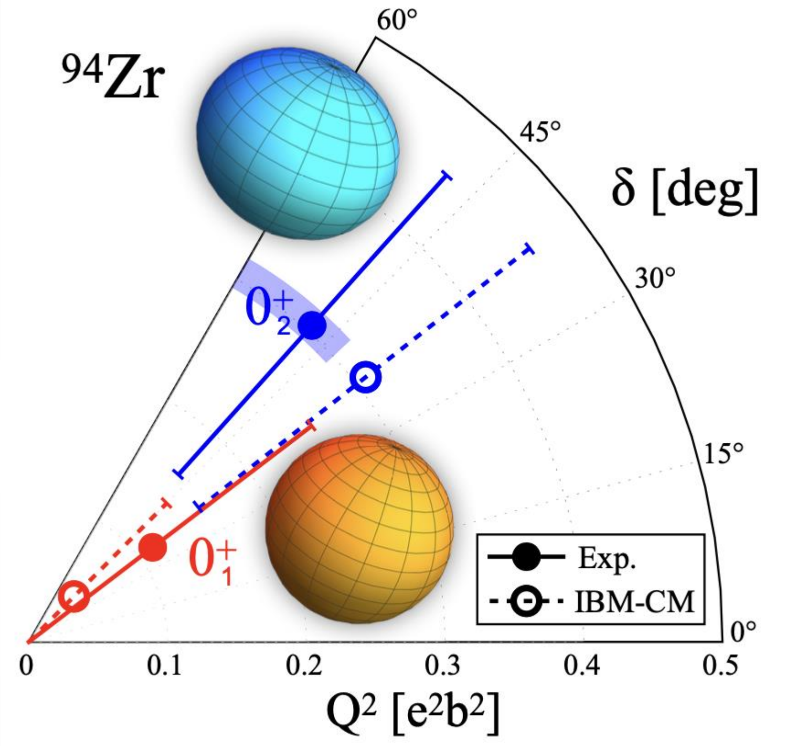

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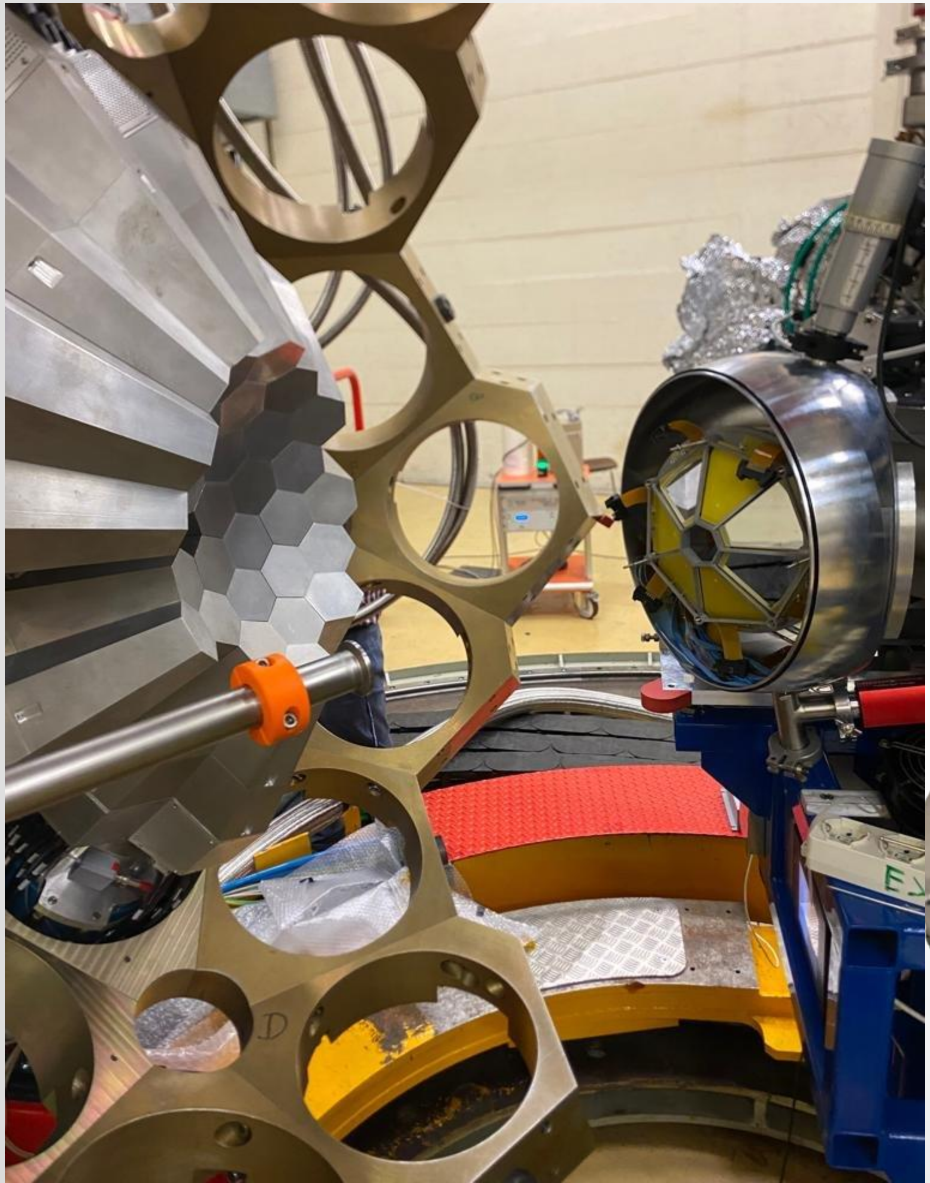
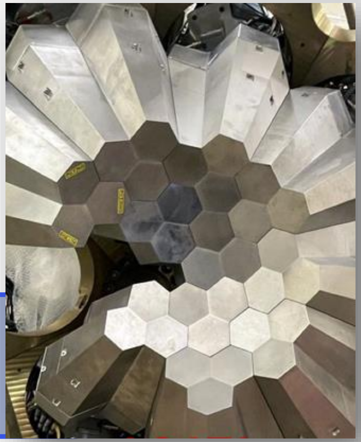
^{96}ZR – COULEX EXPERIMENT @LNL – ANALYSIS ONGOING

