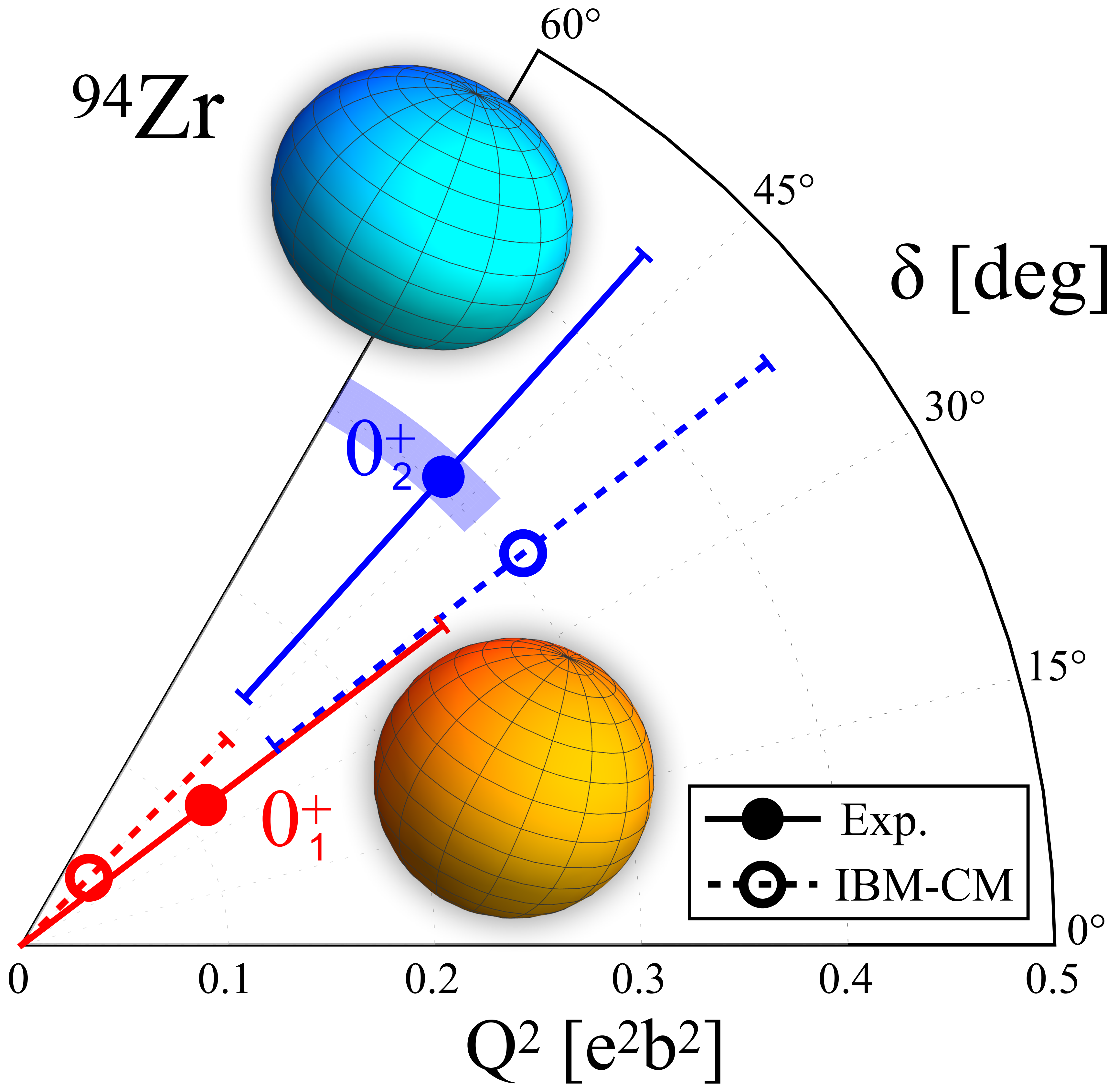
Marco Rocchini
INFN - Istituto Nazionale di Fisica Nucleare
FIRENZE DIVISION

Spherical-Oblate Shape Coexistence in ^{94}Zr and the SPIDER Coulomb-Excitation Campaign at LNL



Low-Energy Coulomb Excitation (aka Coulex)

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

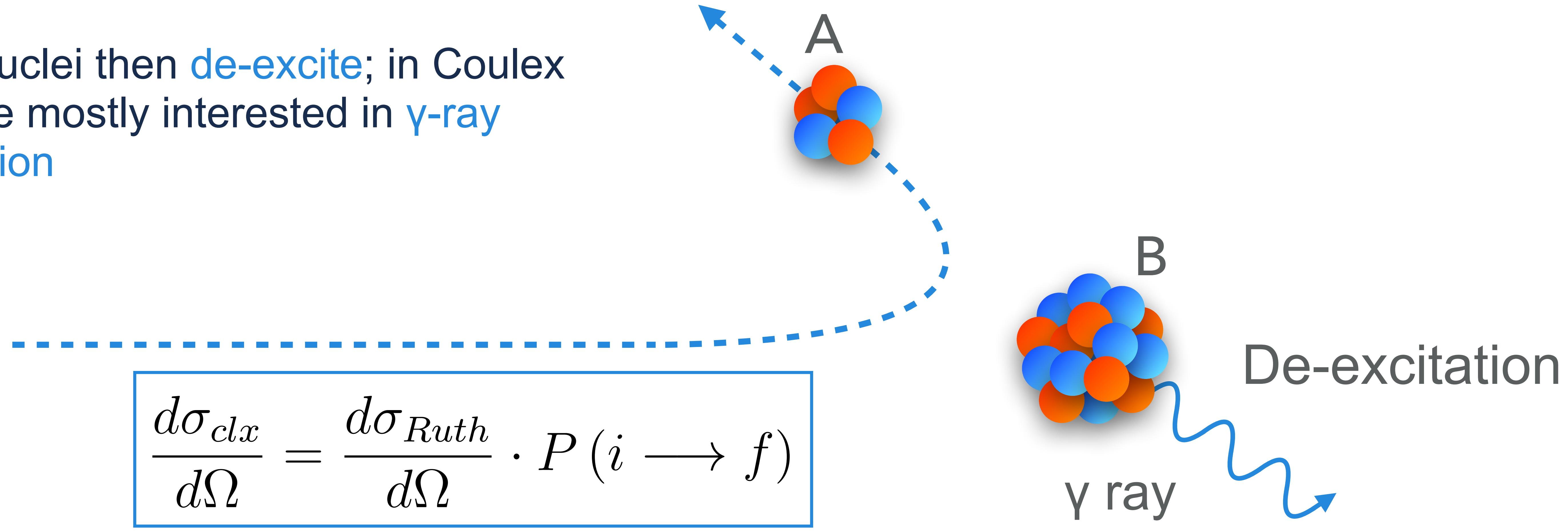
Excited 0+ States in Even-Even Mid-Mass Nuclei

The Zr Isotopic Chain and QPTs

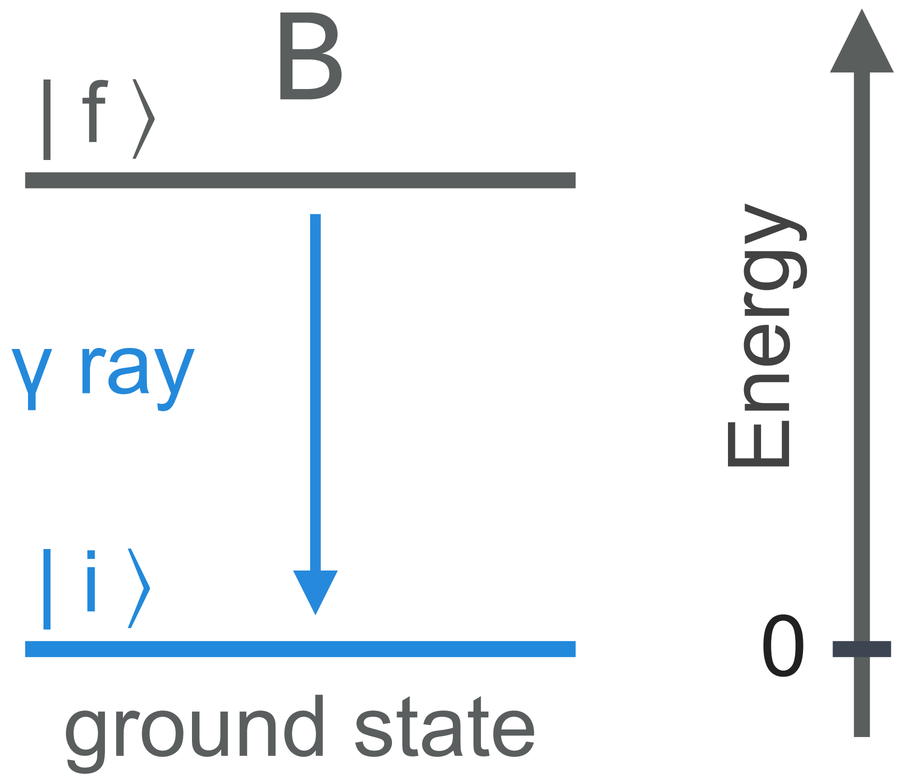
Coulex Experiment on ^{94}Zr

Model-Independent Determination of Shapes in ^{94}Zr

- Inelastic scattering between two interacting nuclei, in the “purely” electromagnetic regime
- The time-dependent electromagnetic field between the two nuclei can induce excitations
- The nuclei then de-excite; in Coulex we are mostly interested in γ-ray emission



$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$



- Example: first 2+ state in an even-even target nucleus

~|⟨2+||E2||0+⟩|²   ~⟨2+||E2||2+⟩

$$P\left(0_1^+ \longrightarrow 2_1^+\right) = F\left(\theta, E_P\right) B(E2) \left[1 + 1.32 \frac{A_P}{Z_T} \frac{\Delta E}{\left(1 + \frac{A_P}{A_T}\right)} Q_s\left(2^+\right) K\left(\theta, E_P\right)\right]$$

Access to: transition probabilities, spectroscopic quadrupole moments

Quadrupole Sum Rules & Rotational Invariants

Low-Energy Coulomb Excitation

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Coulex Experiment on ^{94}Zr

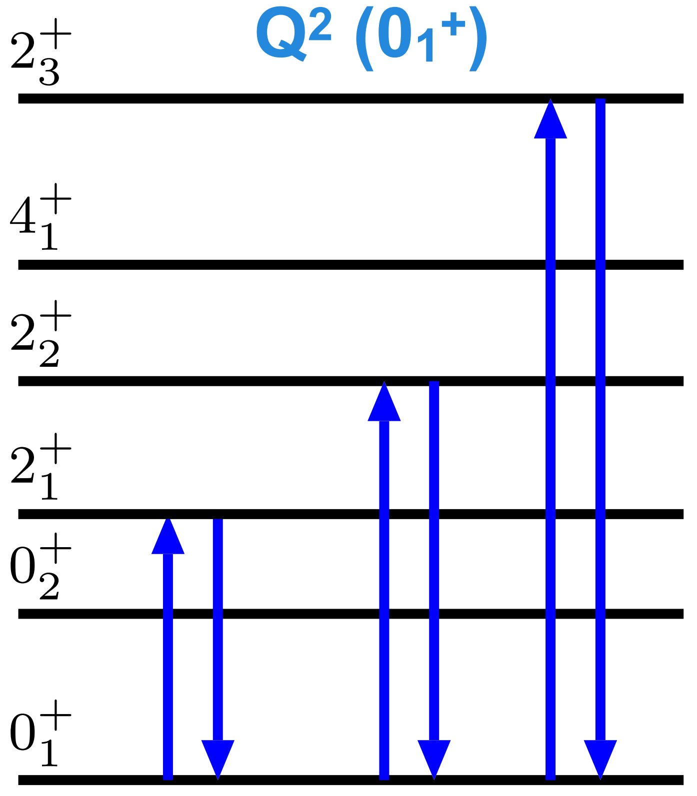
Model-Independent Determination of Shapes in ^{94}Zr

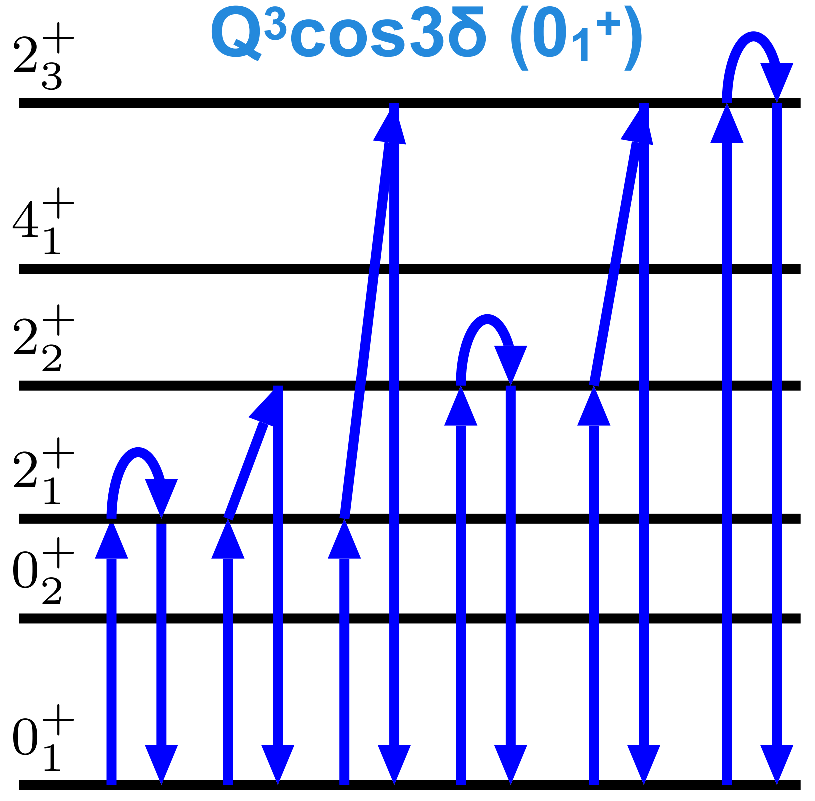
- Unique feature of Coulex ⟹ Possible to get relative signs of transitional matrix elements, together with spectroscopic quadrupole moments of short-living excited states with their sign
- Quadrupole Sum Rules ⟹ (β, γ) deformation parameters for g.s. and excited states in a model-independent way

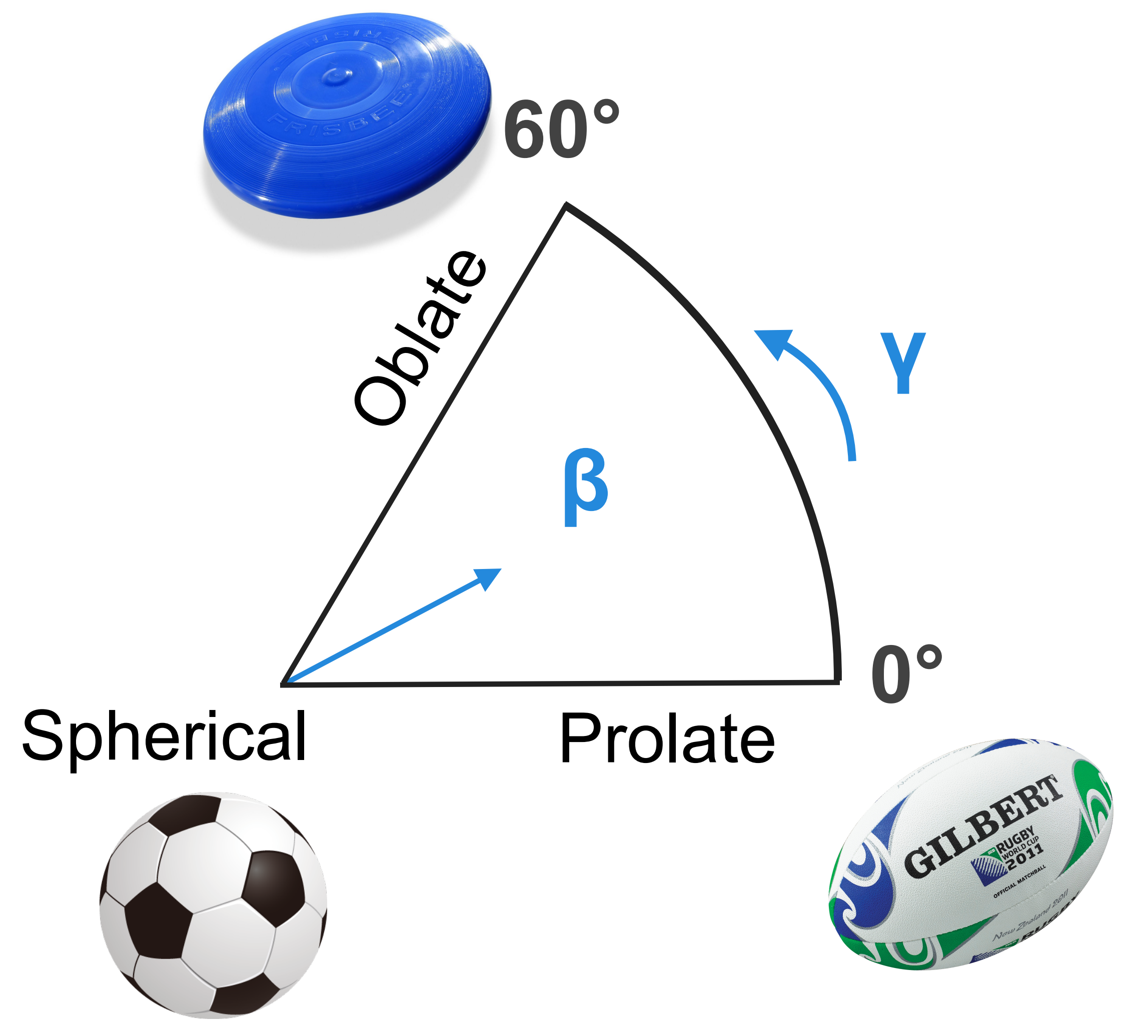
$$\langle i\,|Q^2|\,i\rangle = \frac{\sqrt{5}}{\sqrt{2I_i+1}}\sum_t \langle i\,||E2||\,t\rangle\,\langle t\,||E2||\,i\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$

$$\langle i\,|Q^3\cos(3\delta)|\,i\rangle = -\frac{\sqrt{35}}{\sqrt{2}}\frac{1}{2I_i+1}\sum_{tu} \langle i\,||E2||\,t\rangle\,\langle t\,||E2||\,u\rangle\,\langle u\,||E2||\,i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$

