Shape Transitions Between and Within Zr Isotopes

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Overview

- Introduction to Shape Coexistence / Quantum (Shape) Phase Transition
- The boundary of spherical shape at ^{98}Zr
  - CoulEx of ^{98}Zr: GRETINA & CHICO2 at ATLAS / CARIBU
  - New RDDS Plunger data ^{98}Zr
- Implications for ^{96}Zr ?
  - A data survey and recent ideas

Shape Coexistence & Transitions

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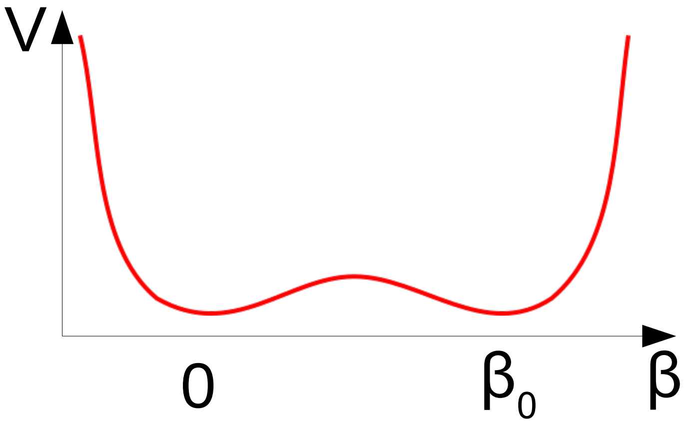
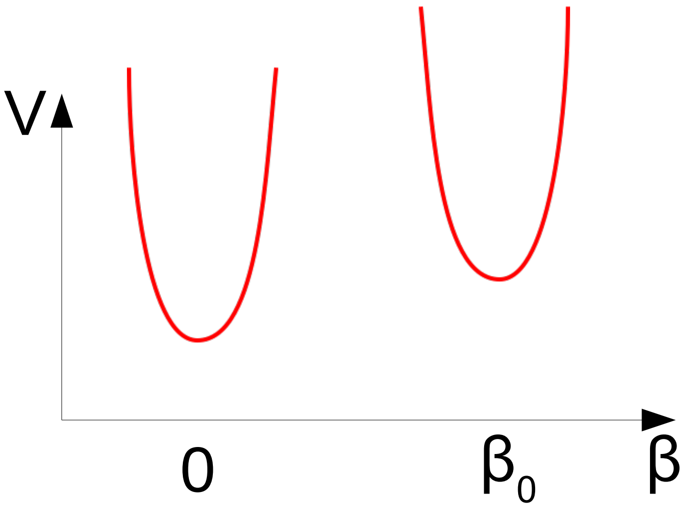
Shape Transition/Coexistence with Strong Mixing / Low Barrier



- Within one valence space
- X(5) / E(5) / CBS

F. Iachello, PRL 85/87 (2000/2001)
N. Pietralla, PRC 70 (2004)

Shape Transition/Coexistence with Weak Mixing / High Barrier



- Two valence spaces (normal + intruder)
- **High-Barrier case**

A. Leviathan, PRC 74 (2006)

Change from one to another as function of
- Valence Nucleon Number
- **Microscopic Configuration !**

T. Togashi, PRL 117 (2016)

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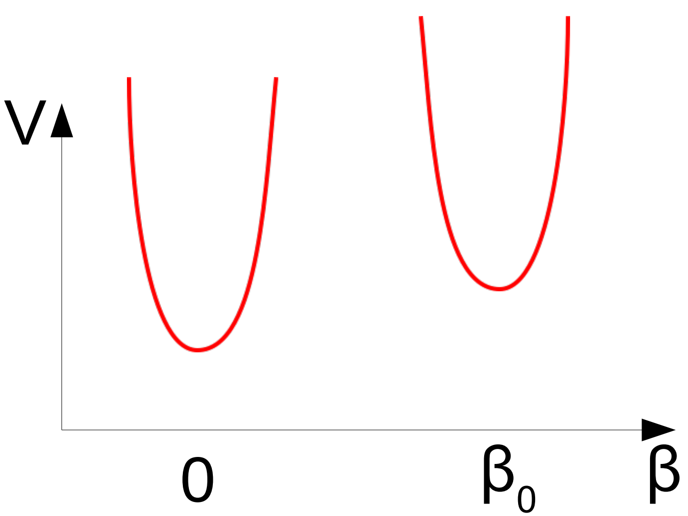