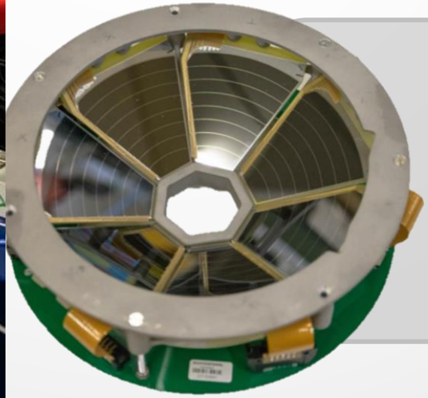


Beam : ^{58}Ni 160 MeV 3 pnA

Target : self-supporting ^{96}Zr 1mg/cm^2

AGATA array (11 ATCs), close-up position.





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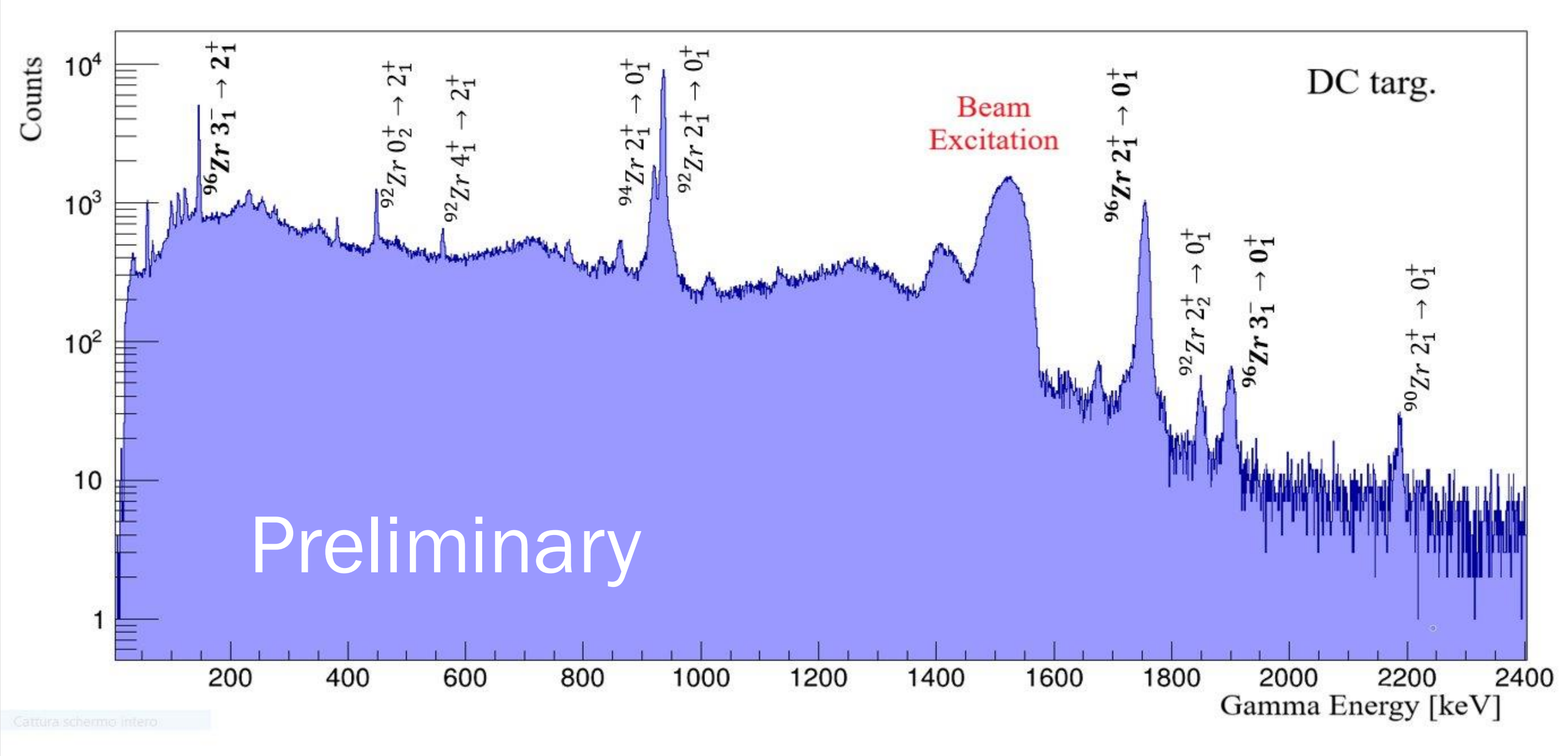
γ -particle spectrum