(Q^2, δ) equivalent to (β, γ)







K. Kumar, Phys. Rev. Lett. 28 (1972) 249 & D. Cline, Annu. Rev. Nucl. Part. Sci. 36 (1986) 683

Low-Energy Coulomb Excitation

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Quad... ...nvariants

Hot topic not only in low-energy nuclear physics ⇒ New studies at high-energy physics facilities, highly complementary to Coulex

- Unique featu... of ... c quadrupole moments of ...
- Quadrupole ... or ... nt way

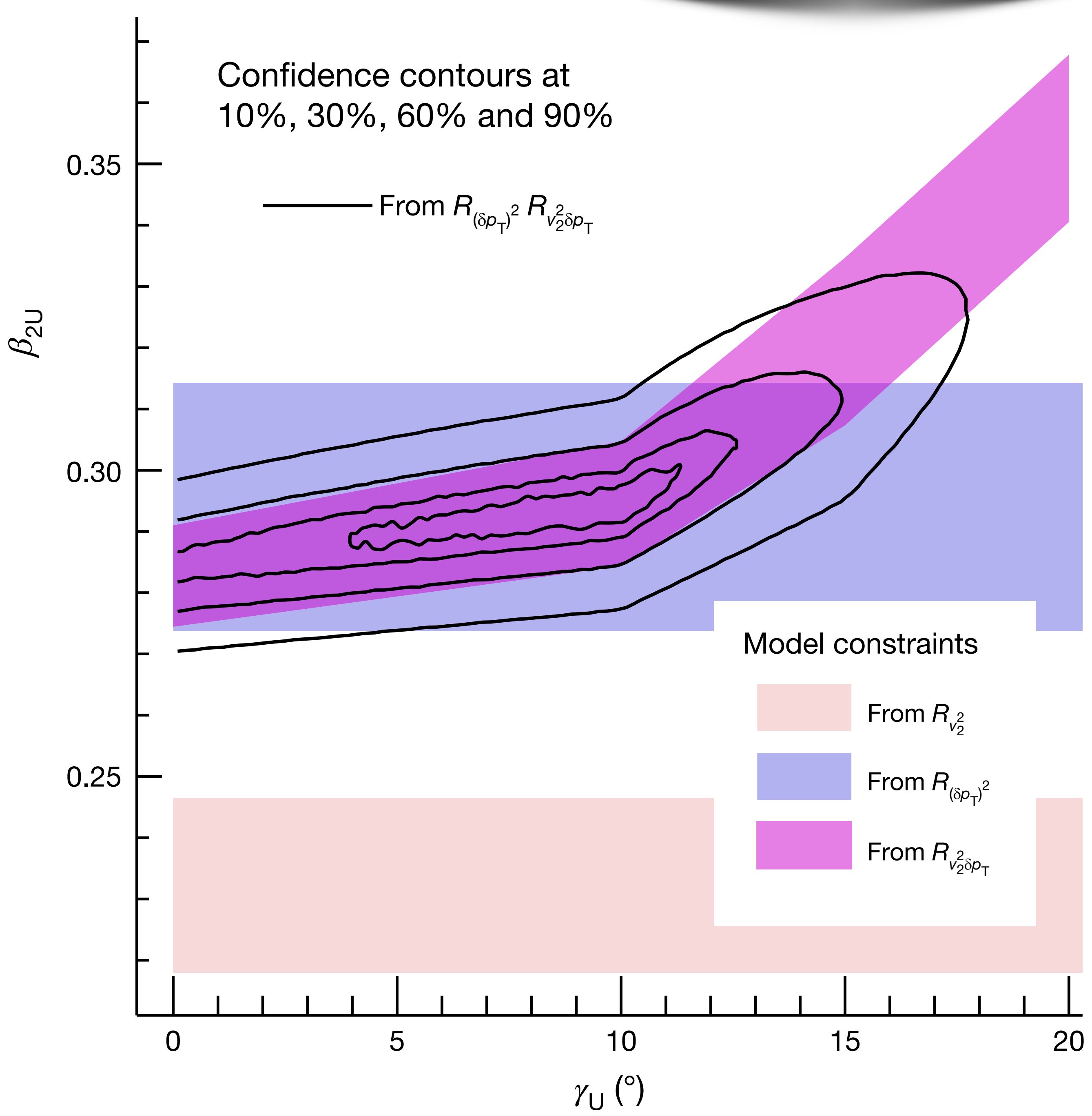
nature

Article | Open access | Published: 06 November 2024

Imaging shapes of atomic nuclei in high-energy nuclear collisions

STAR Collaboration

RHIC - STAR

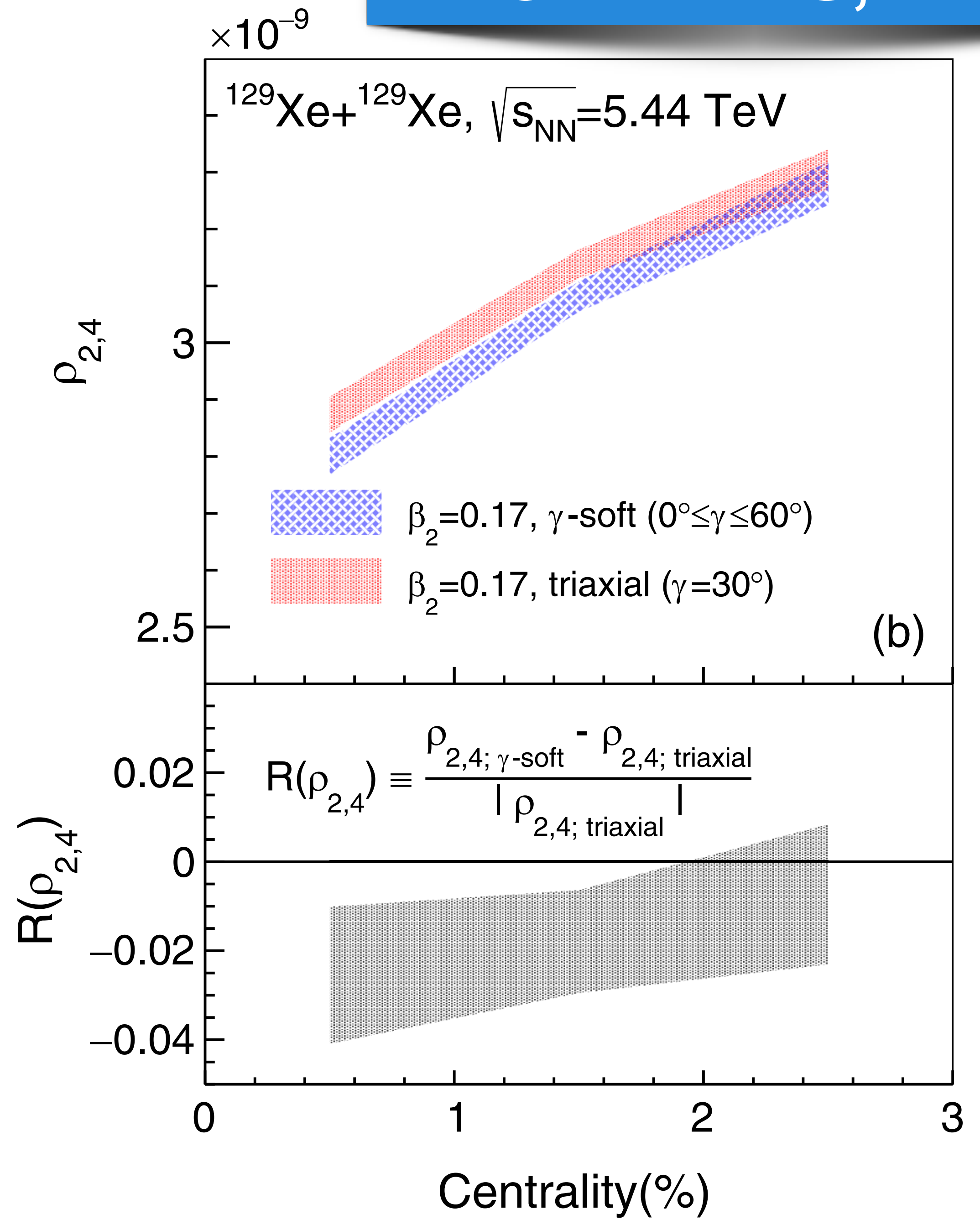


PHYSICAL REVIEW LETTERS 133, 192301 (2024)

Exploring the Nuclear-Shape Phase Transition in Ultrarelativistic ^{129}Xe + ^{129}Xe Collisions at the LHC

Shujun Zhao,[1,2,*] Hao-jie Xu,[2,3,†] You Zhou,[4,‡] Yu-Xin Liu,[1,5,6,§] and Huichao Song[1,5,6,∥]
[1]School of Physics, Peking University, Beijing 100871, China
[2]School of Science, Huzhou University, Huzhou, Zhejiang 313000, China
[3]Strong-Coupling Physics International Research Laboratory (SPiRL), Huzhou University, Huzhou, Zhejiang 313000, China
[4]Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark
[5]Collaborative Innovation Center of Quantum Matter, Beijing 100871, China
[6]Center for High Energy Physics, Peking University, Beijing 100871, China

LHC - ATLAS, ALICE



K. Kumar, Phys. Rev. Lett. 28 (1972) 249 & D. Cline, Annu. Rev. Nucl. Part. Sci. 36 (1986) 683

Experimental Requirements

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

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The Zr Isotopic Chain and QPTs

Coulex Experiment on ^{94}Zr

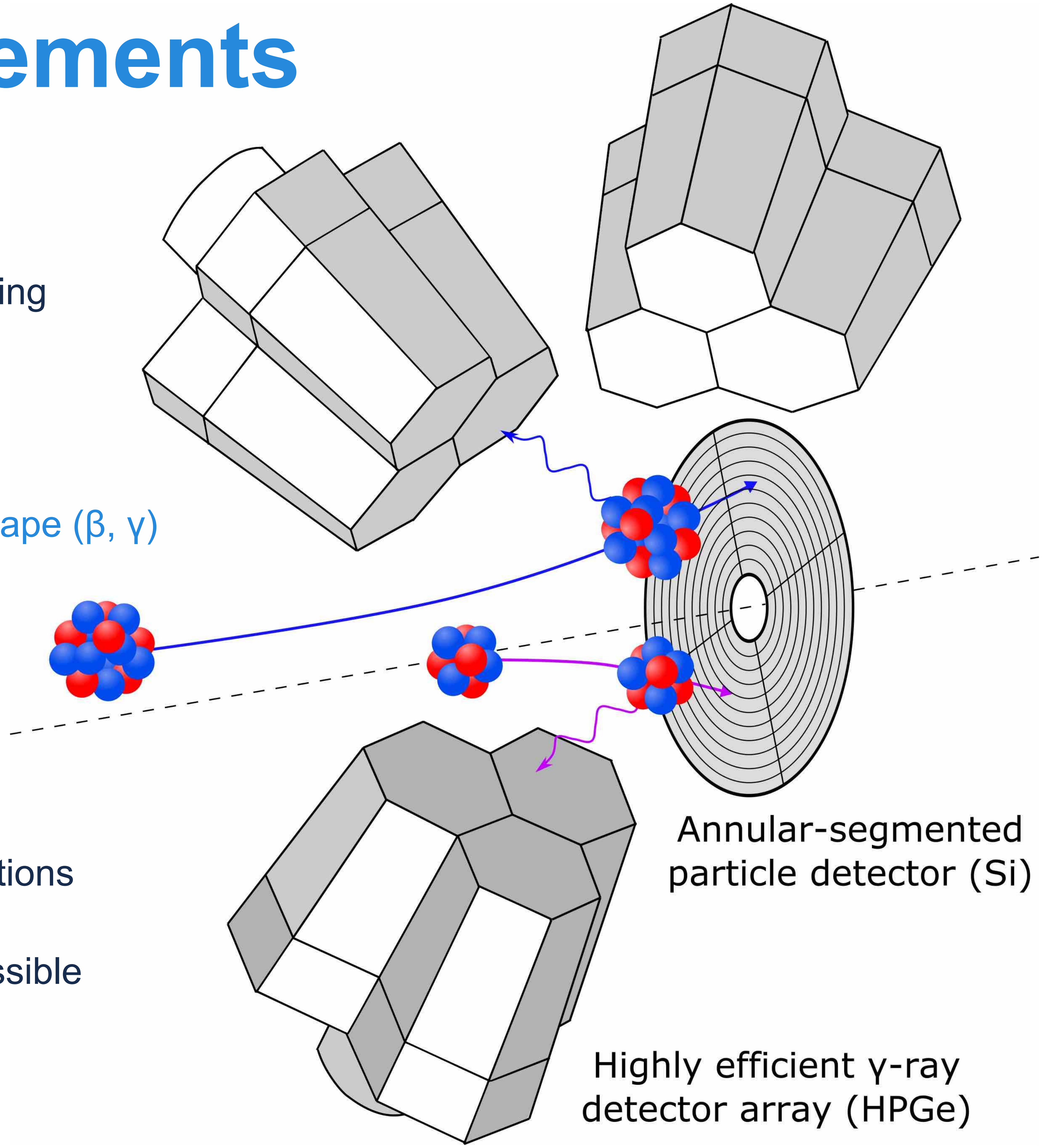
Model-Independent Determination of Shapes in ^{94}Zr

What can we get?

- Reduced transition probabilities for transitions between low-lying states, mainly *E2* and *E3* multipolarities
- Spectroscopic quadrupole moments for excited states
- Rotational invariants (Q, δ) ⟹ Direct access to the nuclear shape (β, γ)

What do we need?

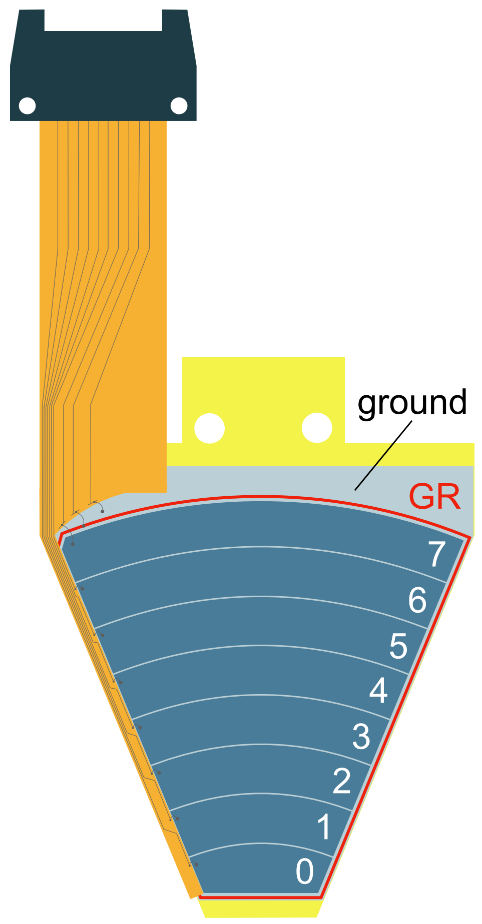
- Beam energies around 3-6 MeV/A
- Good technique for weak-intensity beams ⟹ Large cross sections
- Gamma-ray array and heavy ion detector with as good as possible efficiency, energy or time resolutions, and segmentations

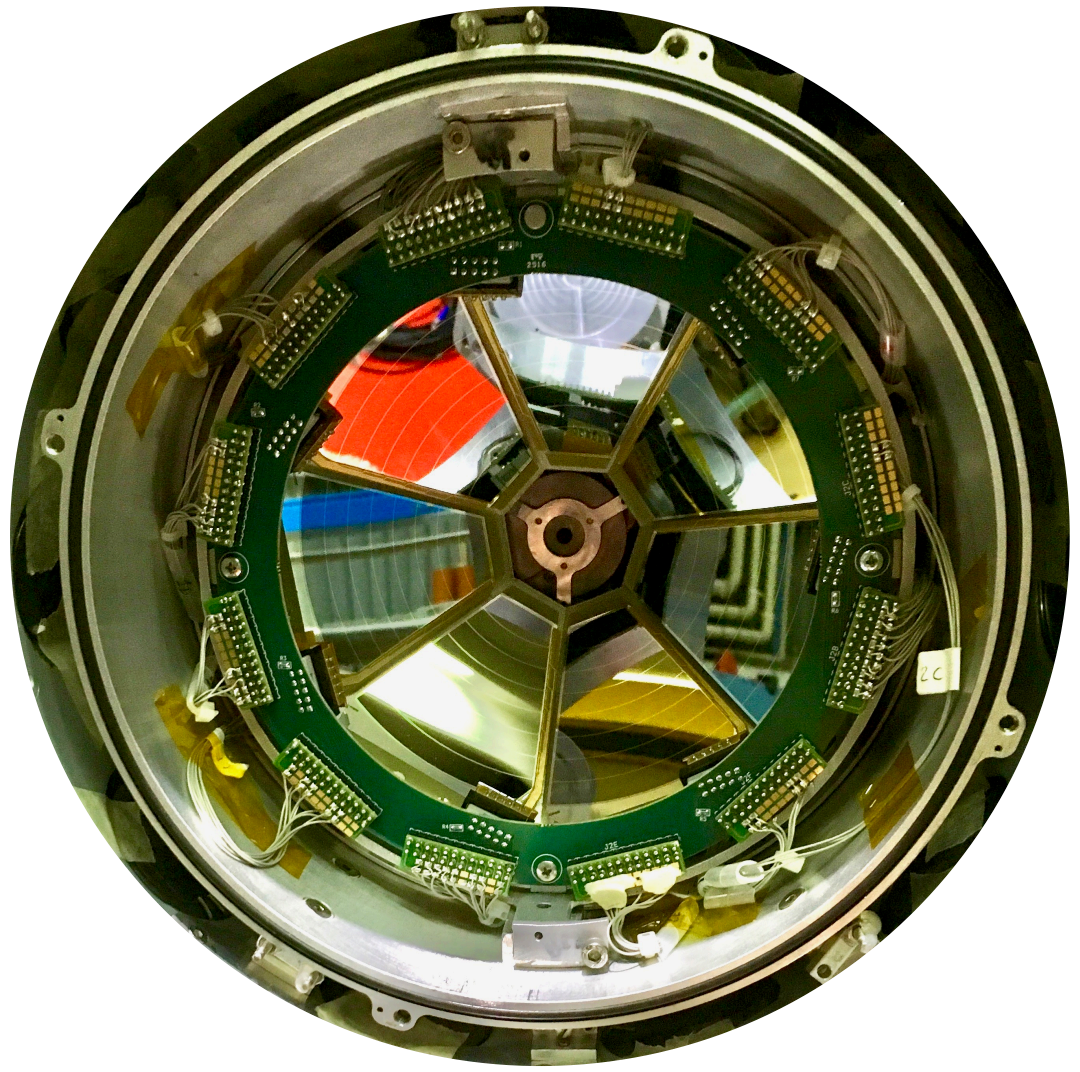


GALILEO with SPIDER (2016 - 2019)