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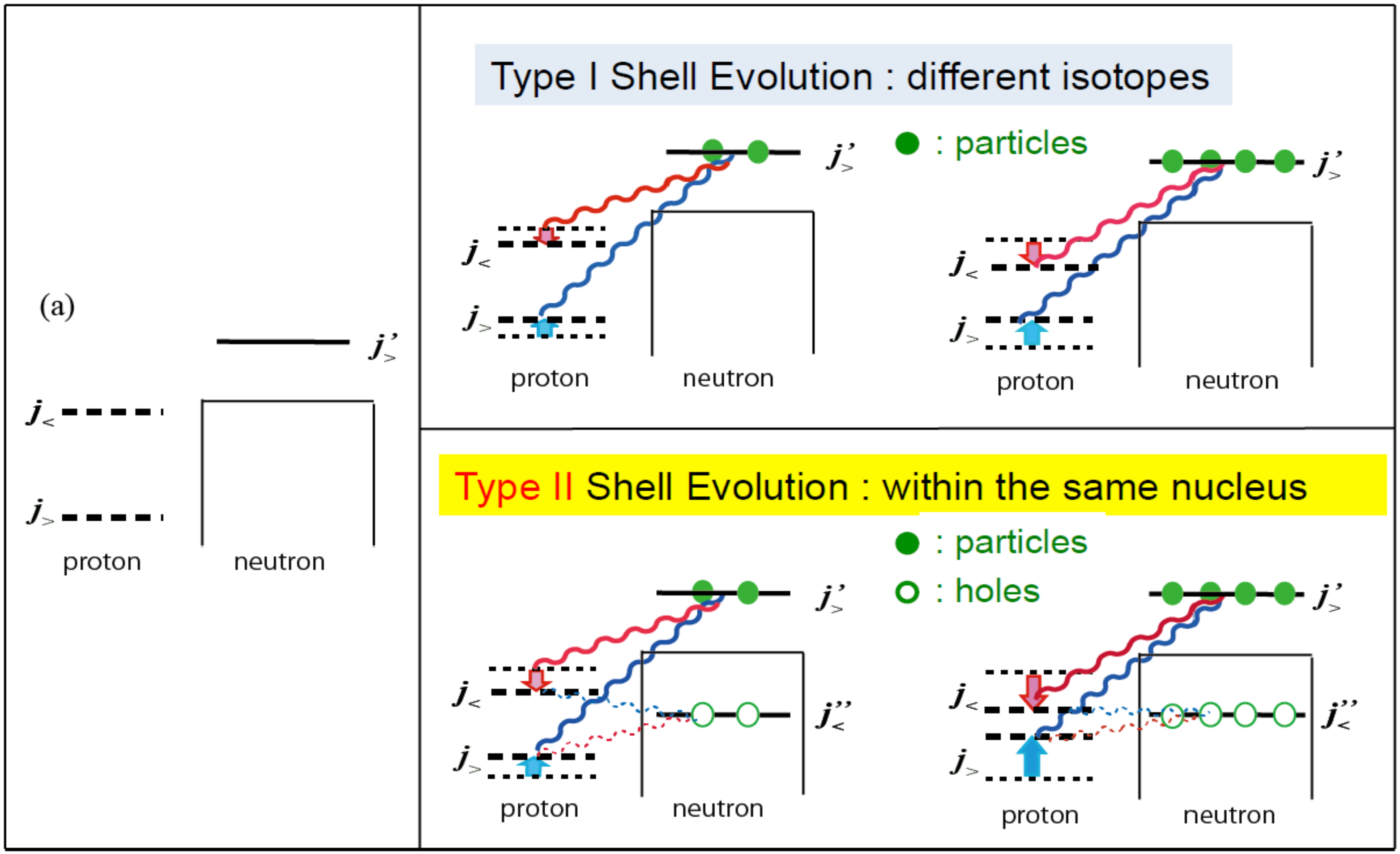
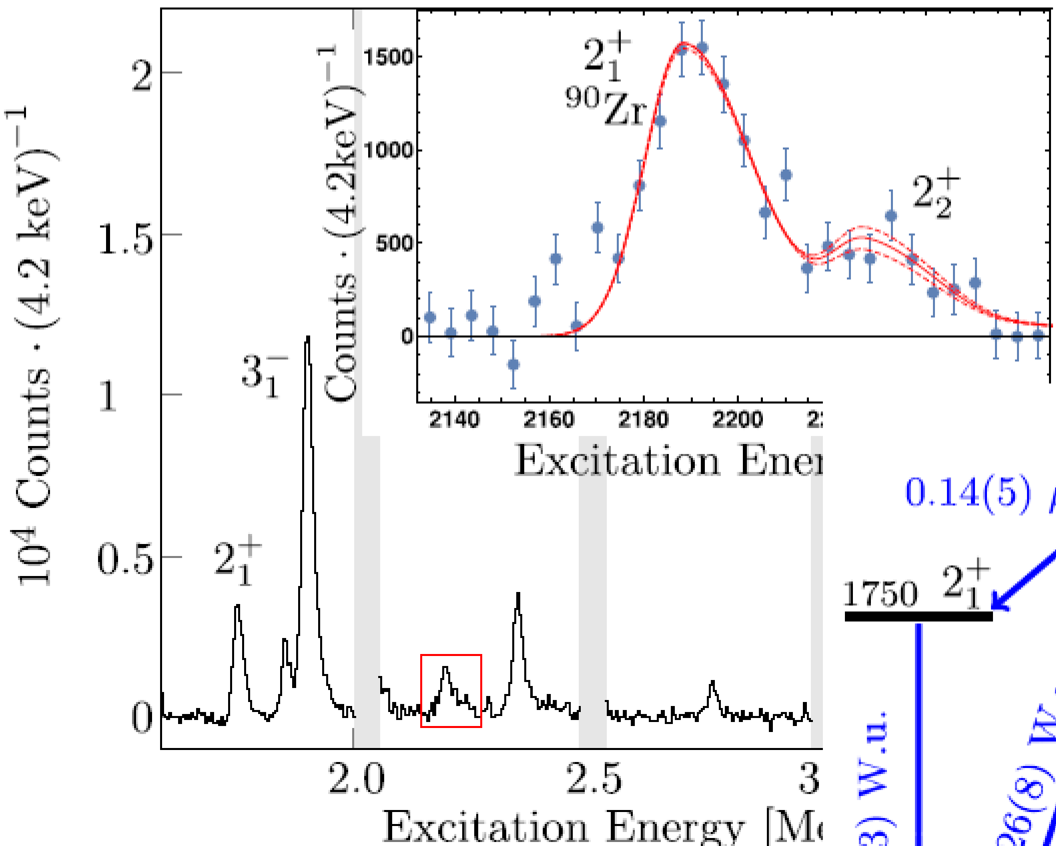
Type II Shell Evolution



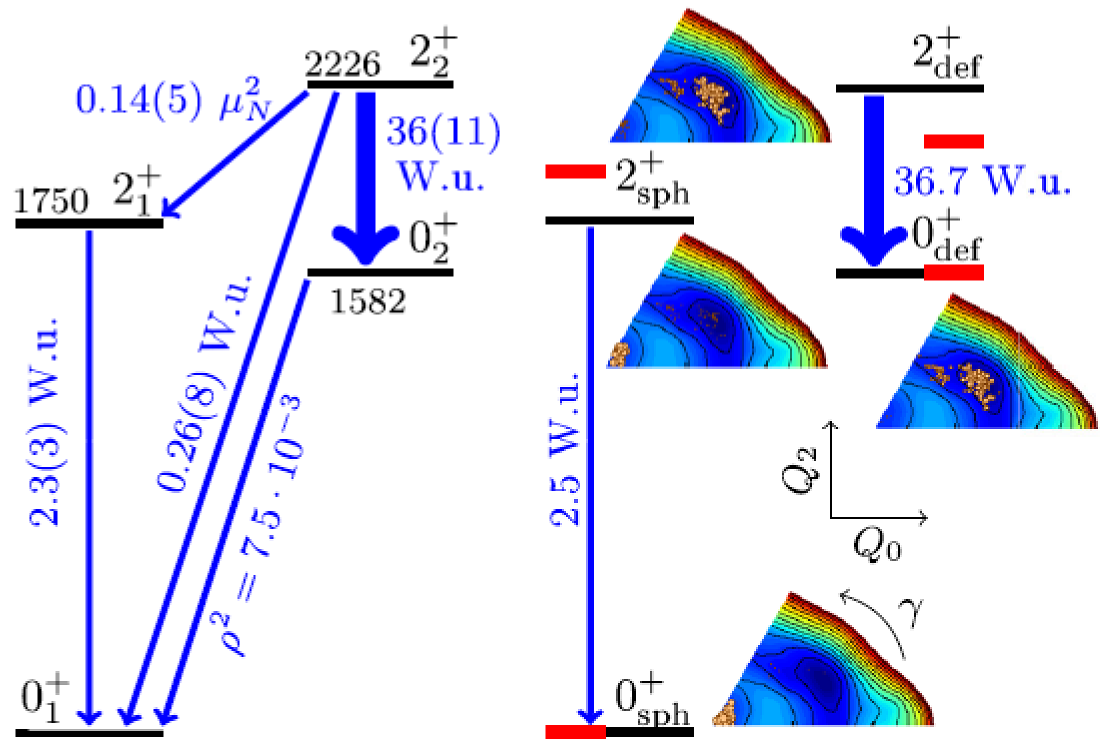
Togashi et al., Phys. Rev. Lett. 117, 172502 (2016)