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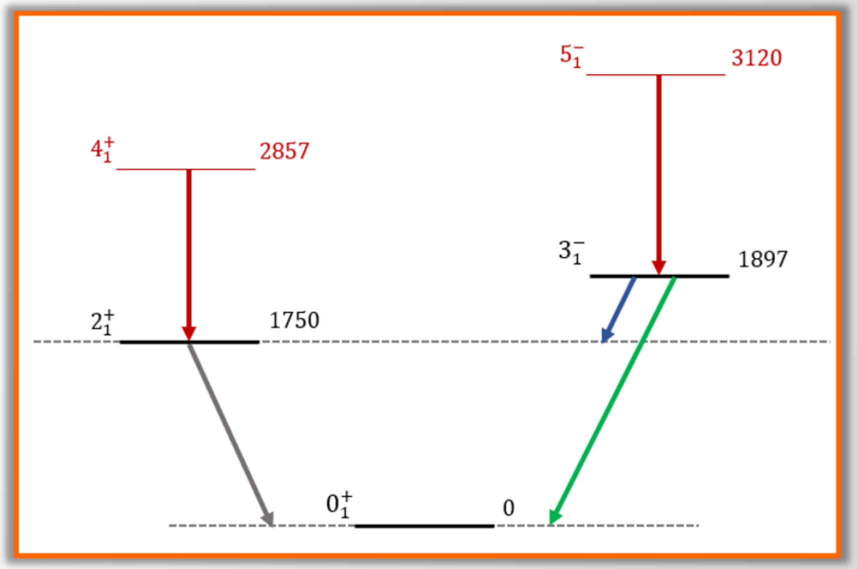
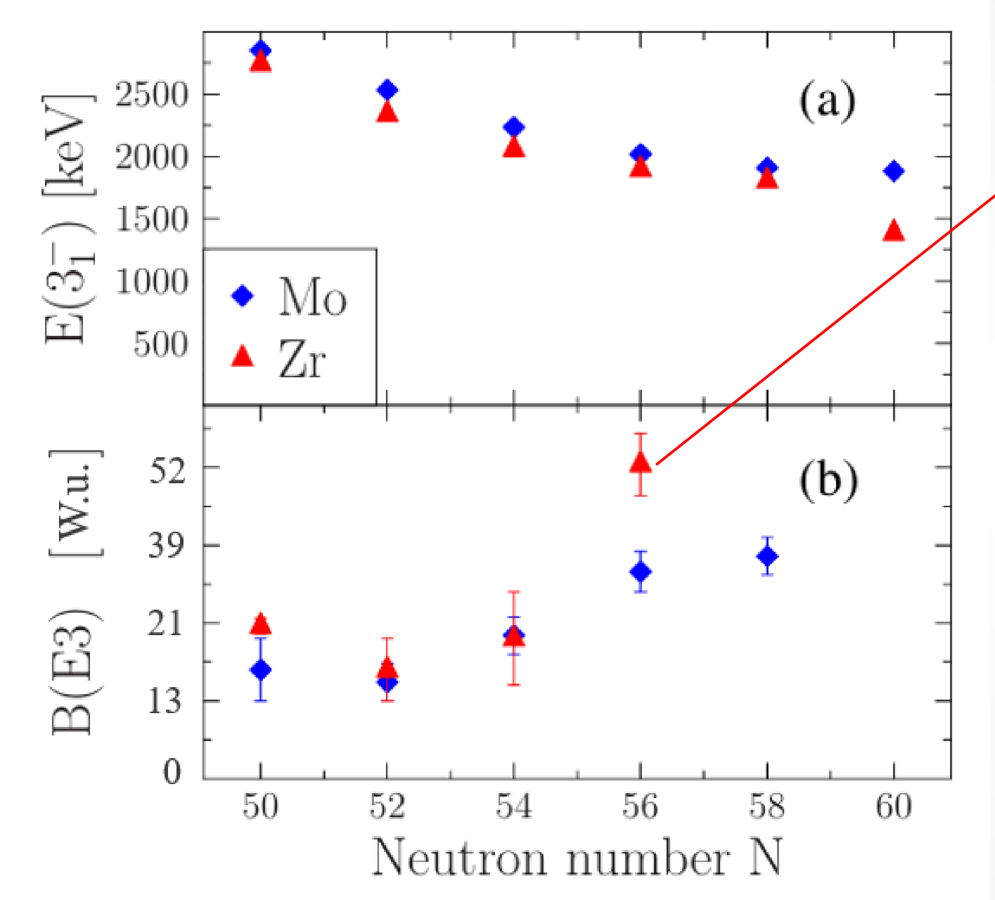