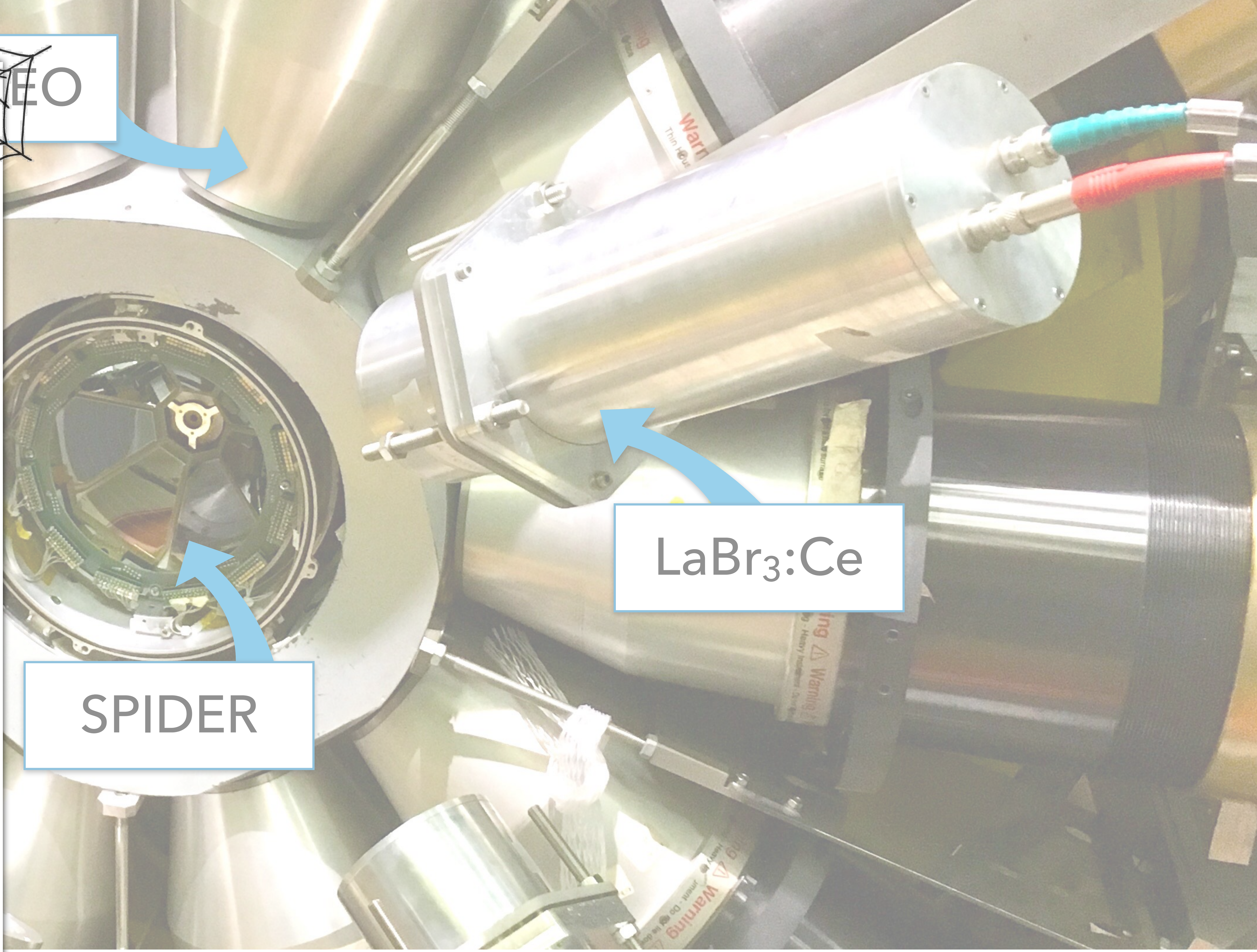
SPIDER: the Silicon PIe DEtectoR

- Modular segmented silicon detector, designed for low-energy Coulomb-excitation measurements
- Independent sectors, 8 strips + guard ring
- Detector thickness ~ 300 µm, dead layers ~ 50 nm in the junction (front) side and ~ 350 nm in the ohmic (rear) side
- Cone configuration (7 sectors) at backward angles: 8.5 cm from the target ⟹ $\Delta\Theta$ = 37.4°, $\Omega/4\pi$ = 17.3%





M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 971 (2020) 164030



SPIDER (2016 - 2019)

INFN

GALILEO

GALILEO: the LNL Resident γ-Ray Spectrometer

- 25 HPGe Compton-suppressed detectors (GASP type)
- FWHM (@1332.5 keV) < 2.4 keV
- Efficiency (@1332.5 keV) = 2.1%
- Full digital electronics (takes advantage of the developments made for AGATA)
- Triggerless DAQ

A. Goasduff, D. Mengoni, F. Recchia, J.J. Valiente-Dobón et al., Nuclear Inst. and Methods in Physics Research A 1015 (2021) 165753

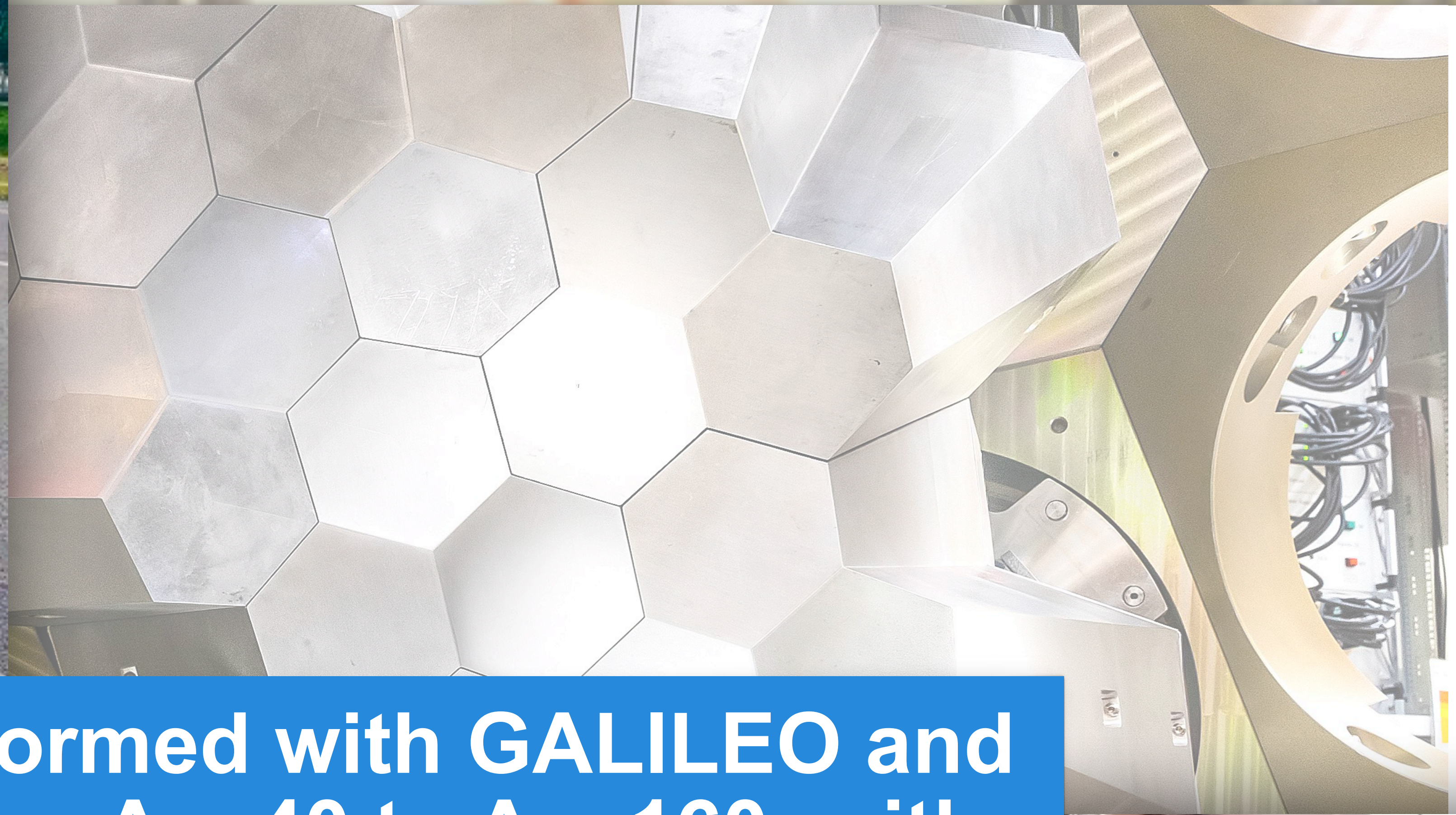
AGATA with SPIDER (2022 - ongoing)

AGATA: the Advanced GAmma Tracking Array

- Last generation γ-ray spectrometer composed of higly-segmented HPGe detectors
- Employs advanced PSA and γ-ray tracking methods to avoid Compton-suppressors and garantee high efficiency

J.J. Valiente-Dobón, R. Menegazzo, A. Goasduff et al., Nuclear Inst. and Methods in Physics Research A 1049 (2023) 168040

AGATA with SPID



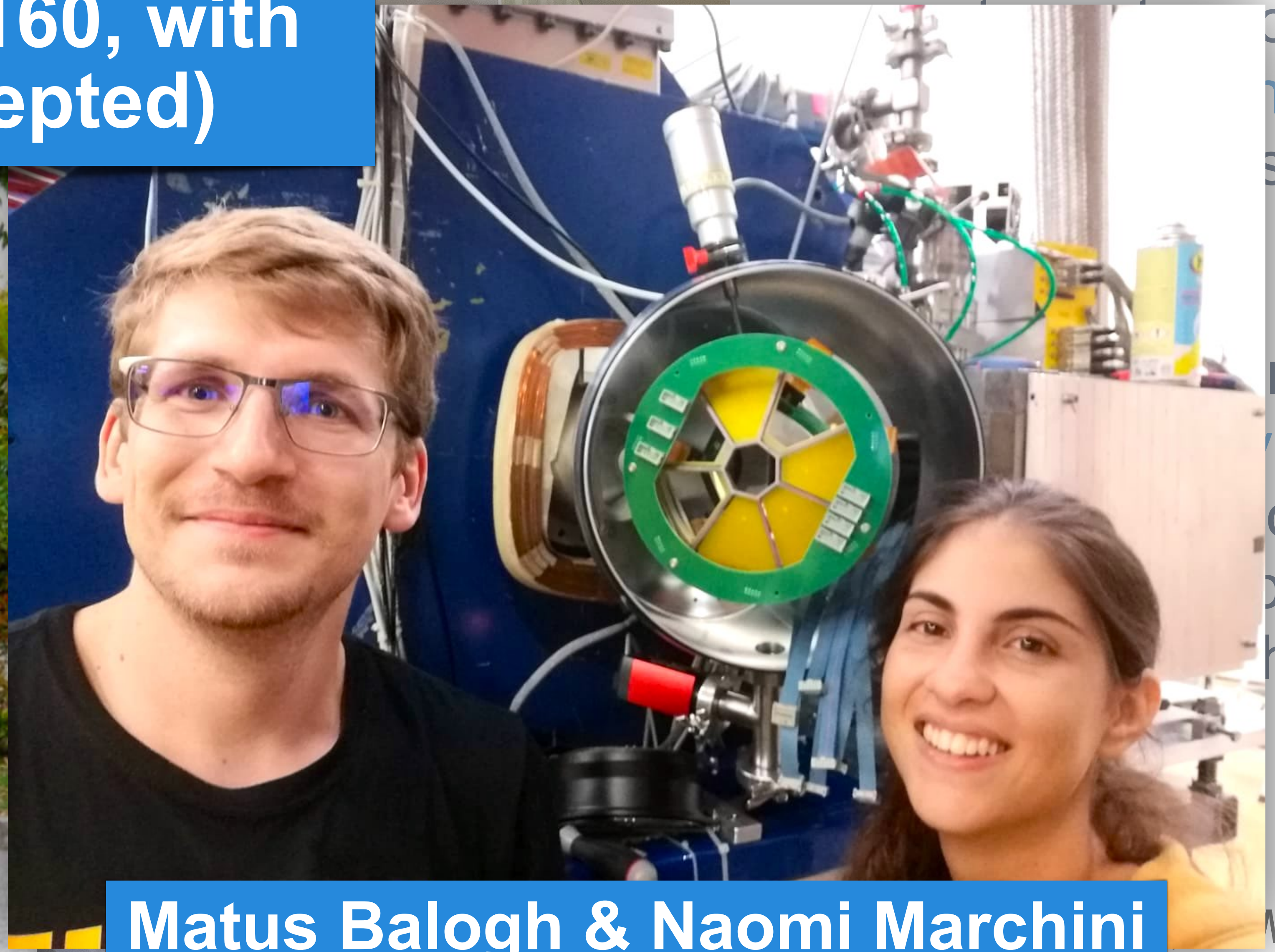
SPIDER

AGATA: the Advanced GAmma Tracking Array

- Last generation γ-ray

Menegazzo, Nuclear Inst. and Research A 1049 (2023) 168040

More than 20 experiments performed with GALILEO and AGATA coupled to SPIDER from A ~ 40 to A ~ 160, with SPs from 3 different continents (other 3 accepted)



Matus Balogh & Naomi Marchini
In charge for SPIDER

Excited 0⁺ States in Mid-Mass Nuclei

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

Excited 0⁺ States in Even-Even Mid-Mass Nuclei

The Zr Isotopic Chain and QPTs

Coulex Experiment on ^{94}Zr

Model-Independent Determination of Shapes in ^{94}Zr

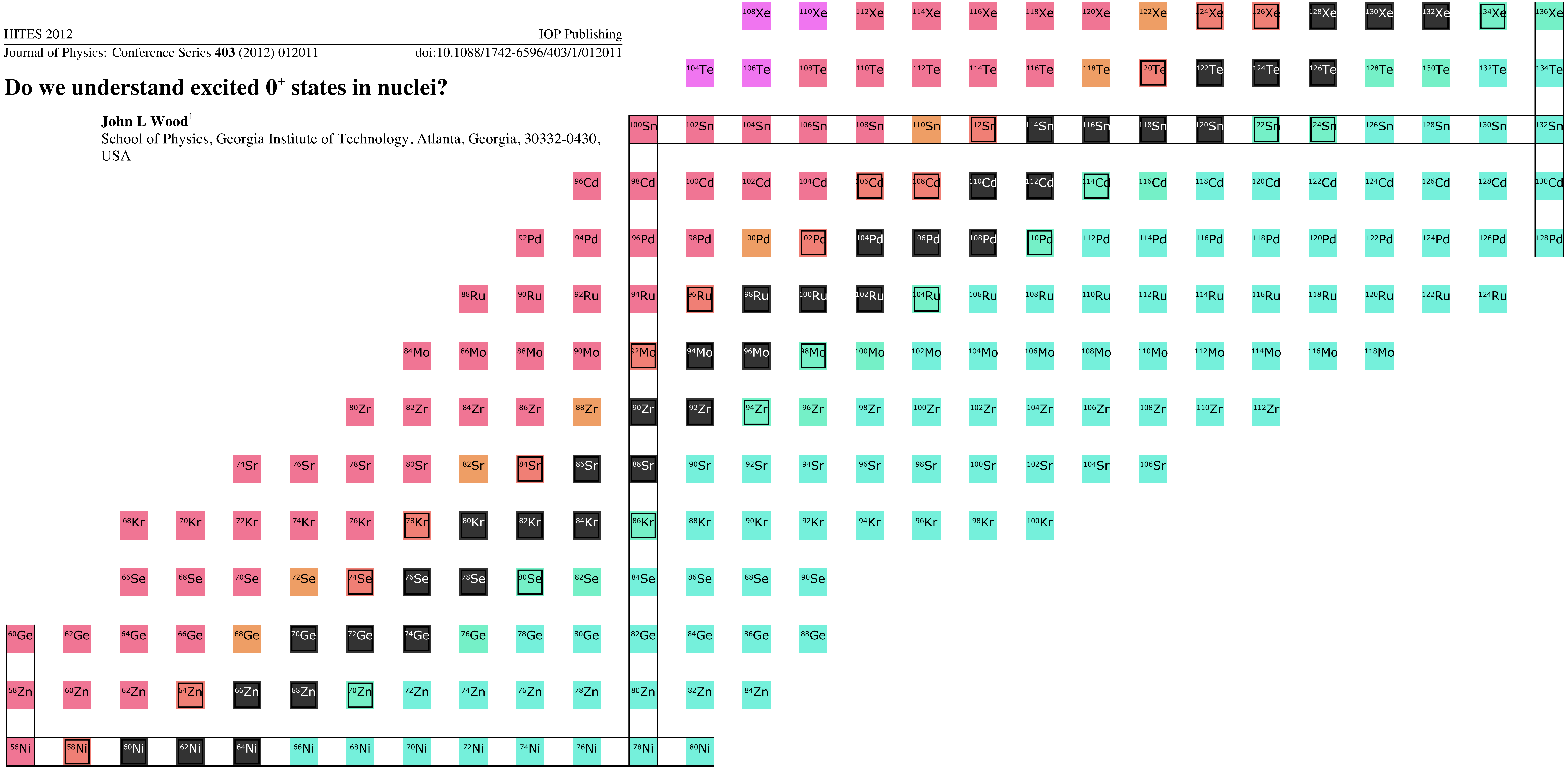
HITES 2012 IOP Publishing

Journal of Physics: Conference Series **403** (2012) 012011 doi:10.1088/1742-6596/403/1/012011

Do we understand excited 0⁺ states in nuclei?