^{96}Zr – Type II Shell Evolution



Electron Scattering at the S-DALINAC

C. Kremer, PRL 117, 172503 (2016)



Well-separated spherical and Deformed minima
=> weakly mixing structures

Zr Isotopes: Systematics

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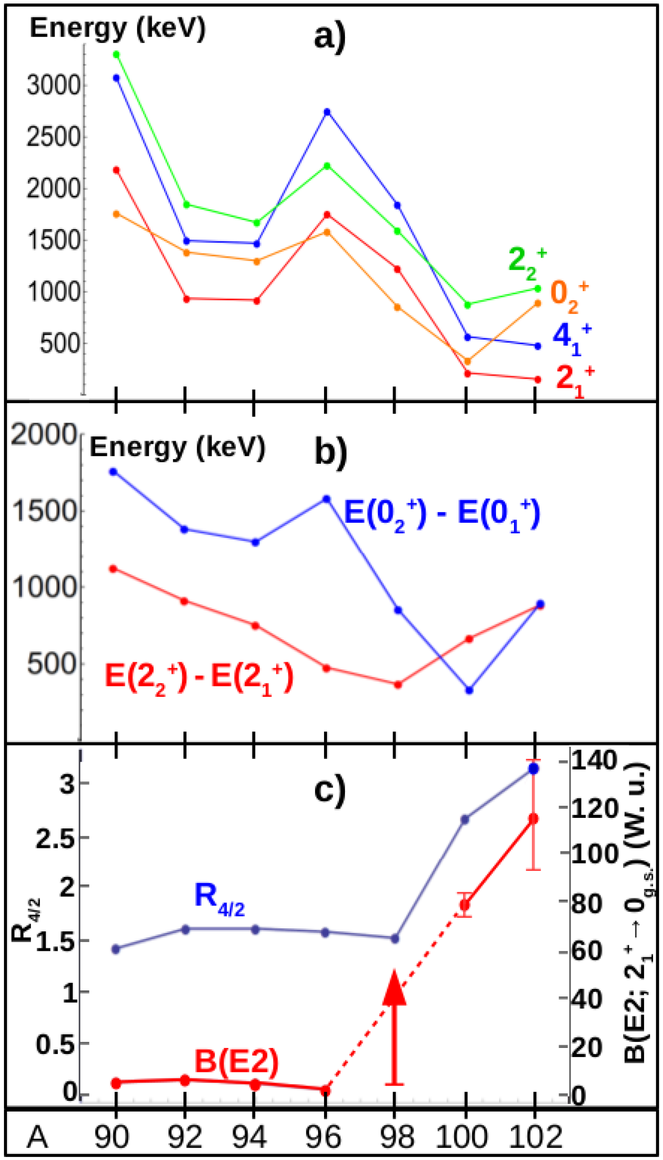


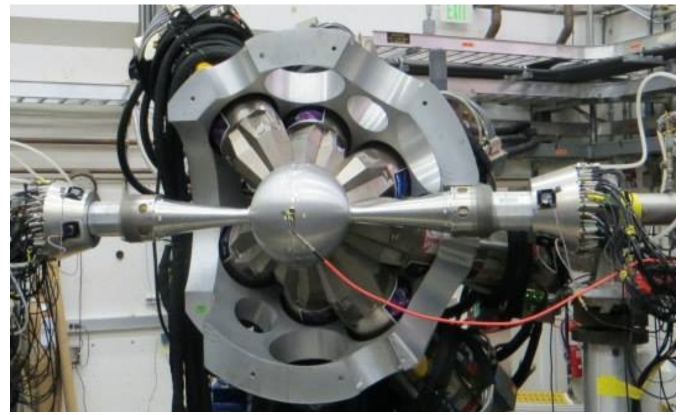
- $d_{5/2}$ neutron sub-shell closed at A=96 → sphericity
- strong ground-state deformation from A=100
- deformed excited structure known at A=94,96

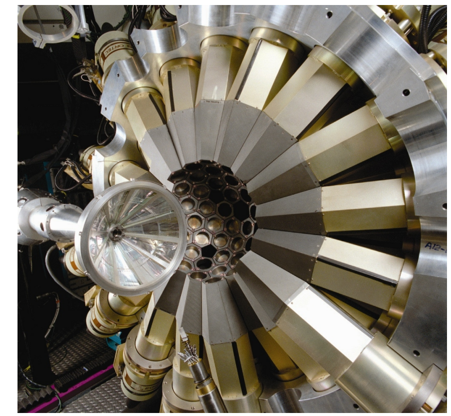
- $0_{1,2}^+$ states closest at A=100 → crossing of structures
- $2_{1,2}^+$ states may cross earlier at A=98

- B(E2) excitation strength at A=98 characterizes 2_1^+ collectivity
- only known with (meaning-less) lower limit