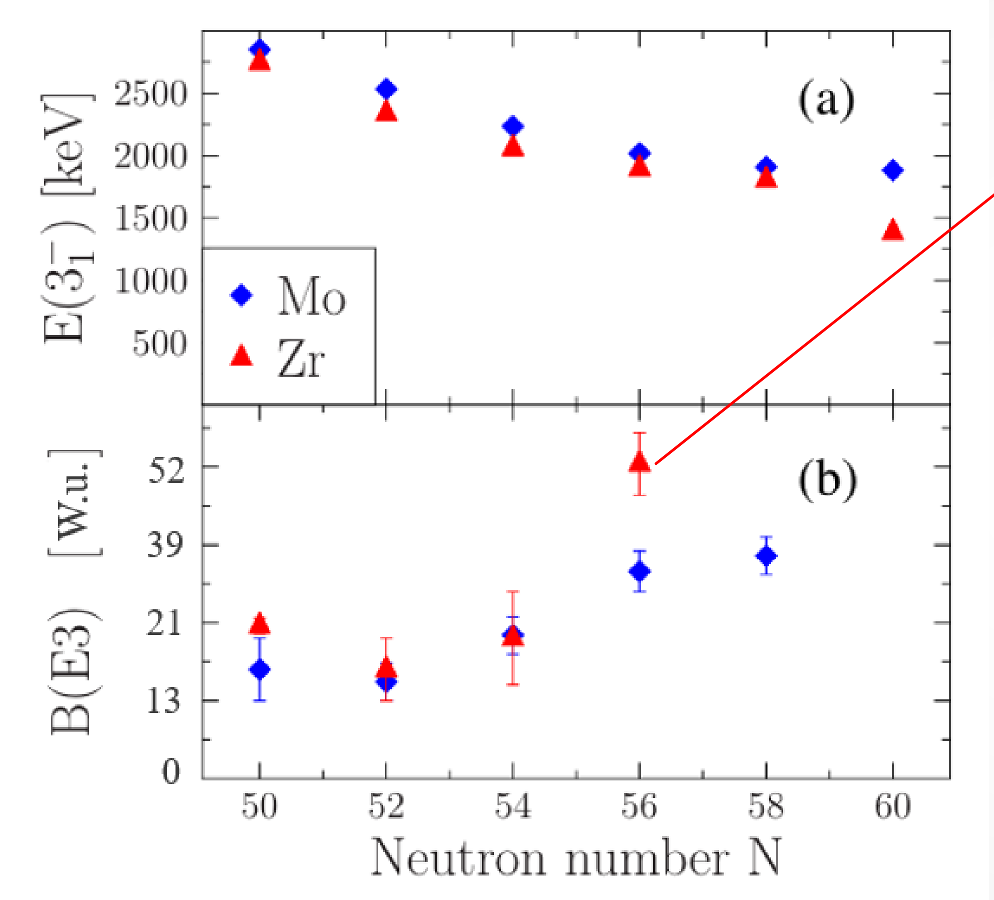
^{96}ZR – COULEX EXPERIMENT @LNL – B(E3)



B(E3, $3_1^- \rightarrow 0_1^+$) value in ^{96}Zr strikingly high (evaluated value: 53(6) W.u.), long-standing challenge for theory

The revised value B(E3) = 42(3) W.u. resulting from a new measurement of E1/E3 branching ratio in ^{96}Zr (Ł. Iskra *et al*, Phys. Lett. B 788 (2019)) is in better agreement with the experimental trend