John L Wood[1]

School of Physics, Georgia Institute of Technology, Atlanta, Georgia, 30332-0430, USA



Low-Energy Coulomb Excitation

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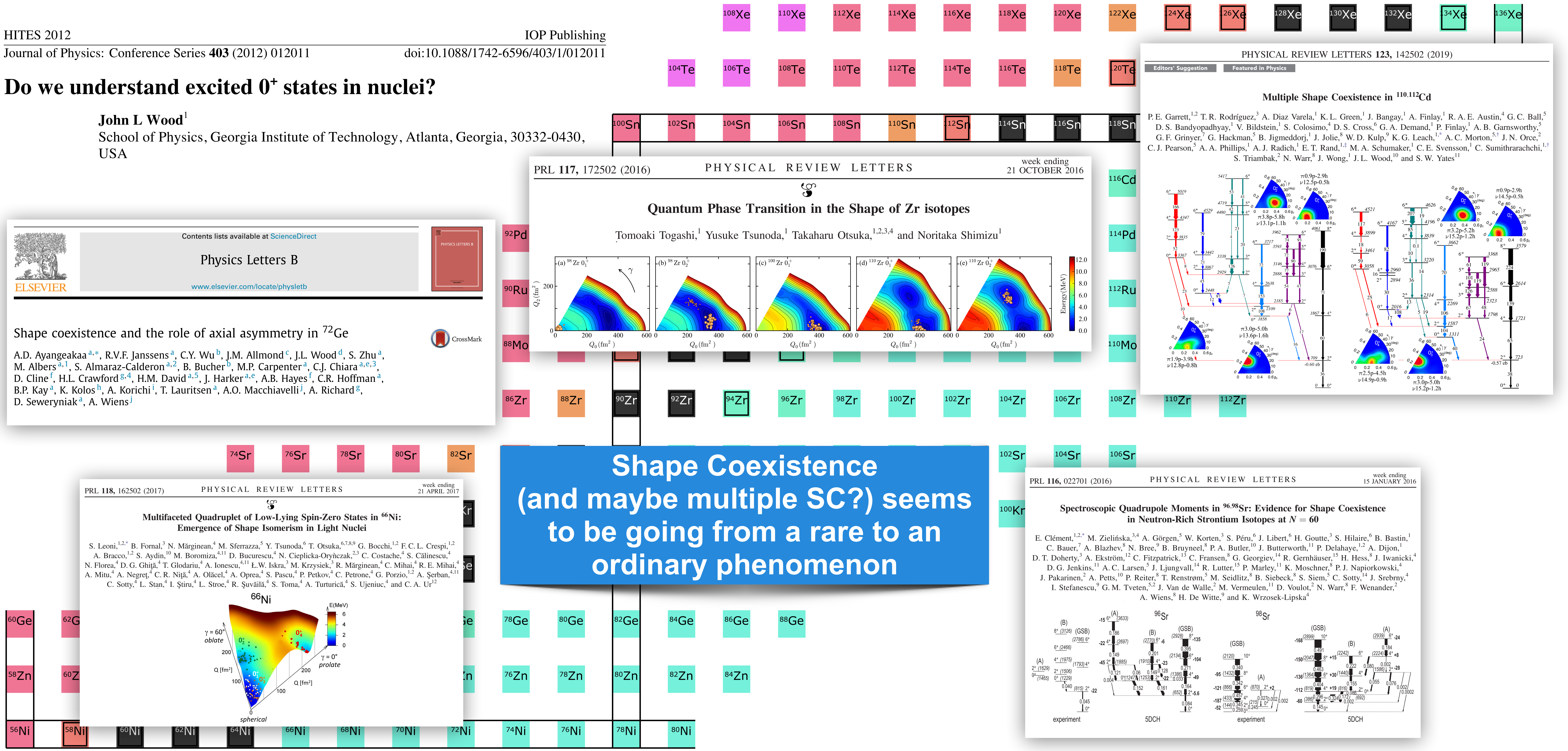
Excited 0+ States in Mid-Mass Nuclei



Zirconium Isotopes

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

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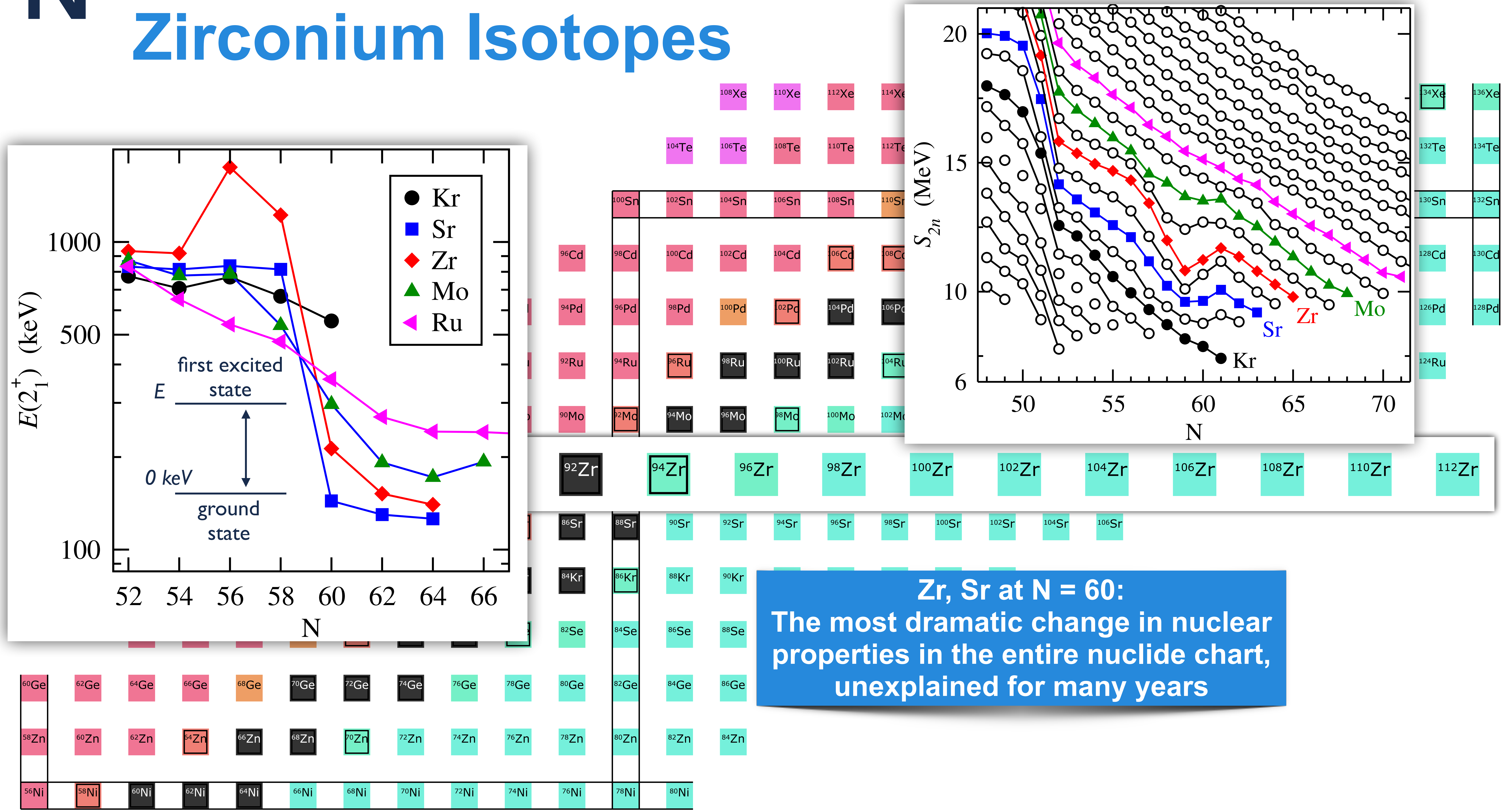

Zr, Sr at N = 60:
The most dramatic change in nuclear properties in the entire nuclide chart, unexplained for many years

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

Excited 0^+ States in Even-Even Mid-Mass Nuclei

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Quantum Phase Transition

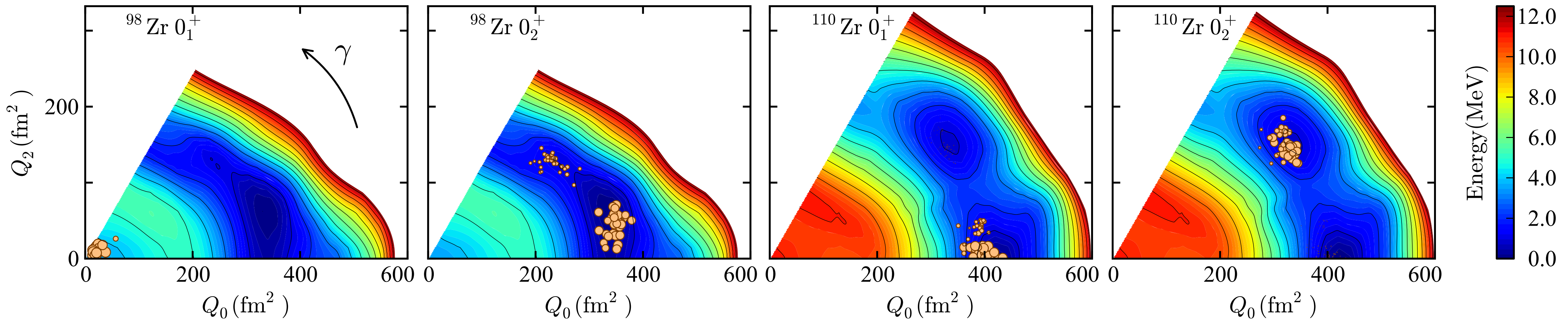
- Monte Carlo Shell Model (MCSM) ⟹ Excellent reproduction of experimental data, also around N = 60

PRL **117,** 172502 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

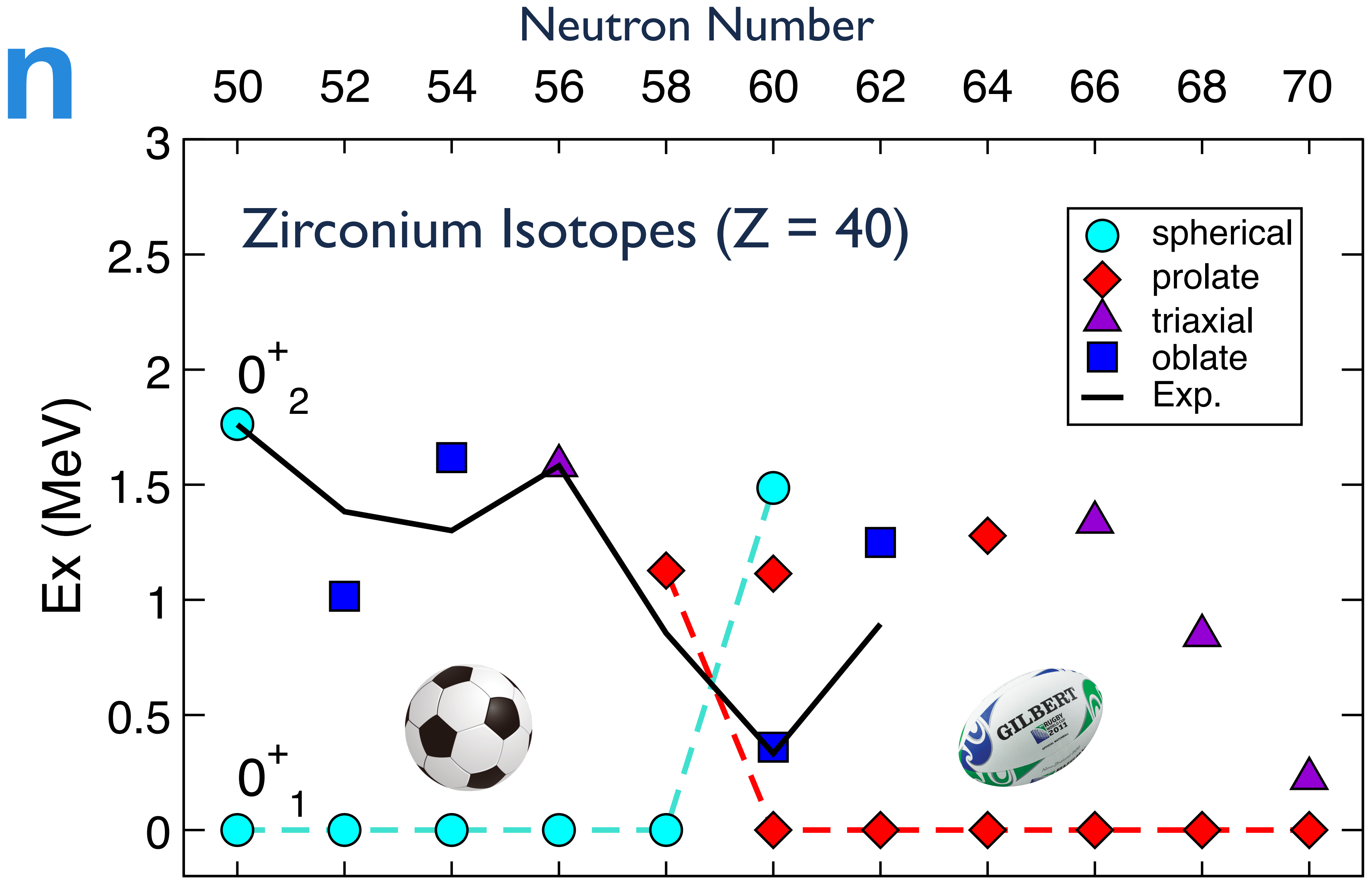
Quantum Phase Transition in the Shape of Zr isotopes

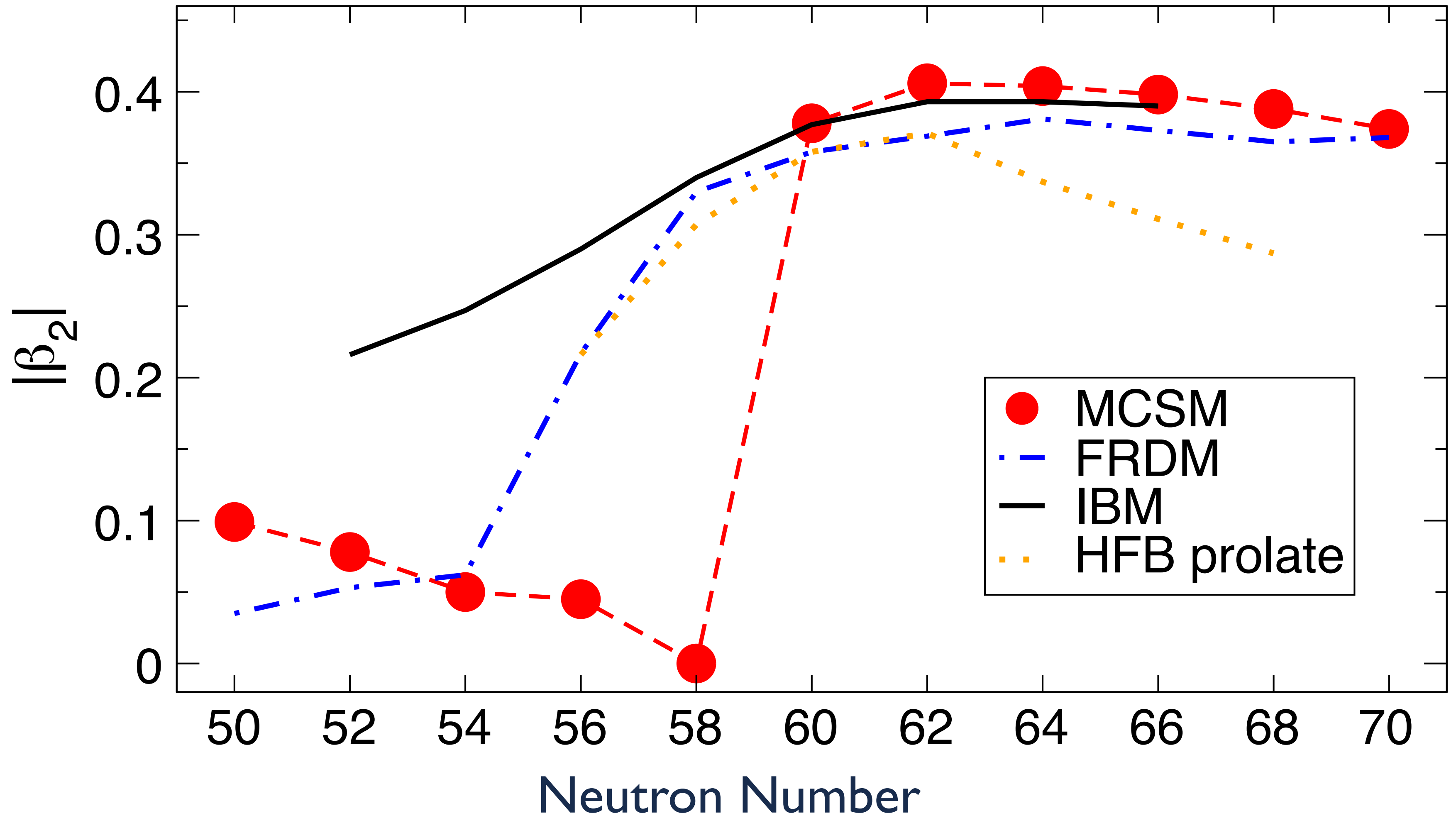
Tomoaki Togashi,[1] Yusuke Tsunoda,[1] Takaharu Otsuka,[1,2,3,4] and Noritaka Shimizu[1]