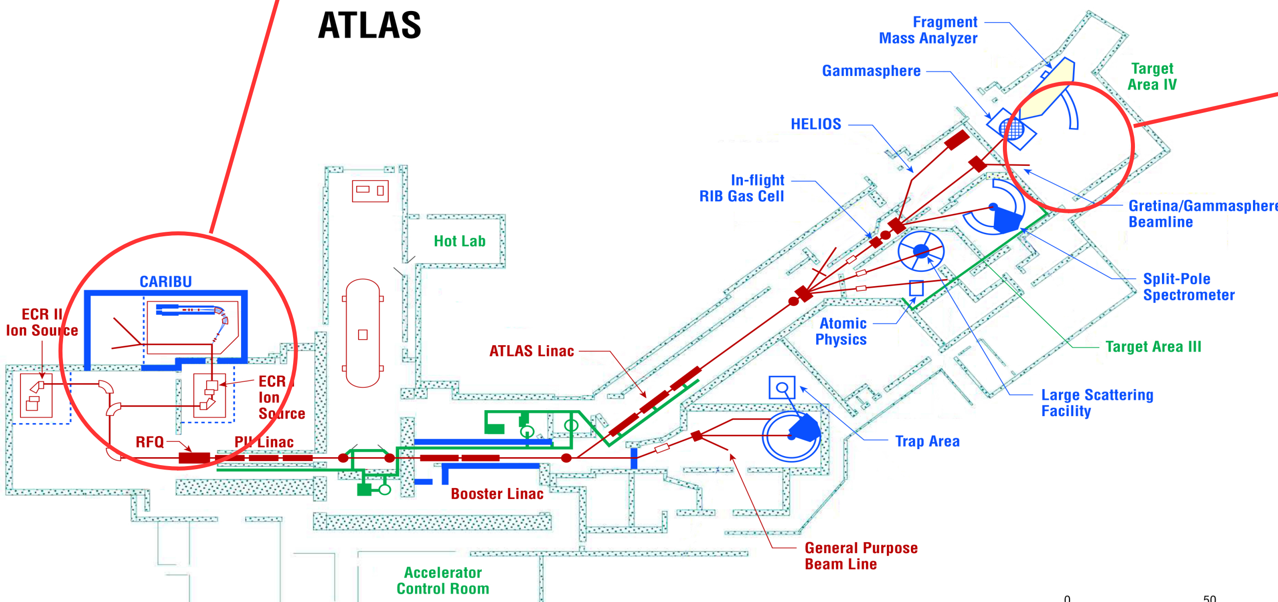
Coulex Experiment

- ^{252}Cf fission source
- Gas catcher
- ECR charge breeder





ATLAS



Figures from www.phy.anl.gov

Argonne NATIONAL LABORATORY

GRETINA & CHICO2
(ε_γ = 6.5%, ΔE/E ~ 1%, Δθ ~ 1°)

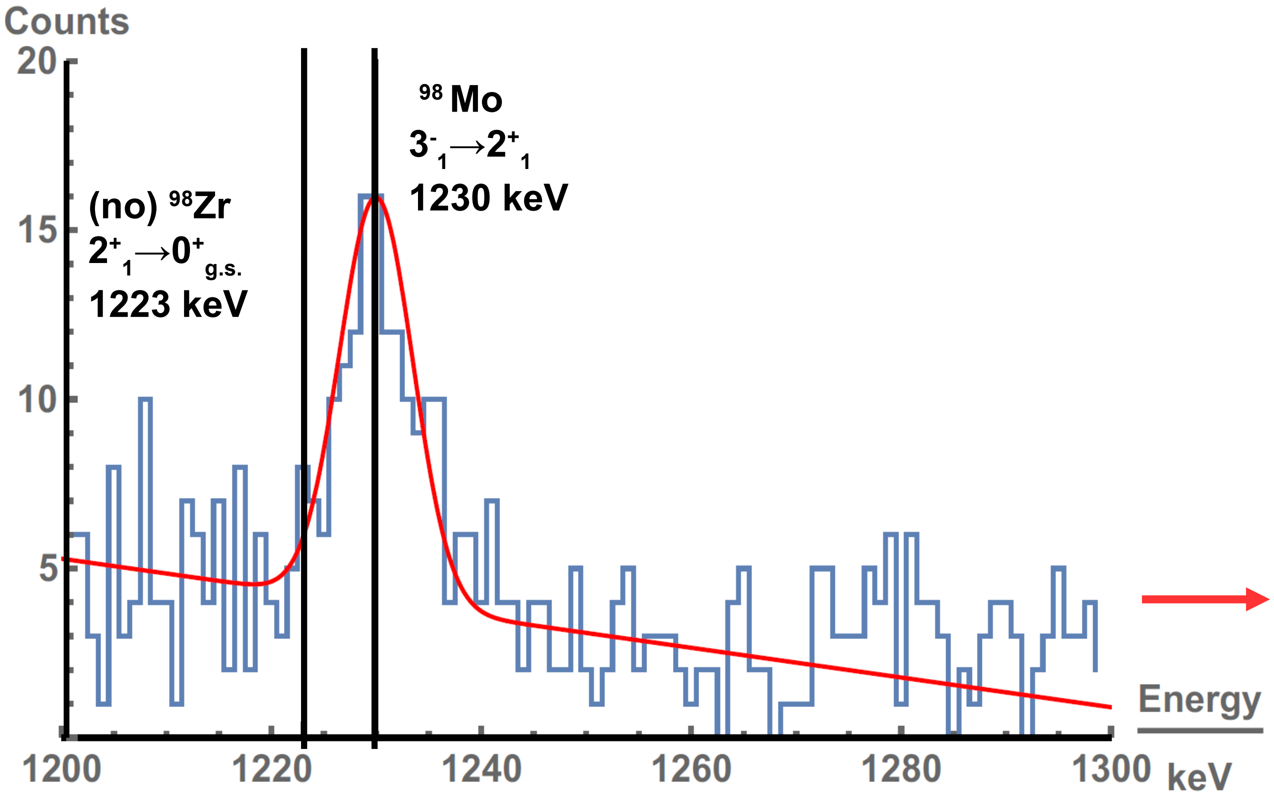
GRETINA:
Highly-segmented HPGe for good Doppler correction (like AGATA in Europe)

CHICO2: PPAC chamber for particle-track reconstruction

Analysis → little ^{98}Zr in-beam

- Reaction partner selection in CHICO2
- Doppler-correction using CHICO2 & GRETINA