^{96}ZR – COULEX EXPERIMENT @LNL – B(E3) PRELIMINARY RESULTS



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Our Preliminary results are:

$$B(E1, 3_1^- \rightarrow 2_1^+) = 114(13) \cdot 10^{-4}\ W.u.$$

$$B(E3, 3_1^- \rightarrow 0_1^+) = 41(3)\ W.u.$$

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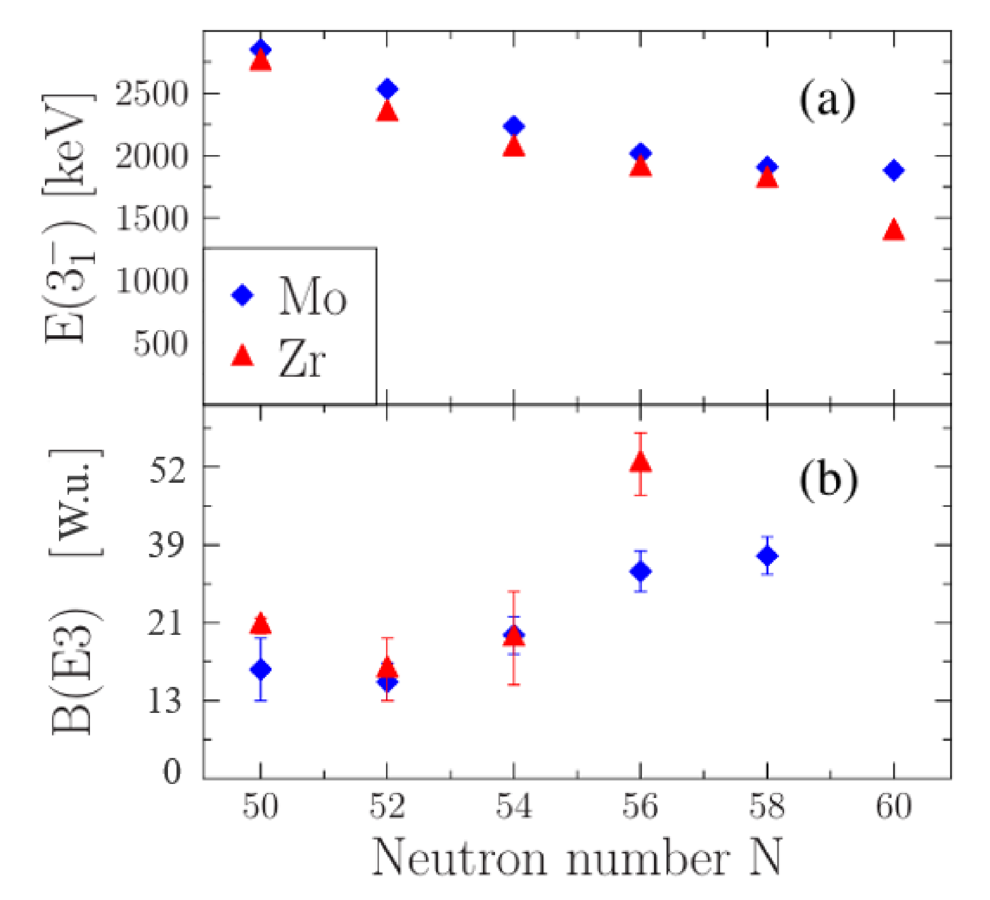