- Use of T-Plots for a direct calculation of the nuclear shape:



- Quantum Phase Transition (QPT):
  - Control Parameter ⟹ Neutron number
  - "Macroscopic" Quantity ⟹ Shape





Intertwined Quantum Phase Transitions

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

Excited 0^+ States in Even-Even Mid-Mass Nuclei

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Model-Independent Determination of Shapes in ^{94}Zr

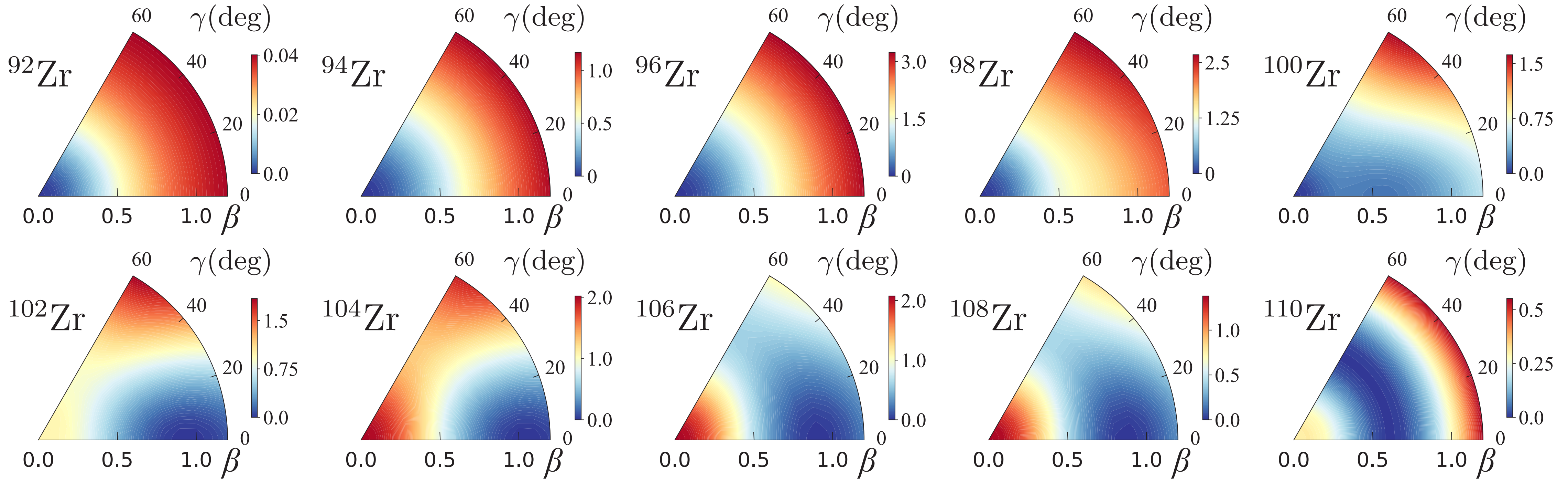
- Interacting Boson Model with Configuration Mixing (IBM-CM) $\Longrightarrow$ Excellent reproduction of experimental data, also around N = 60

PHYSICAL REVIEW C **105**, 014305 (2022)

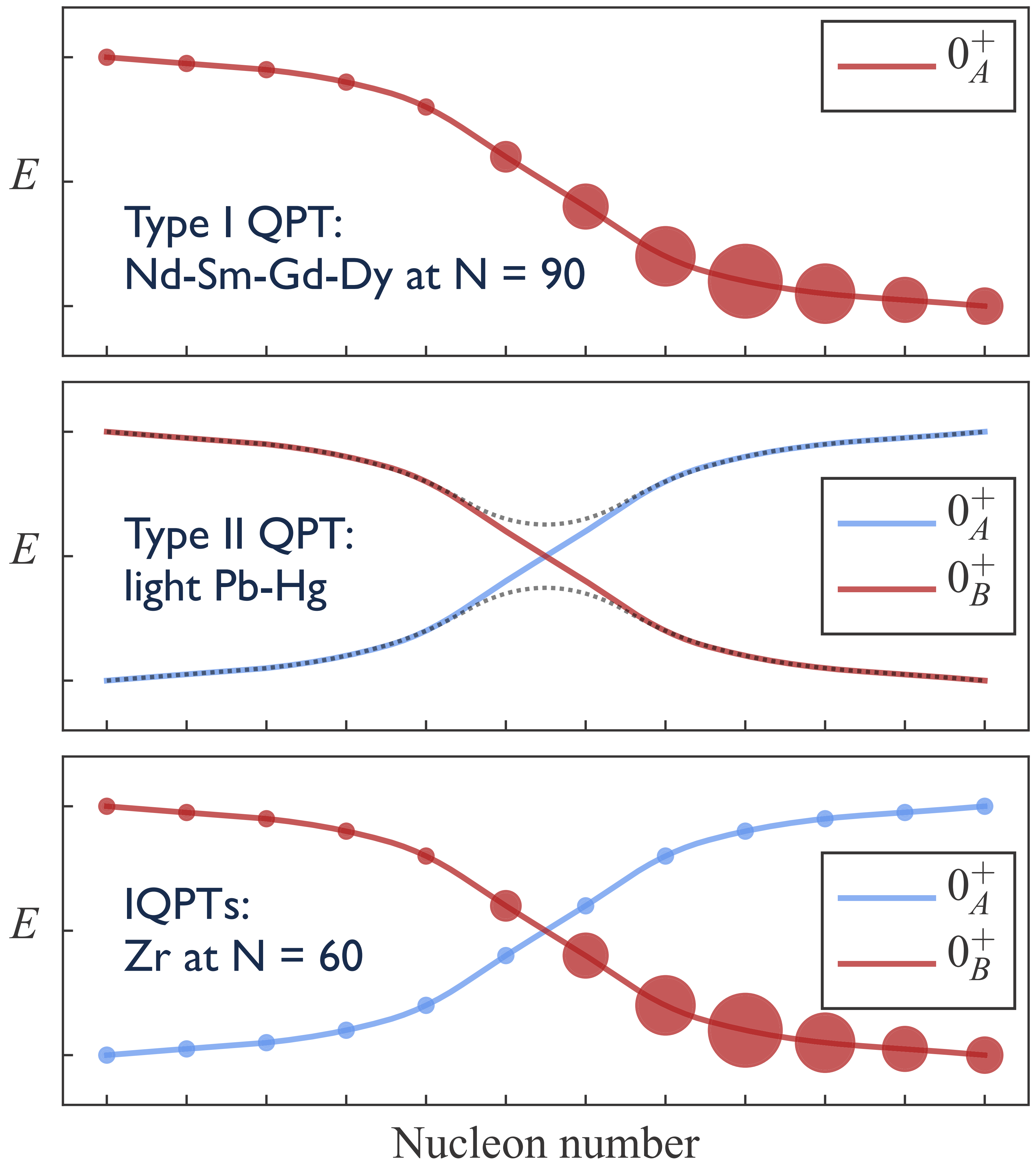
Zr isotopes as a region of intertwined quantum phase transitions

N. Gavrielov,[1,2,*] A. Leviatan,[1,†] and F. Iachello[2,‡]
[1] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
[2] *Center for Theoretical Physics, Sloane Physics Laboratory, Yale University, New Haven, Connecticut 06520-8120, USA*

- Two Intertwined Quantum Phase Transitions (IQPTs) exist in the Zr isotopic chain, appearing in the first two 0^+ states:
  - As in MCSM, the mixing between the coexisting 0^+ states is weak
  - At variance with MCSM, the ground state for N < 60 (0_2^+ state for N > 60) is always U(5)-like (i.e., weakly deformed)



(Size of circles ∝ Deformation)



Experimental Knowledge on 0^+ States in Zr

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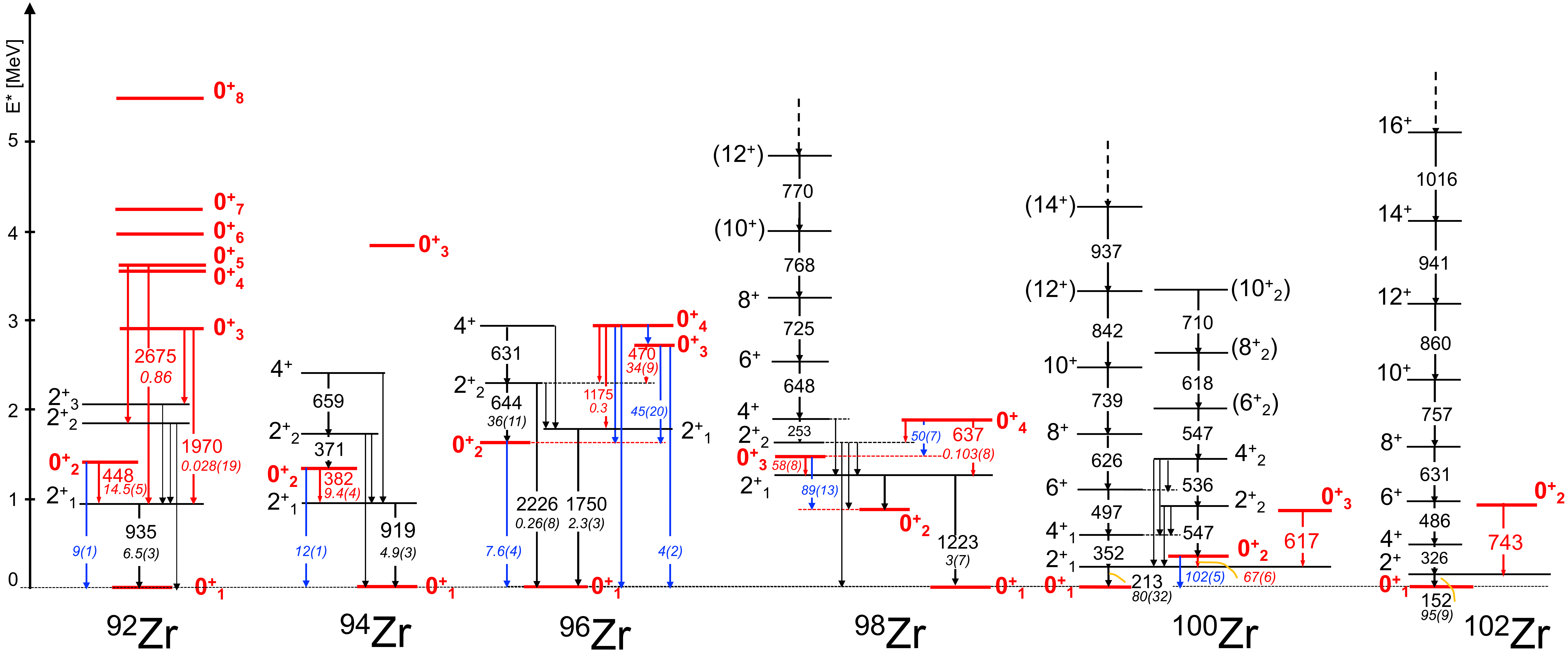

S. Leoni et al. Progress in Particle and Nuclear Physics 139 (2024) 104119

Experimental Knowledge on 0^+ States in Zr

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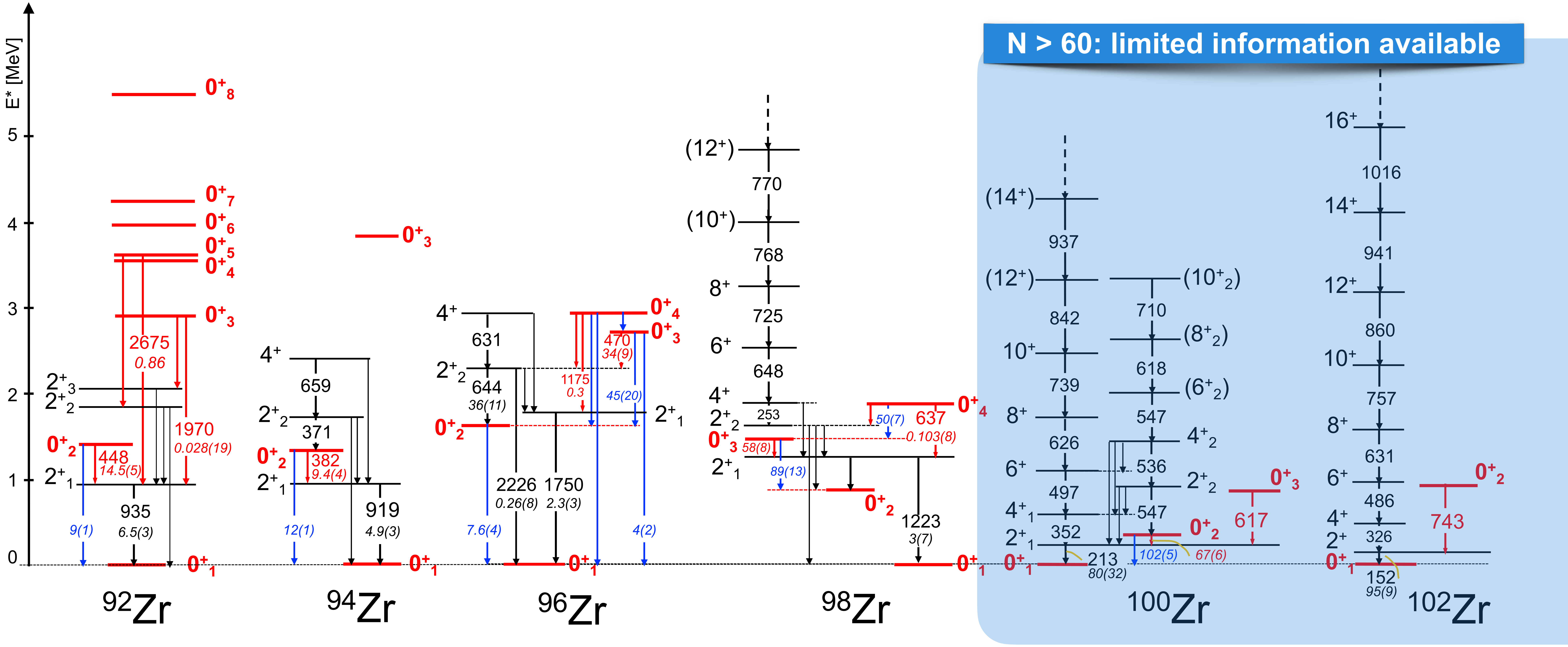
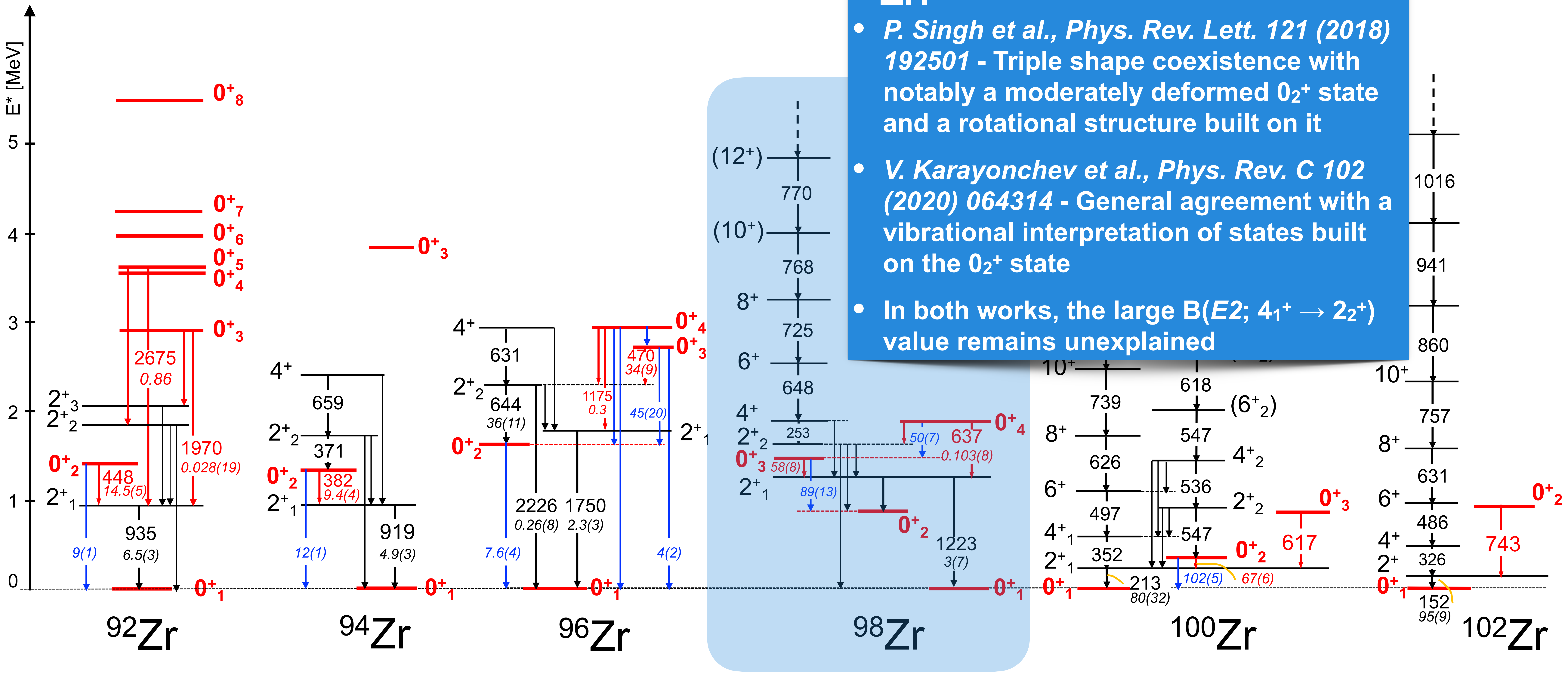