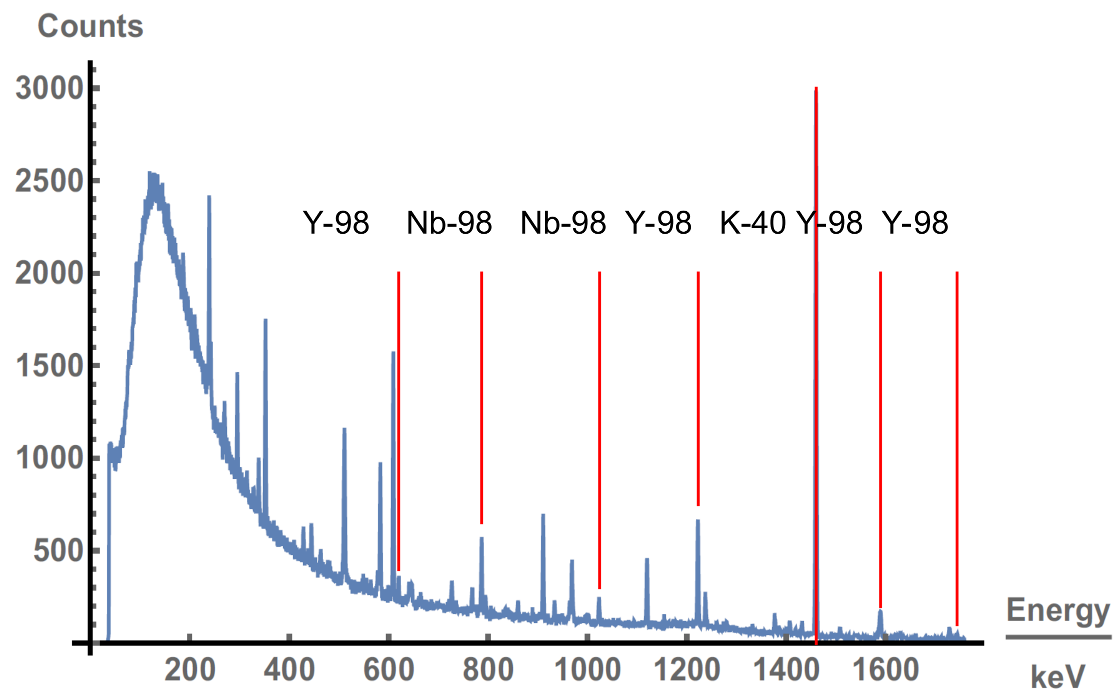
Beam dominated by ^{98}Mo

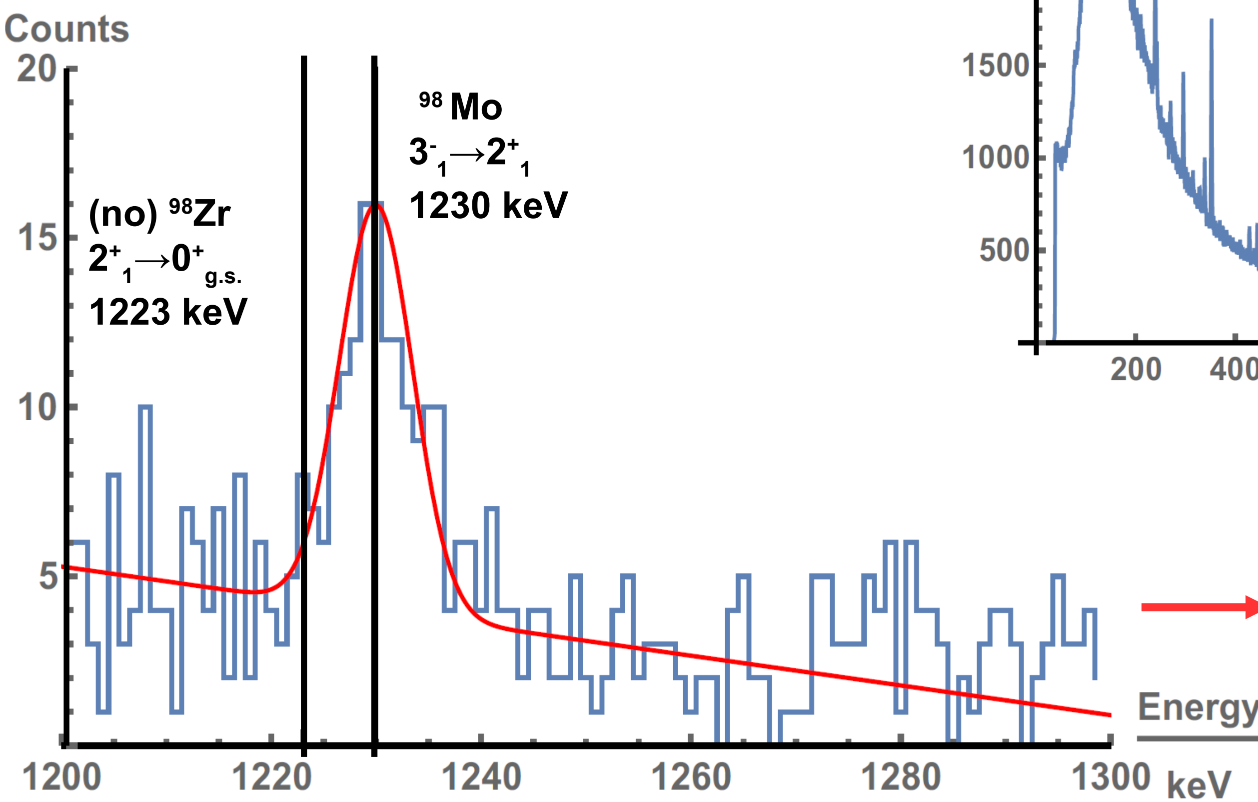


→ ***No*** ^{98}Zr $2^+_1 \rightarrow 0^+_{g.s.}$ – transition observed

Analysis → little ^{98}Zr in-beam

- **Beam composition analysis at beam dump !**

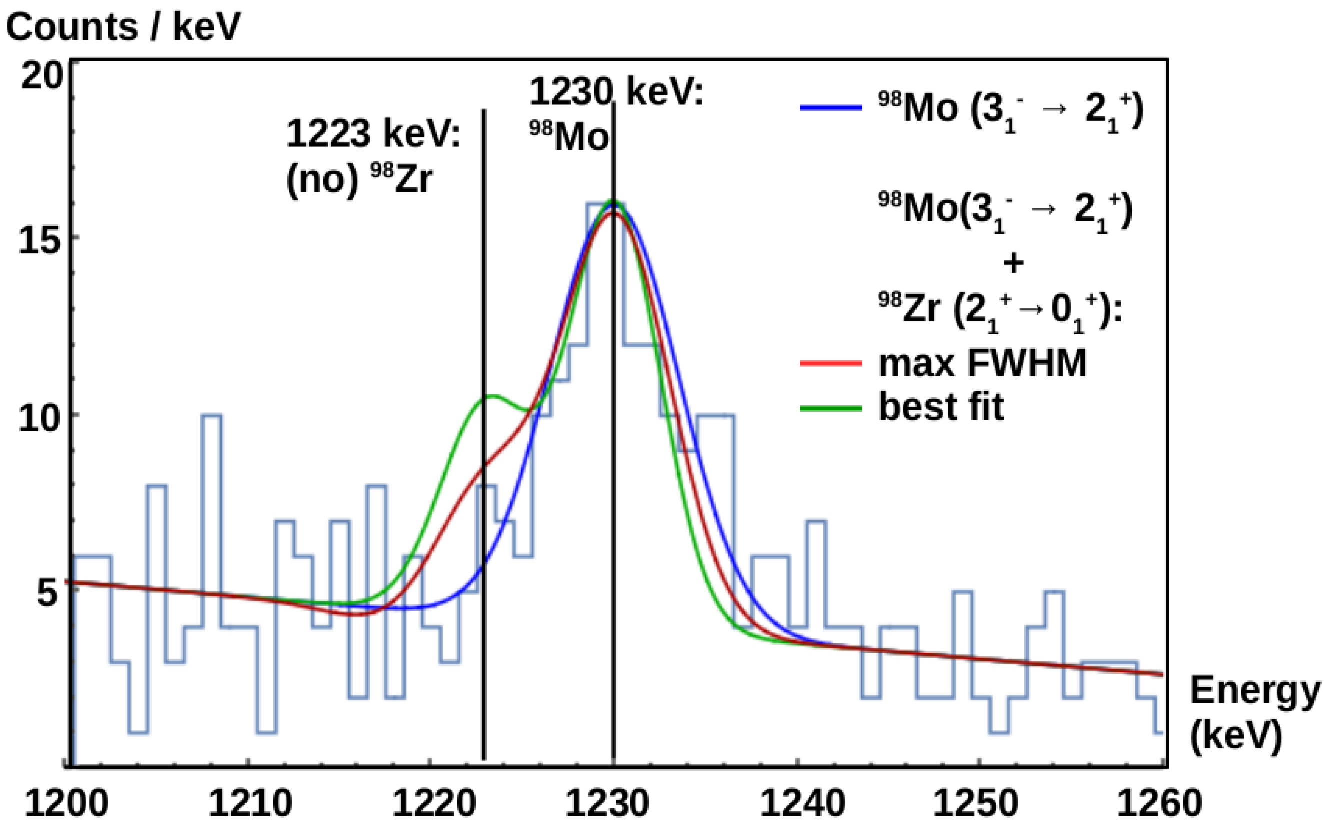




→ ***No***
^{98}Zr $2^+_1 \to 0^+_{g.s.}$ – transition observed

New Stringent B(E2) Limits

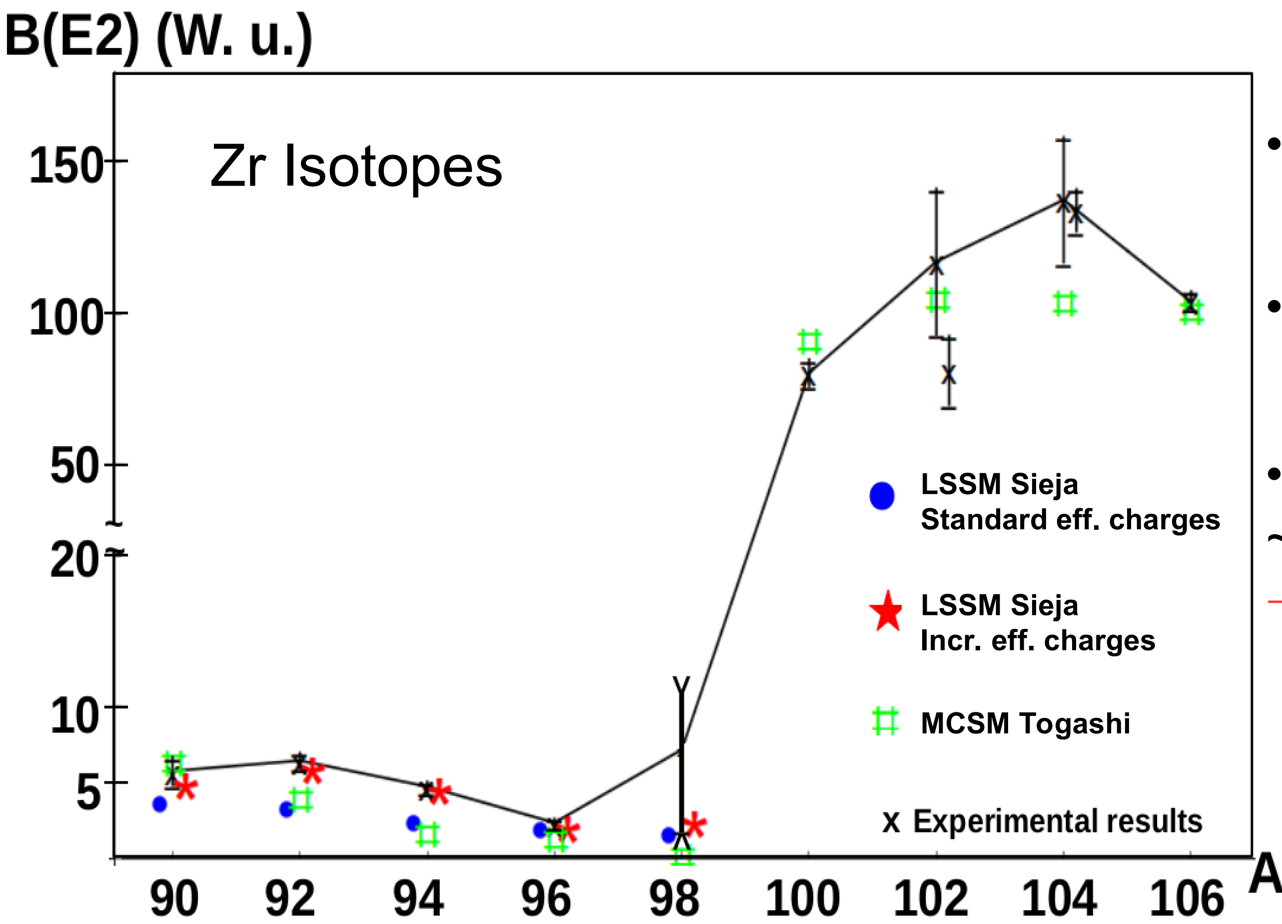
- Stopped Beam Analysis →152(64) pps ^{98}Zr in beam