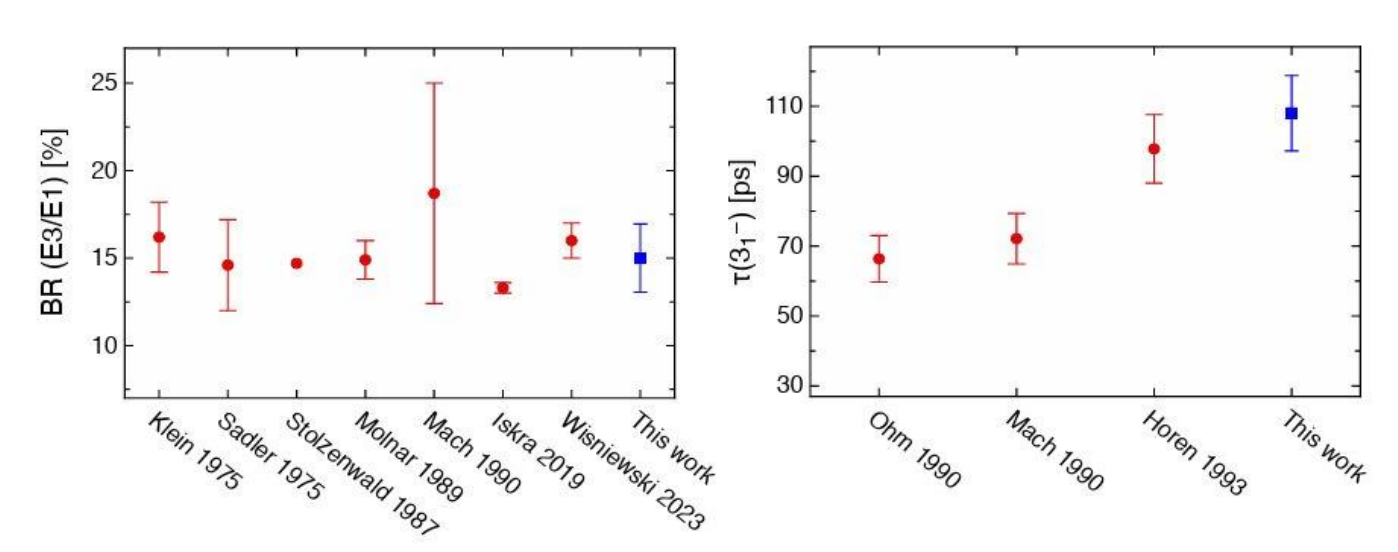

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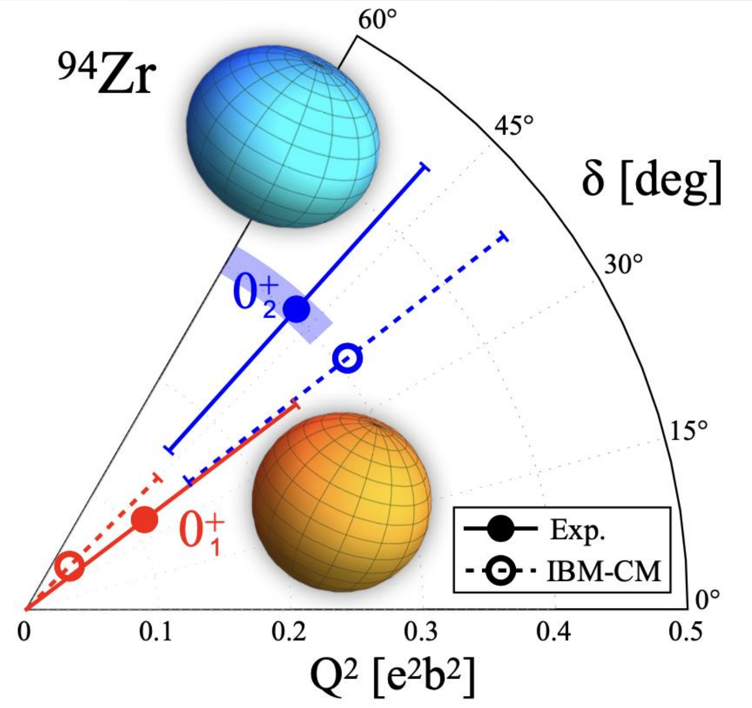
^{96}ZR – COMPLEMENTARY EXPERIMENTS @LNL

- Two-phonon octupole excitation in ^{96}Zr :
  - Measured E3/E1 branching ratio in the 3^- decay.
  - Observation of $6^+ \rightarrow 3^-$ transition
  - SETUP: AGATA + SAURON + PLUNGER

- Combined lifetime and transition-probability measurements in ^{96}Zr via unsafe Coulomb excitation :
  - Investigating the properties of 2^+ and 4^+ band members to provide detailed spectroscopic data on presumed coexisting structures
  - Verify the lifetime of the 6^+, 3^- states and understanding the puzzling trend in octupole collectivity in Zr isotopes and testing the two-phonon vibration hypothesis
  - SETUP: AGATA + PRISMA + PLUNGER

CONCLUSION

- ^{94}Zr : Spectroscopic quadrupole moments extracted for the first and the second 2^+ states
  Quadrupole invariants extracted for the ground state and the 0_2 state