S. Leoni et al. Progress in Particle and Nuclear Physics 139 (2024) 104119

- Low-Energy Coulomb Excitation
- SPIDER with GALILEO and AGATA
- Excited 0^+ States in Even-Even Mid-Mass Nuclei
- The Zr Isotopic Chain and QPTs
- Coulex Experiment on ^{94}Zr
- Model-Independent Determination of Shapes in ^{94}Zr

Experimental Knowledge on 0^+ States in Zr



^{98}Zr:

- ***P. Singh et al., Phys. Rev. Lett. 121 (2018) 192501*** **- Triple shape coexistence with notably a moderately deformed 0_2^+ state and a rotational structure built on it**
- ***V. Karayonchev et al., Phys. Rev. C 102 (2020) 064314*** **- General agreement with a vibrational interpretation of states built on the 0_2^+ state**
- **In both works, the large B($E2$; $4_1^+ \rightarrow 2_2^+$) value remains unexplained**

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

Experimental Knowledge on 0^+ States in Zr

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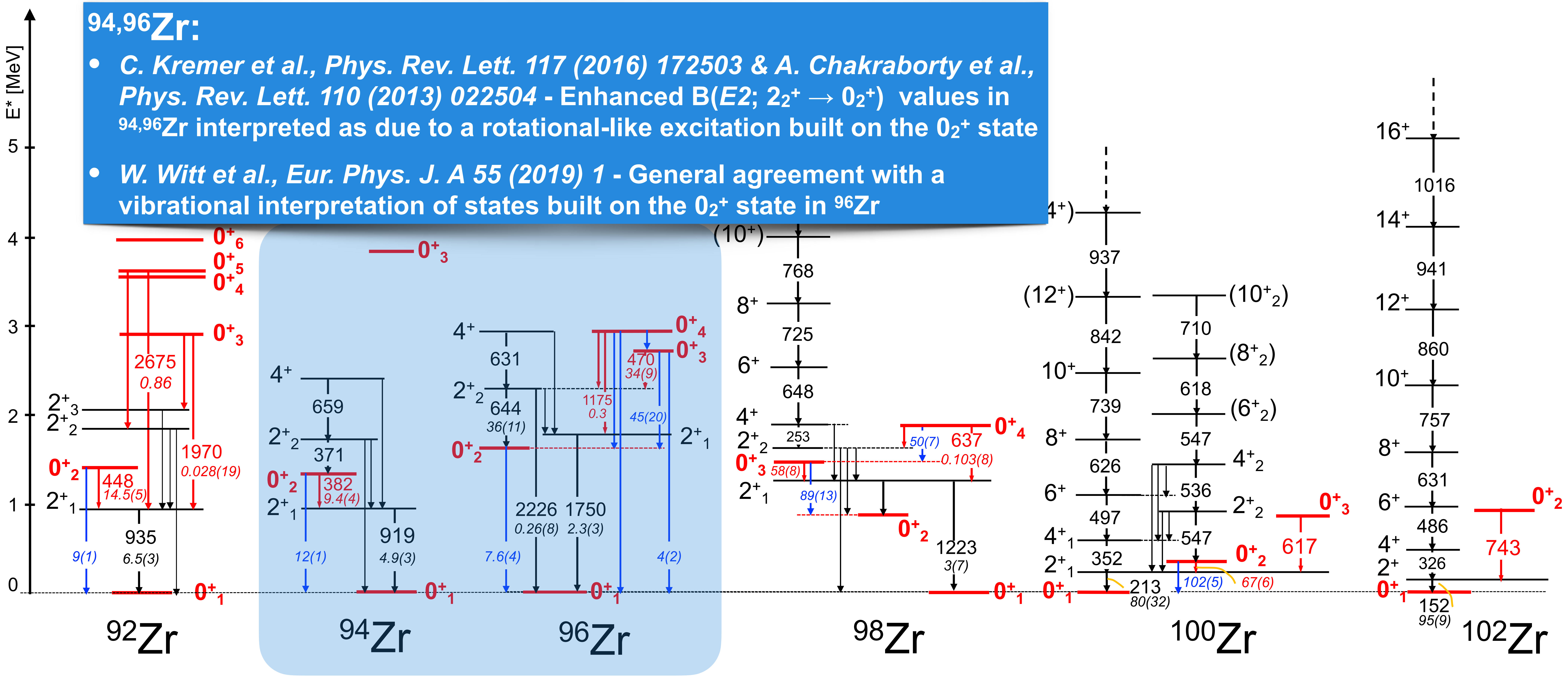
^{94,96}Zr:

- *C. Kremer et al., Phys. Rev. Lett. 117 (2016) 172503 & A. Chakraborty et al., Phys. Rev. Lett. 110 (2013) 022504* - Enhanced $B(E2; 2_2^+ \rightarrow 0_2^+)$ values in ^{94,96}Zr interpreted as due to a rotational-like excitation built on the 0_2^+ state
- *W. Witt et al., Eur. Phys. J. A 55 (2019) 1* - General agreement with a vibrational interpretation of states built on the 0_2^+ state in ^{96}Zr



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

Experimental Knowledge on 0^+ States in Zr

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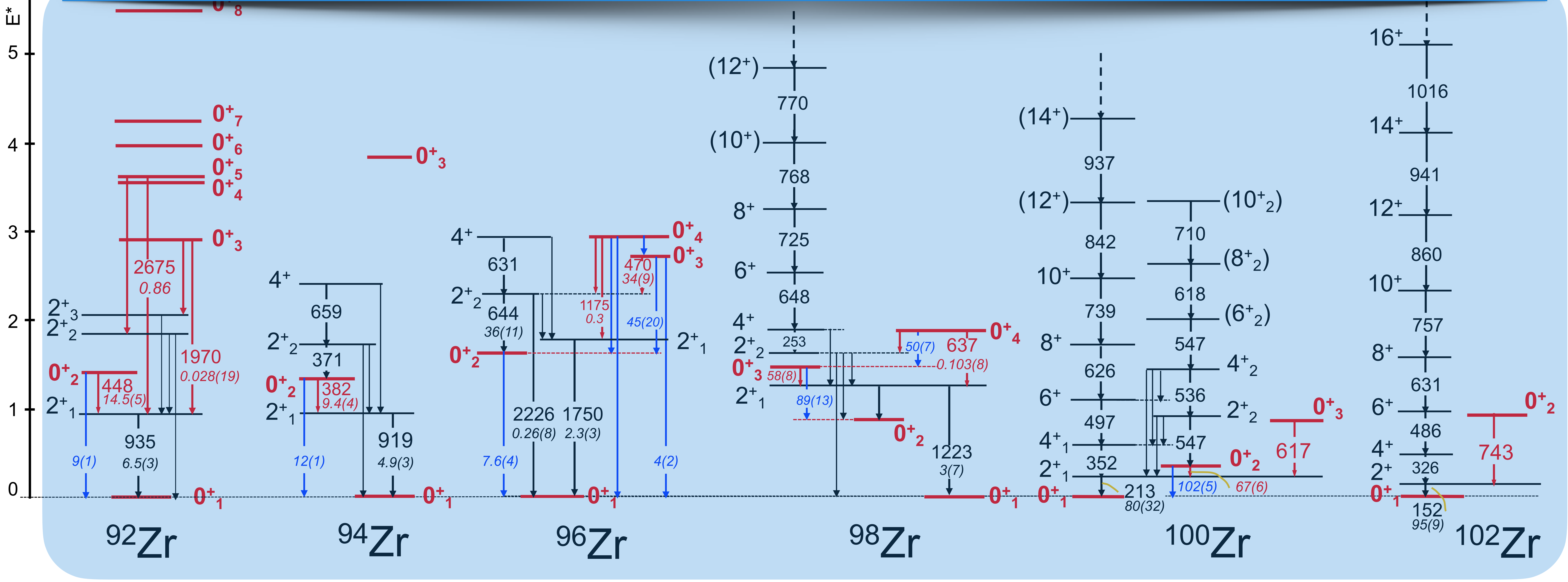
Model-Independent Determination of Shapes in ^{94}Zr

Need for key and direct observables capable of distinguishing between the different interpretations to validate the physics suggested from theory, both in stable and neutron-rich isotopes
⇒ Broad campaign from our collaboration at LNL (Italy), TRIUMF (Canada), and MLL (Germany)



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

Coulomb Excitation of ^{94}Zr

Low-Energy Coulomb Excitation
SPIDER with GALILEO and AGATA
Excited 0^+ States in Even-Even Mid-Mass Nuclei
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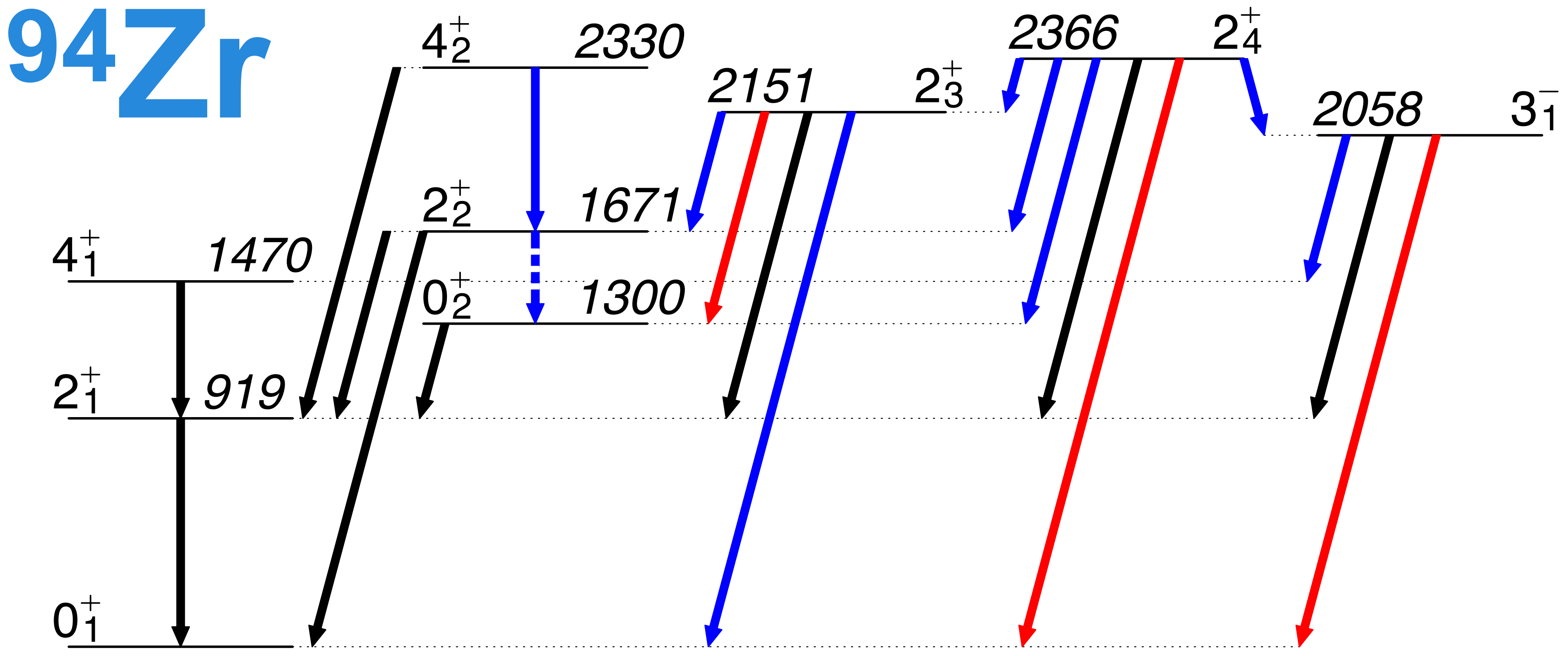
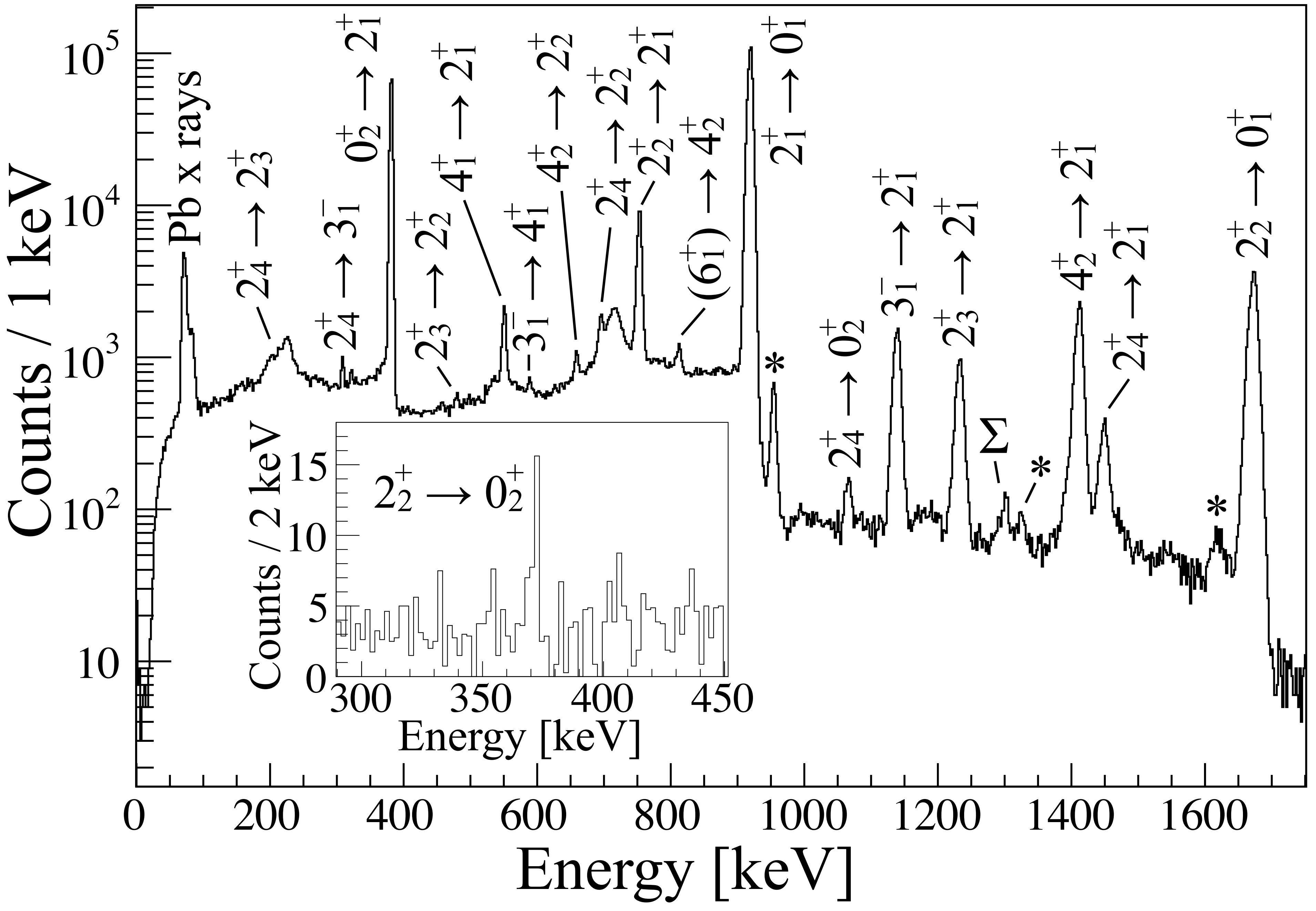
Coulex Experiment on ^{94}Zr
Model-Independent Determination of Shapes in ^{94}Zr

- Experiment performed with GALILEO and SPIDER:
  - ^{94}Zr beam @370 MeV (0.1 pnA) on a self-supporting ^{208}Pb target with 1 mg/cm^2 thickness
  - GALILEO with 25 HPGe Compton-suppressed detectors
  - SPIDER at backward angles (126° - 162°)
  - 6 $LaBr_3$:Ce detectors to increase the efficiency in γ-γ coinc.
  - *Spokespersons: D.T. Doherty (University of Surrey, UK), M. Rocchini, M. Zielinska (CEA Saclay, France)*
  - *Analysis by: N. Marchini (INFN Firenze), M. Rocchini*
- 18 gamma-ray transitions observed, 8 states populated
- Known spectroscopic data added in the analysis:
  - 13 branching ratios, 10 lifetimes, 7 mixing ratios