- Transition would have been observed with >40 counts in peak
- Coulomb-excitation calculations used to translate into B(E2) limit



→ B(E2) < 11 W.u.

11 W.u. > $B_{Zr\text{-}98}(E2; 2^+_1 \text{->} 0^+_{g.s.})$ > 0.7 W.u. (Ansari et al, 2017)

Ground state still near-spherical



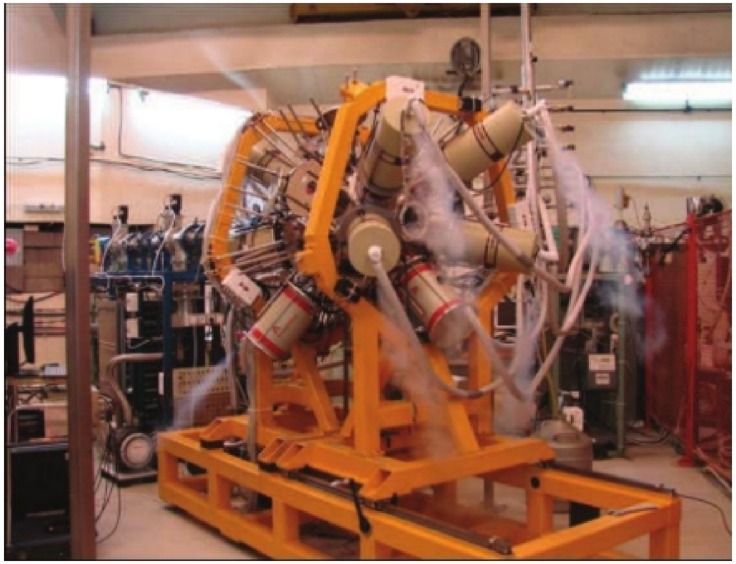
- Little collectivity in ground state (like in $^{94,96}Zr$)
- Agreement with Togashi et al. (PRL 117, 2016)
- $B(E2; 2_1^+ \rightarrow 0_2^+)$