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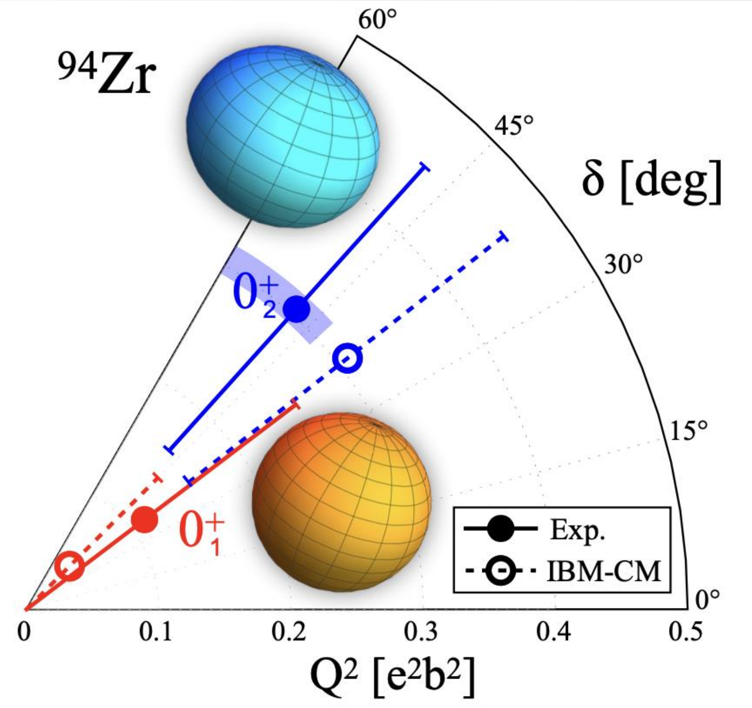
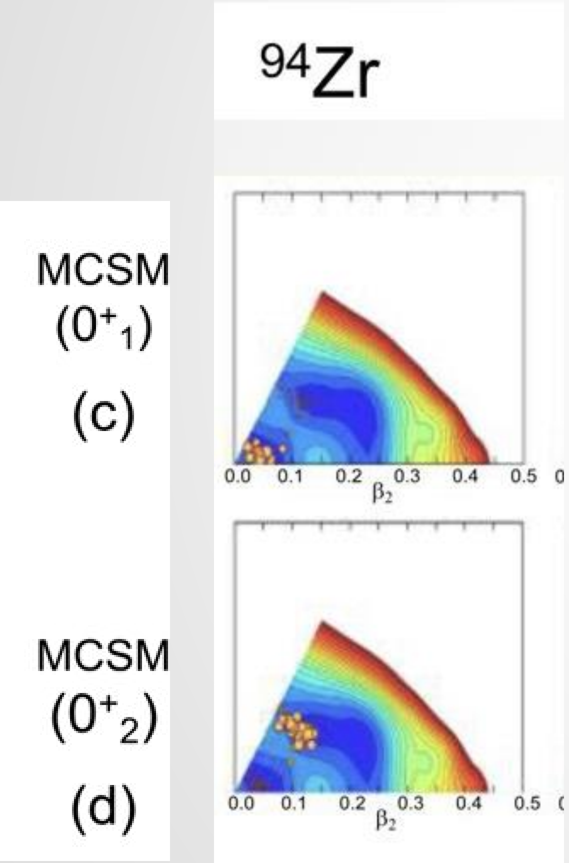


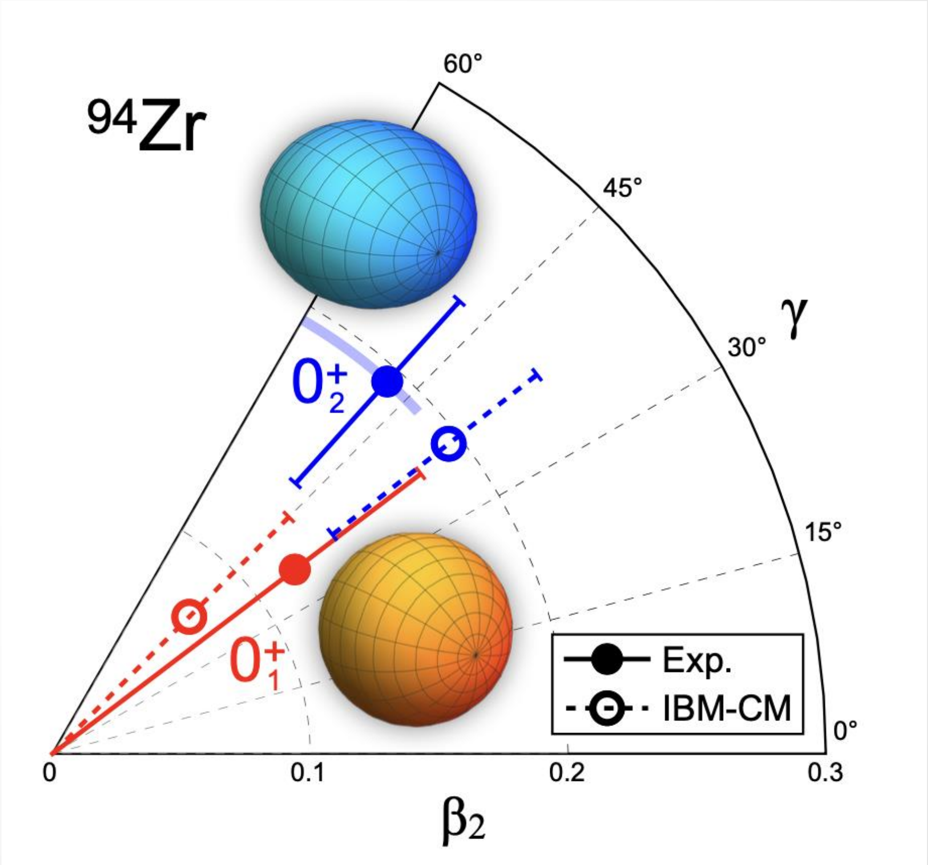
- ^{96}Zr : Octupole collectivity under analysis