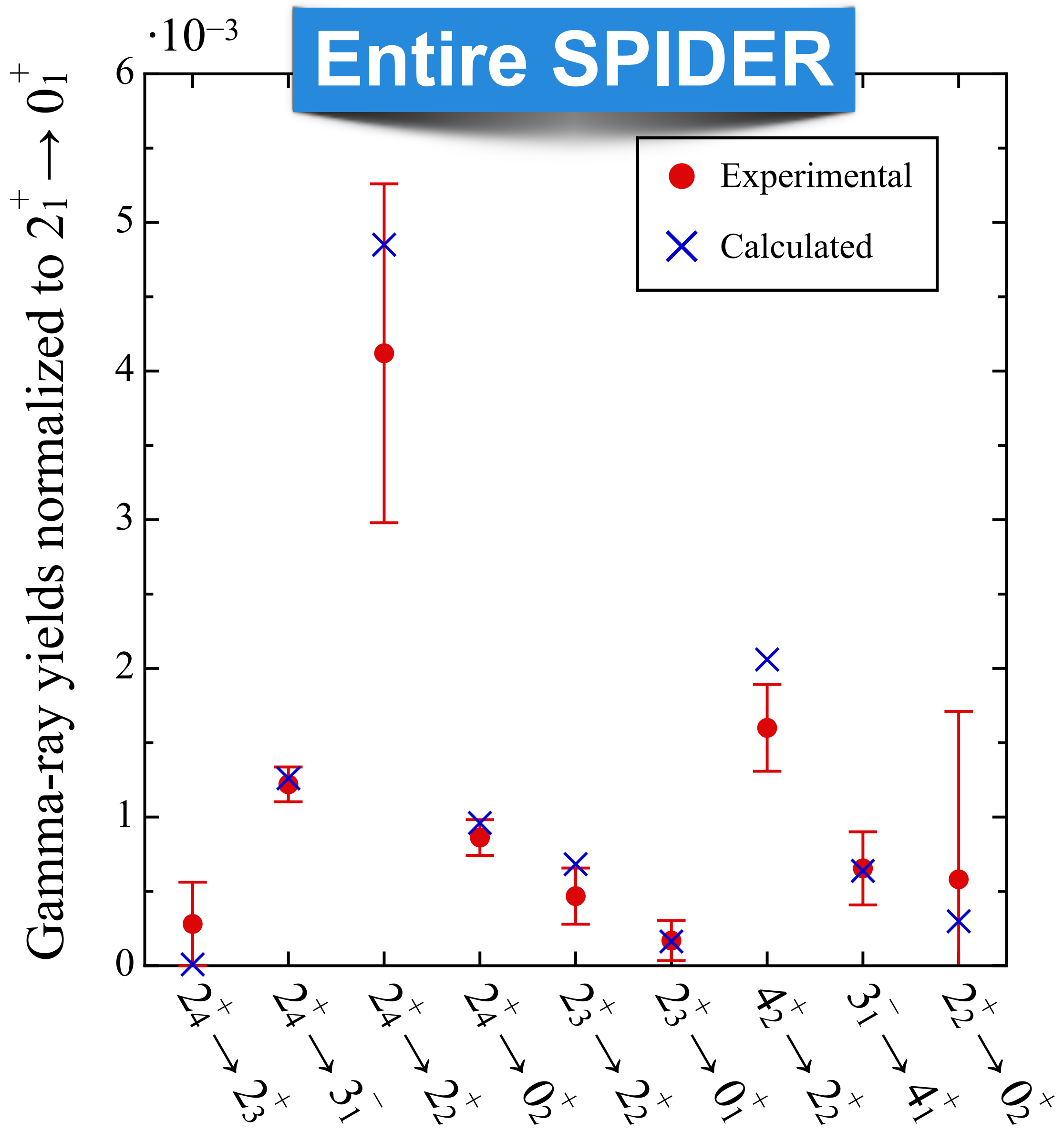


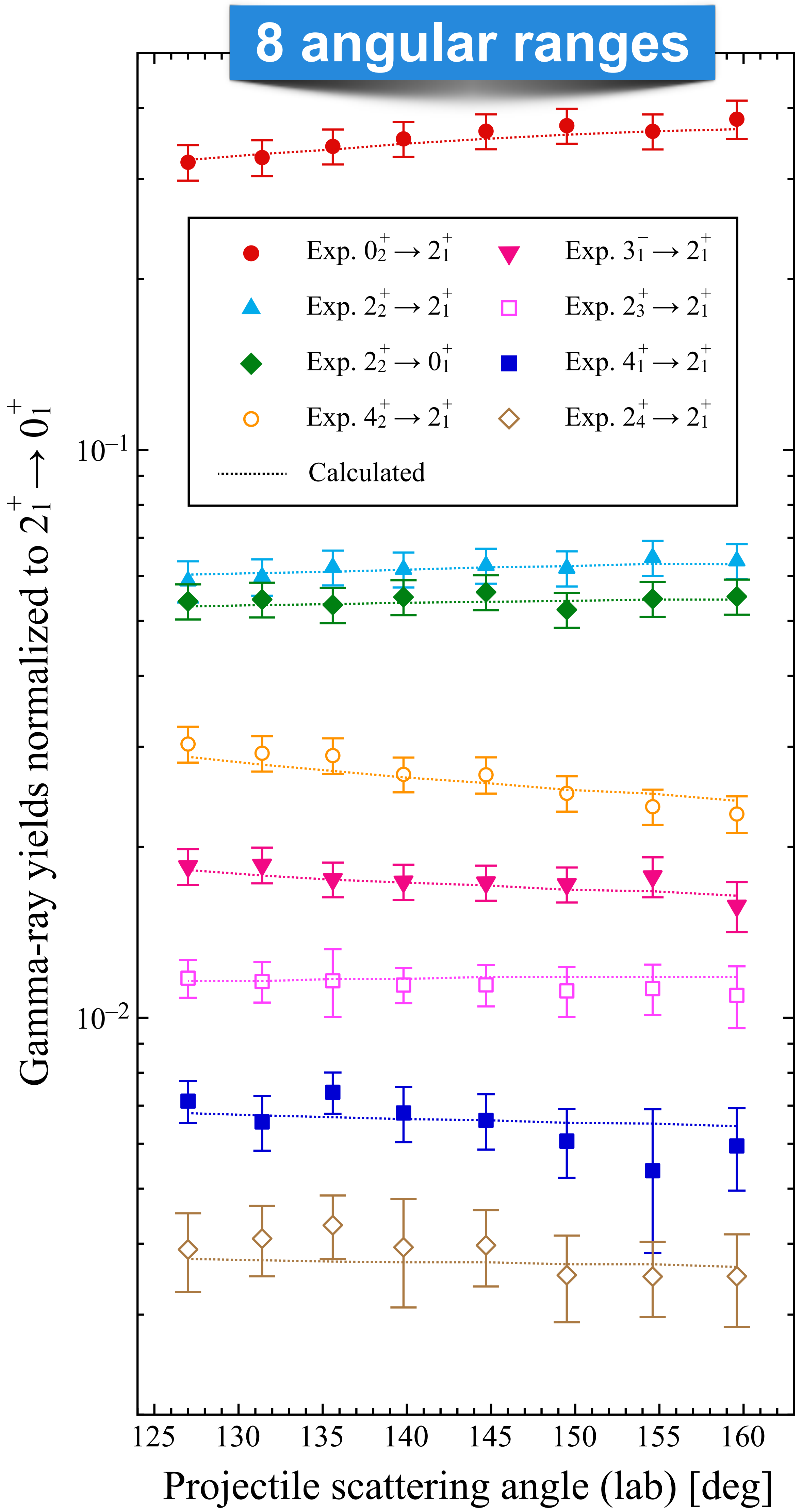


N. Marchini, M. Rocchini, M. Zielinska et al. submitted to Phys. Lett. B

Results

- 8 transitions analysed by dividing the statistics into 8 angular ranges, 9 transitions considering the entire SPIDER
- GOSIA analysis: excellent reproduction of experimental yields





17 reduced transition probabilities extracted + new IBM-CM calculations

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

[a] Sign imposed in the analysis (see text for details).
[b] Determined from literature data.
[c] Outside IBM-CM model space (see Ref. [24] for details).
[d] Positive sign determined.

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Shapes of the $0^+_{1,2}$ States

Low-Energy Coulomb Excitation

SPIDER with GALILEO and AGATA

Excited 0+ States in Even-Even Mid-Mass Nuclei

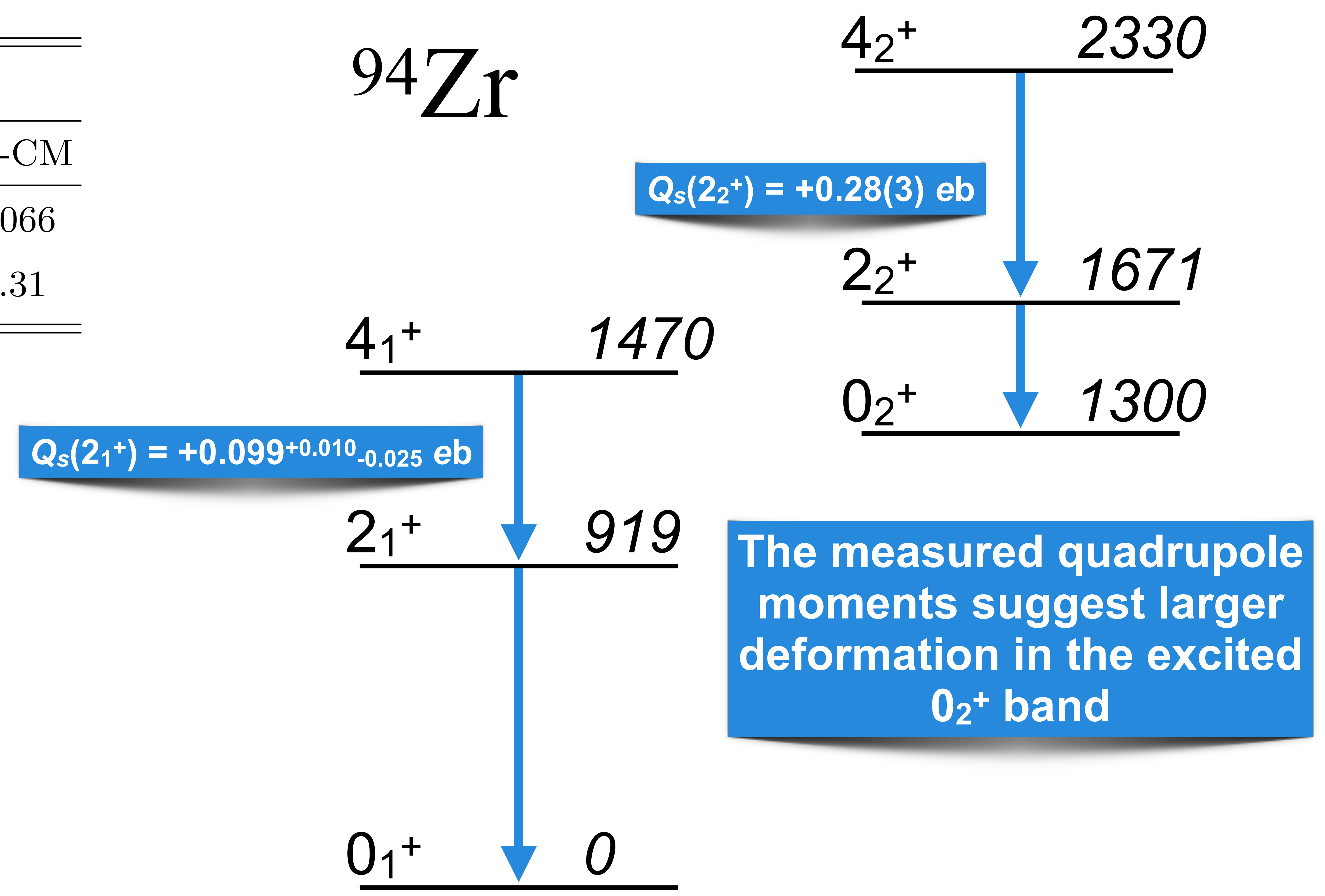
The Zr Isotopic Chain and QPTs

Coulex Experiment on ^{94}Zr

Model-Independent Determination of Shapes in ^{94}Zr

- First determination of spectroscopic quadrupole moments for the $2^+_{1,2}$ states in the Zr isotopic chain:

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	$+0.37(4)$	$+0.28(3)$	$+0.31$



The measured quadrupole moments suggest larger deformation in the excited 0_2^+ band

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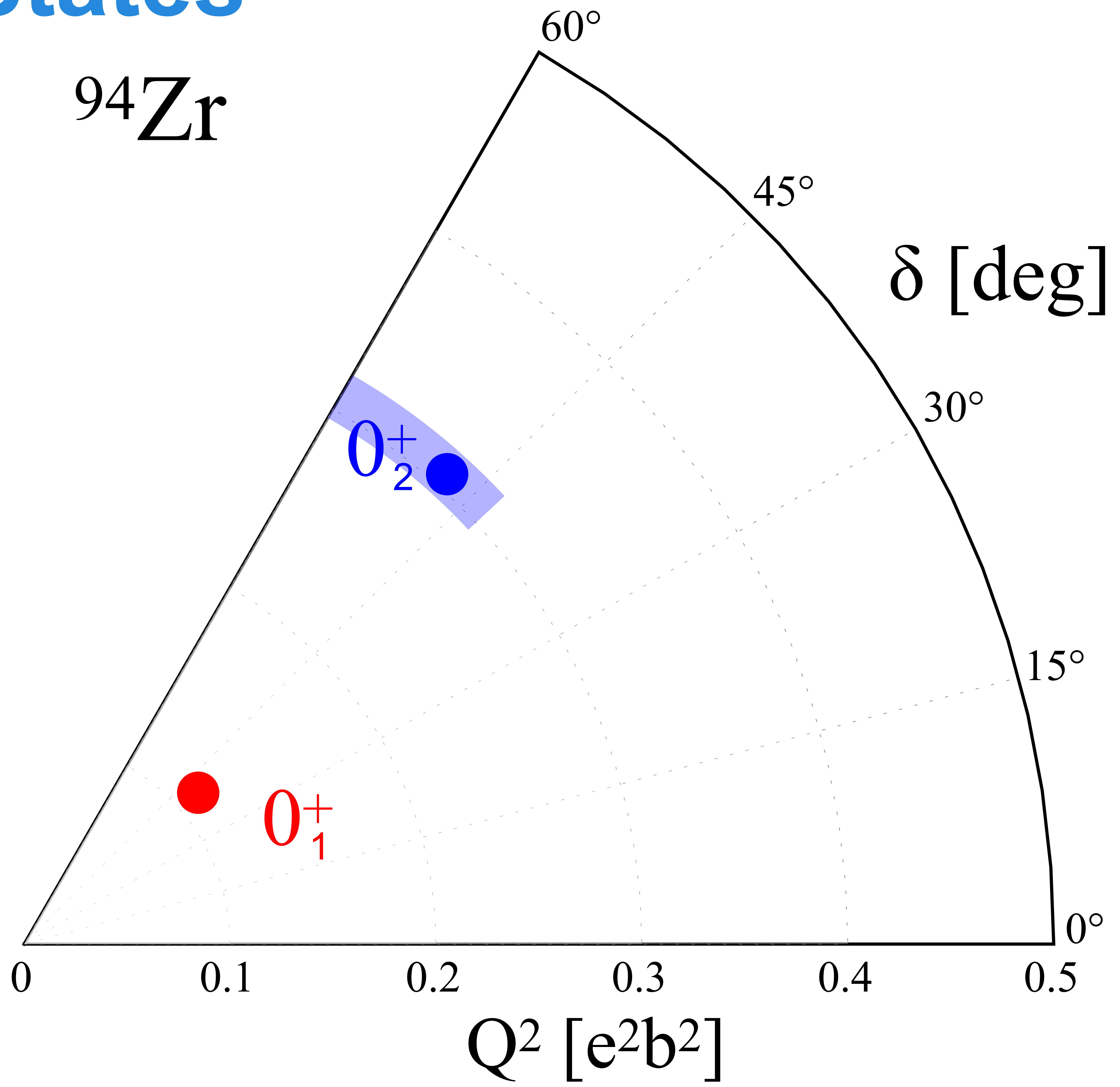
- First experimental application of quadrupole sum rules to the $0_{1,2}^+$ states in the Zr isotopic chain, and one of the few determinations of $\sigma(Q^2) = (\langle Q^4 \rangle - (\langle Q^2 \rangle)^2)^{1/2}$ in the entire nuclide chart:

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)				−0.37(7)	
0_2^+	0.305(12)				−0.8(2)	



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Generic Ellipsoid

$$R(\theta,\phi) = R_0 \left[1 + \beta \sqrt{\frac{5}{16\pi}} \left(\cos\gamma \left(3\cos^2\theta - 1\right) + \sqrt{3}\sin\gamma \sin^2\theta \cos 2\phi \right) \right]$$

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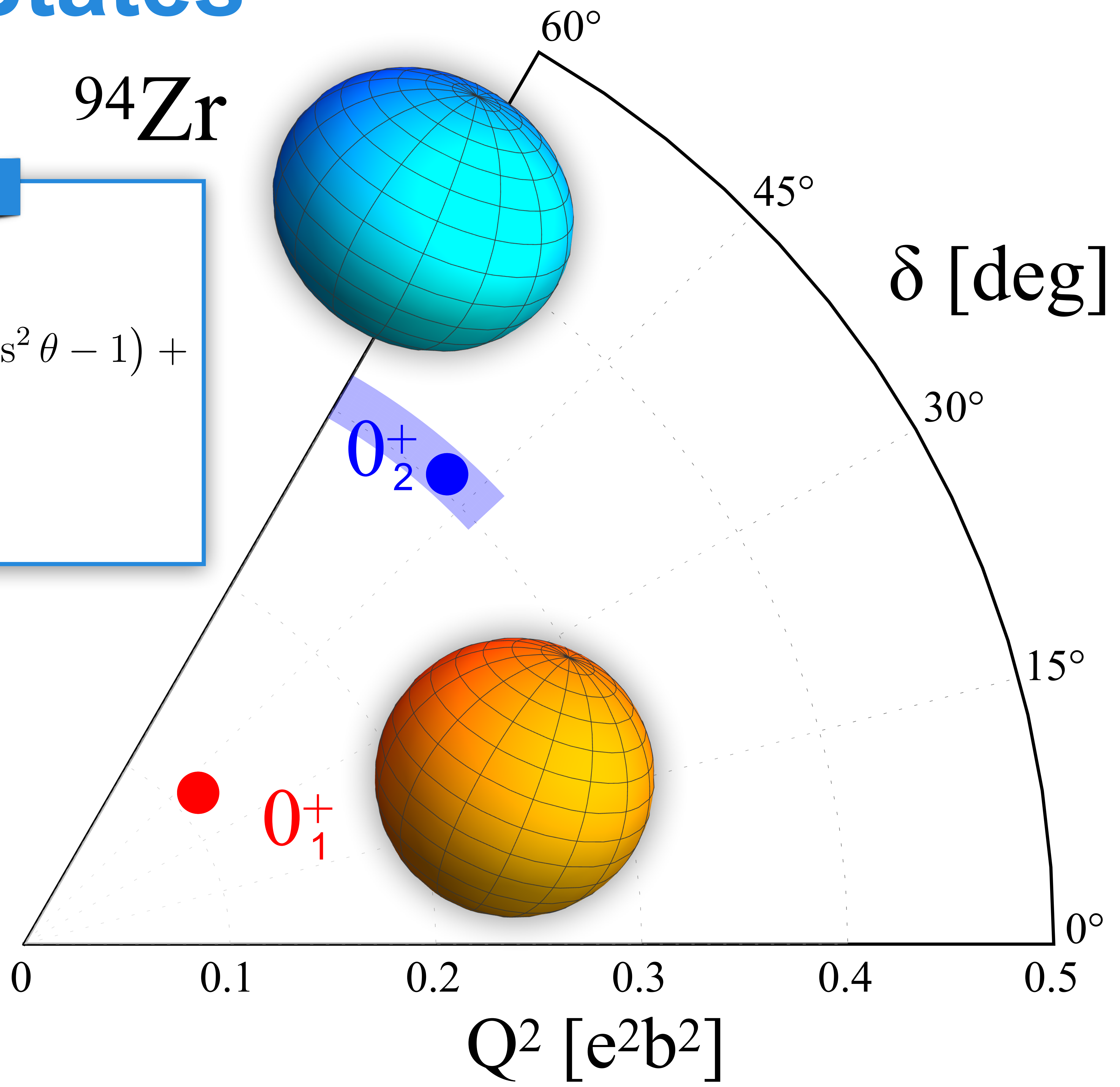