~ magnitude higher

$\rightarrow 2_1^+$ coll. exc. on 0_2^+

W. Witt, V.W. et al., PRC 98, 041302(R) (2018)

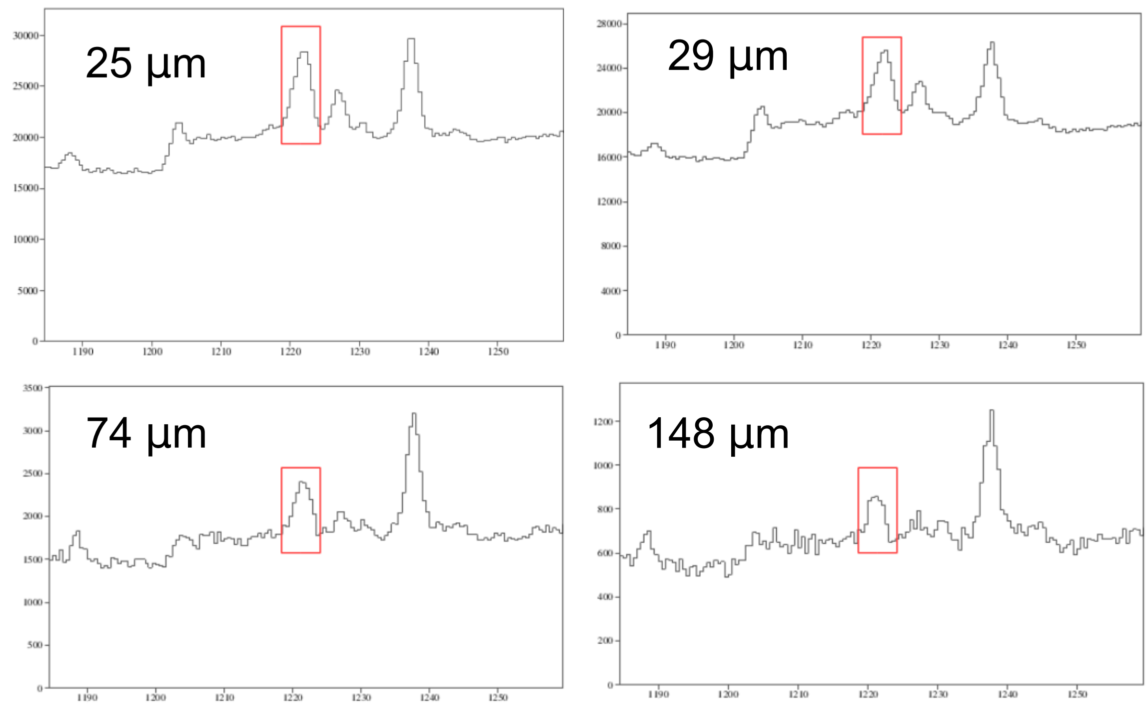
RDDS at IFIN-HH / ROSPHERE



^{18}O (^{96}Zr,^{98}Zr) ^{16}O

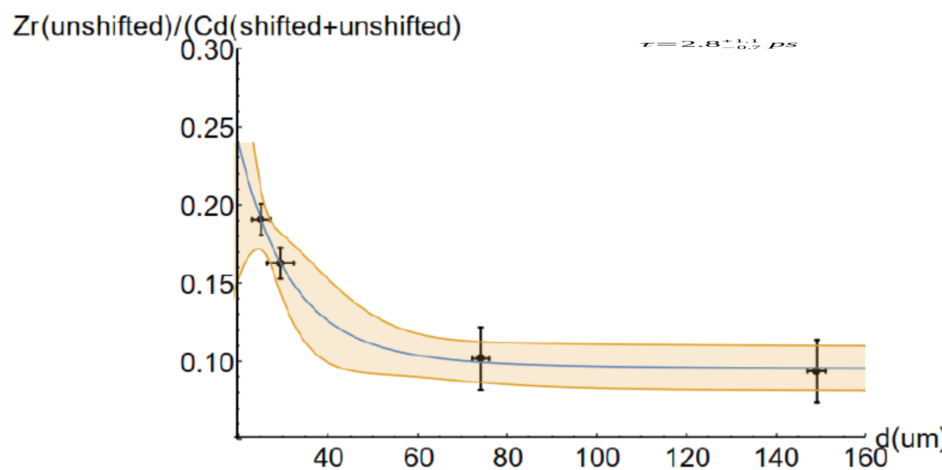
- Target: 0.8 mg/cm^2 ^{96}Zr (57.4%)
- Stopper: ~10 mg/cm^2 Au
- (additional 9.2 mg/cm^2 ^{96}Zr target for DSAM / level scheme)
- Cologne-type Plunger device
- Tandem accelerator: ^{18}O beam @ 49 MeV
- Strongest channels from fusion evaporation (e.g. ^{110}Cd) – with known lifetimes aid to fix τ-curve
- 2n – transfer: ~60 mb