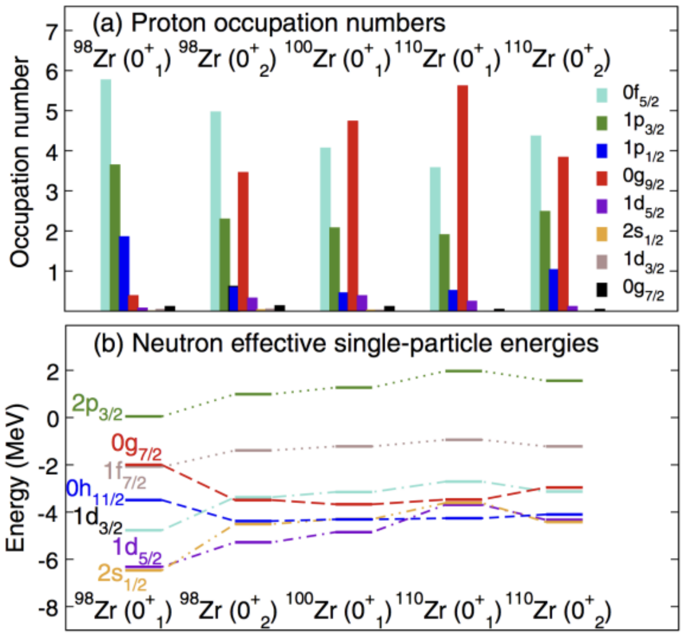
$$B(E3, 3_1^- \rightarrow 0_1^+) = 41(3)\, W.u.$$

Thank you!

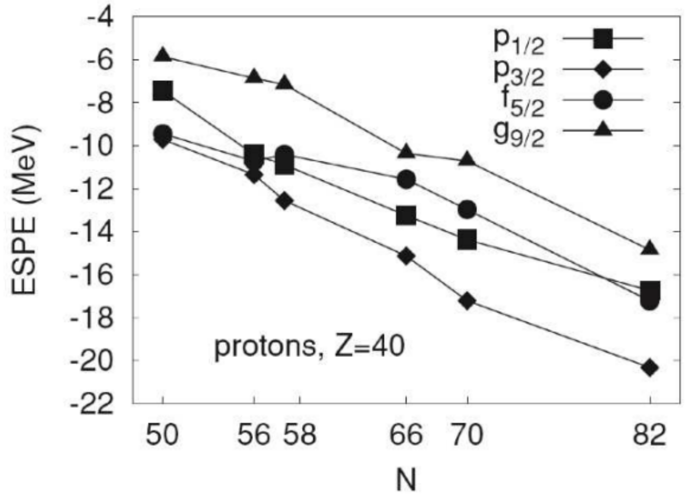
$\langle\beta_2\rangle = (\frac{3}{4\pi}ZR^2)^{-1} \cdot \sqrt{\langle Q^2\rangle}$, where $R = 1.2A^{1/3}$ [fm], and $\langle\gamma\rangle = \langle\delta\rangle$ [38]. For ^{94}Zr, $\langle\beta_2\rangle \approx 0.35\sqrt{\langle Q^2\rangle}$.



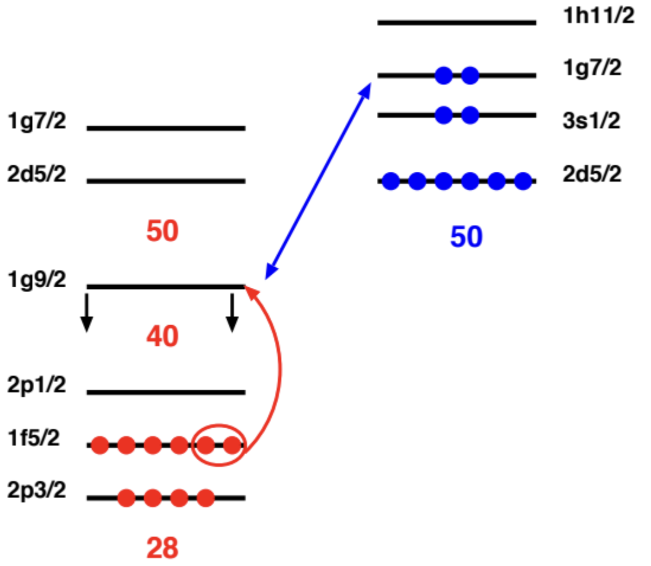




T. Togashi et al, PRL 117, 172502 (2016)



K. Sieja et al, PRC 79, 064310 (2009)



- p-n tensor interaction reduces the Z=40 gap when ν g7/2 is being filled
- 0_2^+ states created by 2p-2h (+ 4p-4h...) excitation across Z=40
- very different configurations and small mixing of 0_1^+ and 0_2^+