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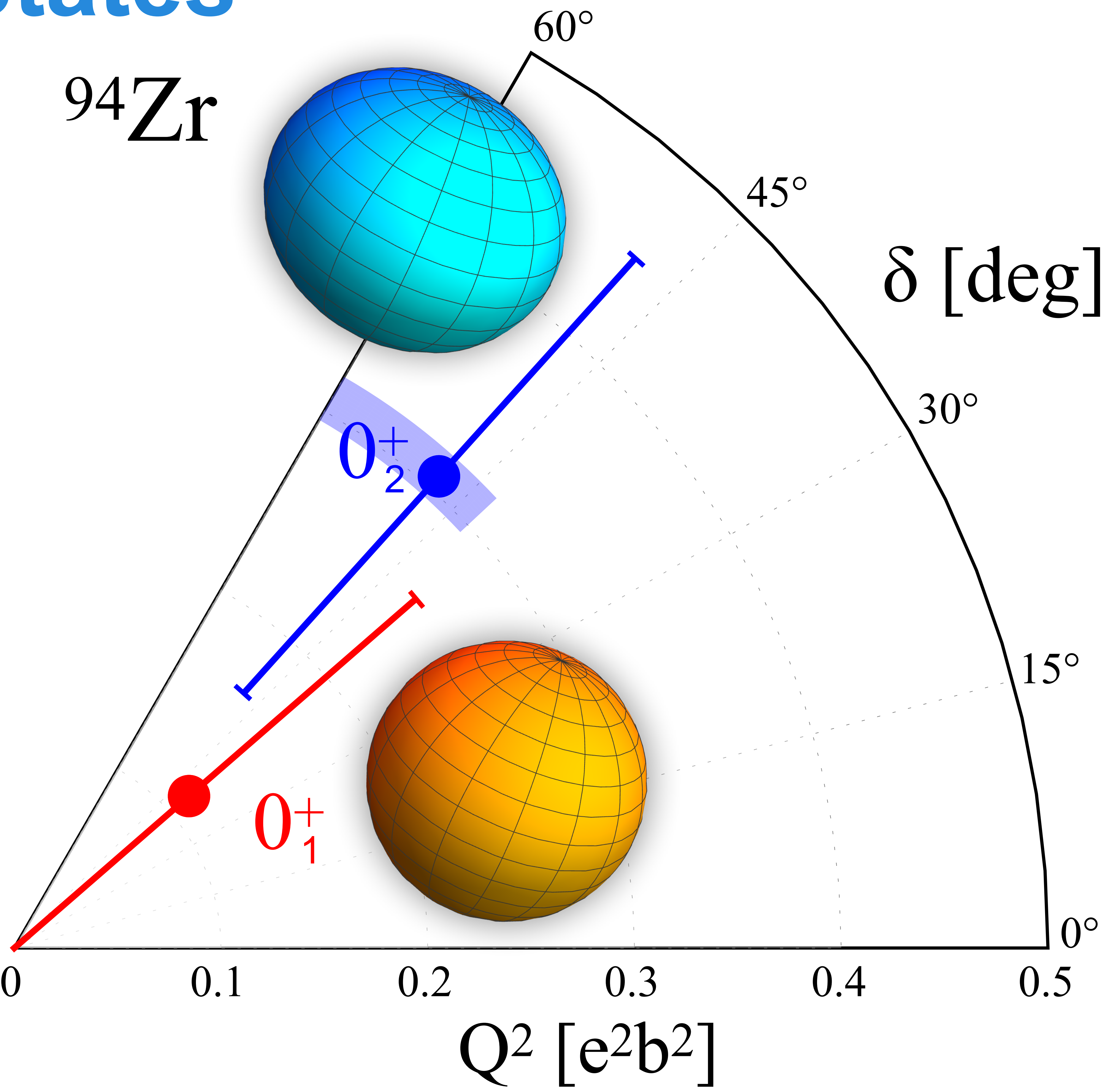
0_1^+	0.112(4)		0.143(4)		−0.37(7)	
0_2^+	0.305(12)		0.14(3)		−0.8(2)	



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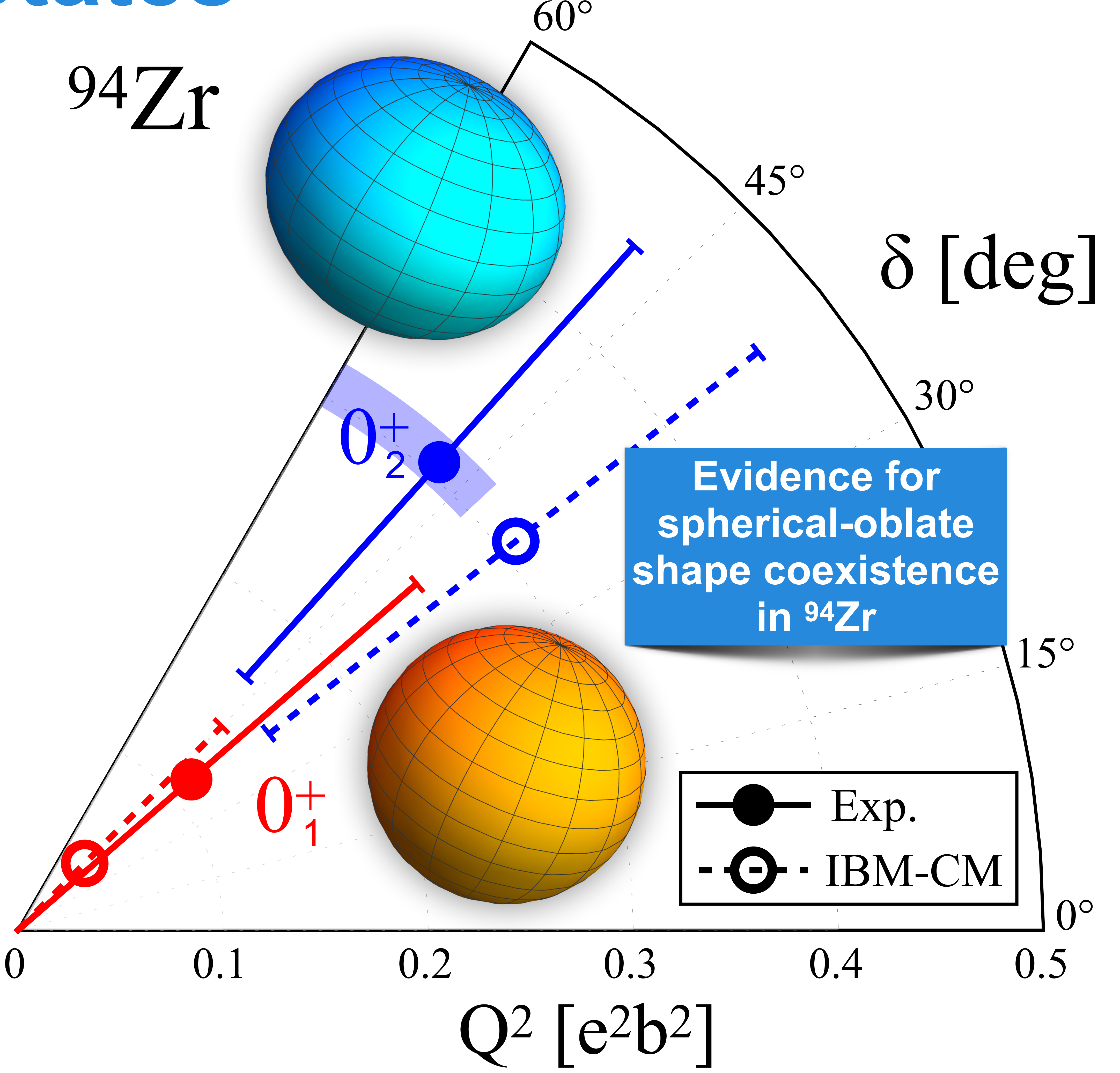
	Exp.	Th.	Exp.	Th.	Exp.	Th.
0^+_1	0.112(4)	0.046	0.143(4)	0.094	−0.37(7)	−0.72
0^+_2	0.305(12)	0.308	0.14(3)	0.153	−0.8(2)	−0.4



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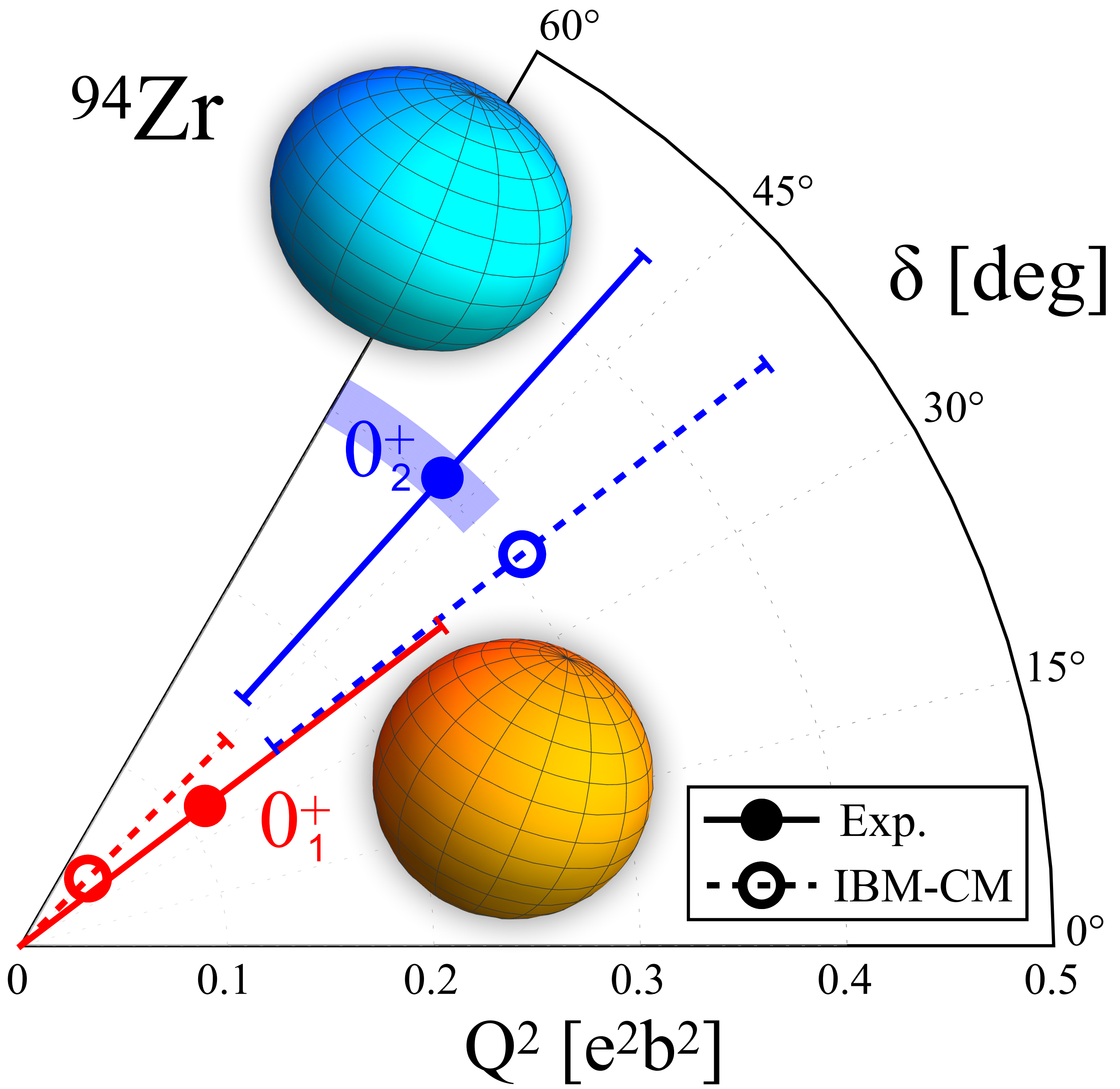
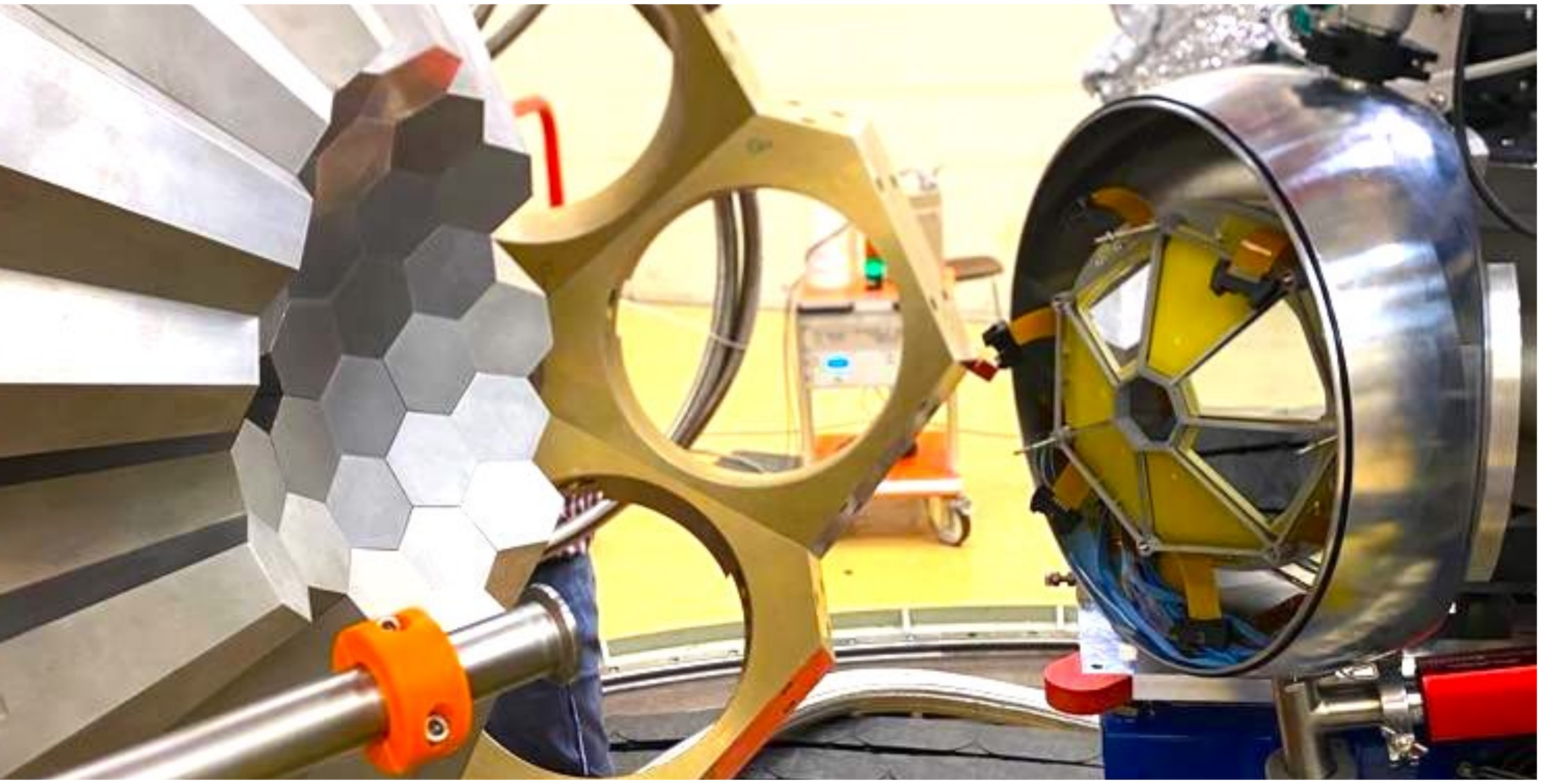
Summary



Low-energy Coulomb excitation at LNL

- Well-established activity which involves many users and institutions
- Currently exploiting AGATA and SPIDER with stable beams
- New possibilities will be offered soon by SPES



Coulex of ^{94}Zr

- A high-statistics Coulomb-excitation experiment was performed at LNL
- 17 transitional matrix elements with relative signs and 2 diagonal matrix elements with absolute signs extracted
- Model-independent determination of spherical-oblate shape coexistence from the obtained quadrupole moments and rotational invariants

INFN

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FIRENZE DIVISION

THANK YOU FOR THE ATTENTION