Lifetime Curve 2_1^+, ^{98}Zr

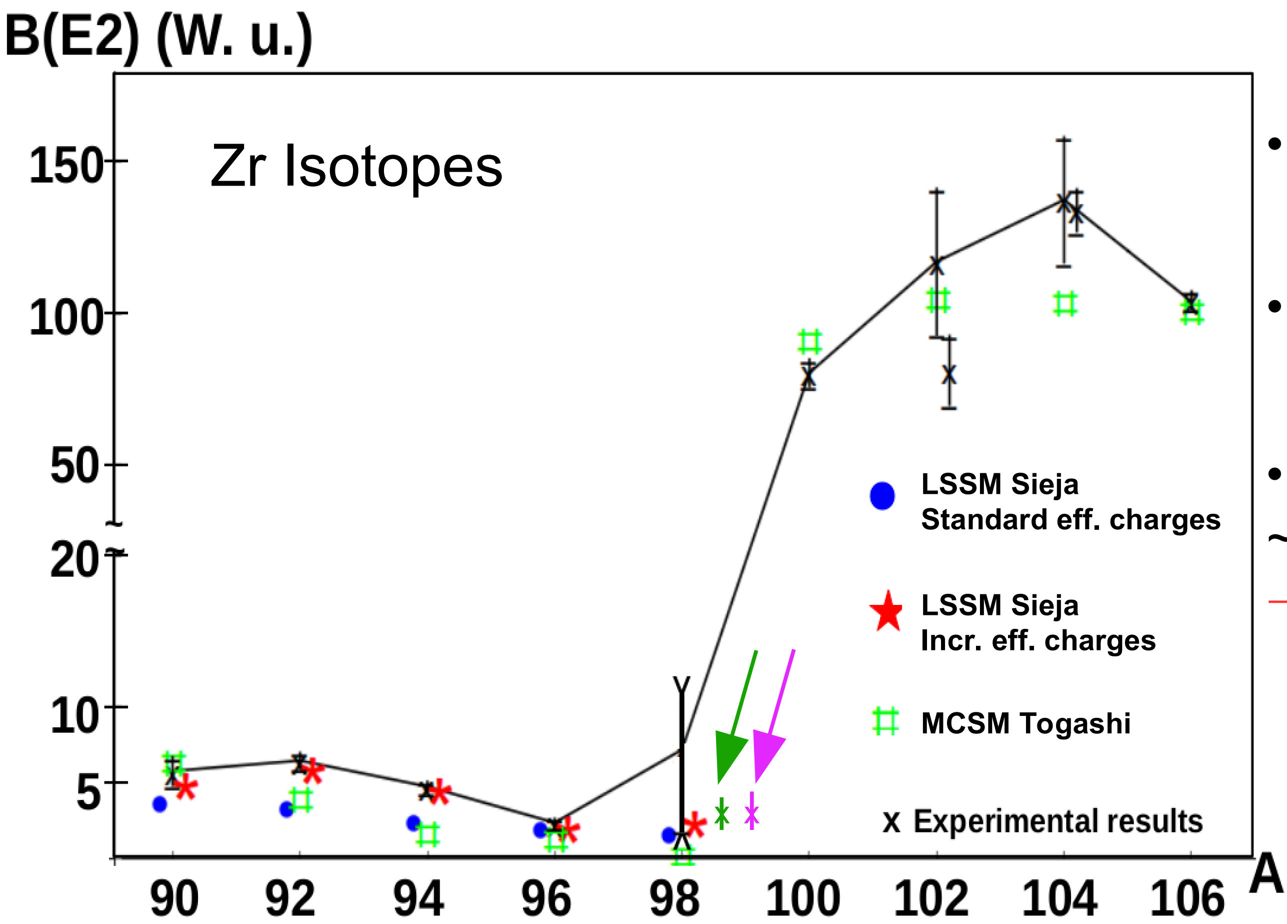


- v_{recoil} calculated 0.5-1 %
- verified from coinc. data summed over all distances
- Statistitics too low to disentangle shifted peak from bg
- Singles-analysis, stop peak only

- feeding from observed states subtracted
- feeder lifetimes (limits) known
  → feeding uncertainties excluded



2_1^+ B(E2) Fixed !



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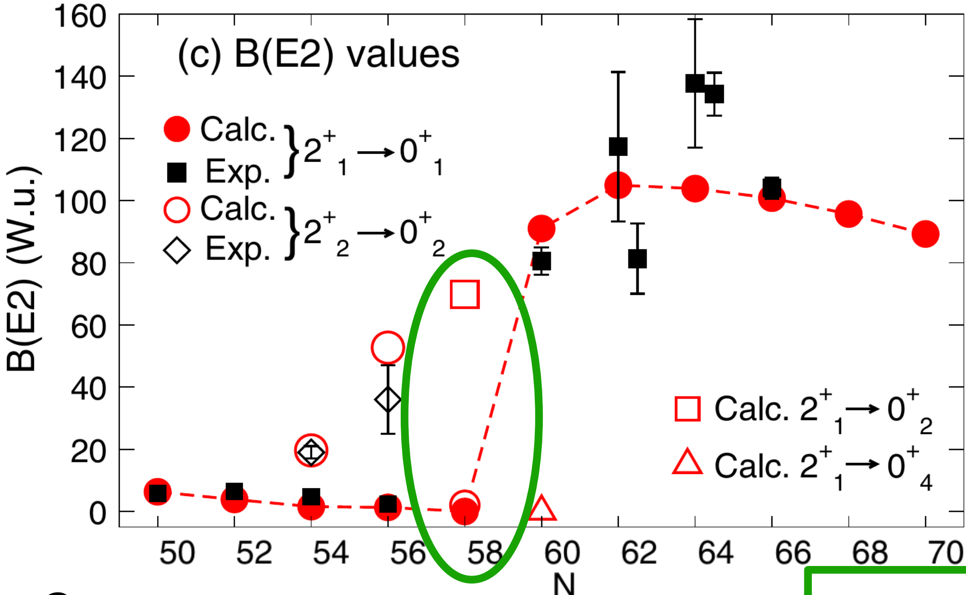
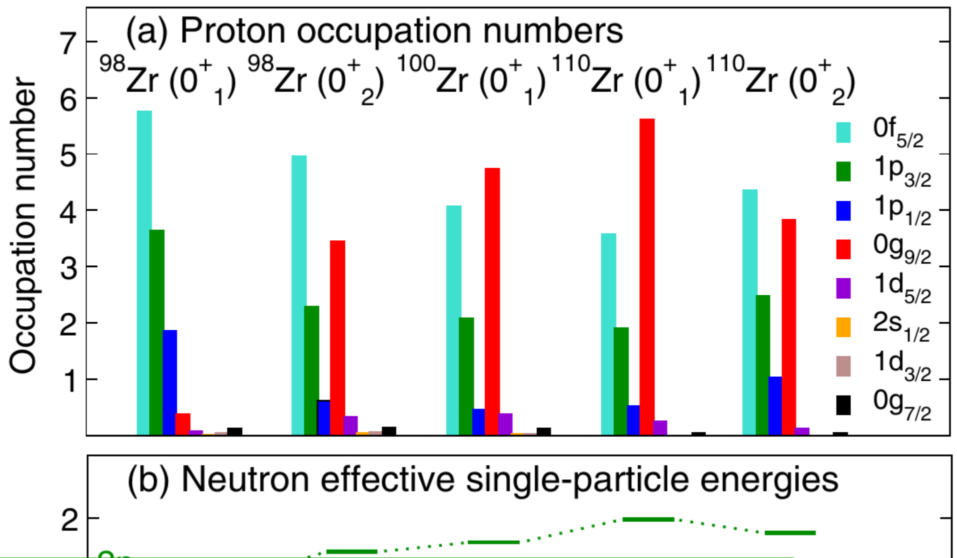
W. Witt, V.W. et al., PRC 98, 041302(R) (2018)
P. Singh et al., PRL 121, 192501 (2018)
W. Witt, V.W. et al., *in preparation*

MCSM Wave Functions

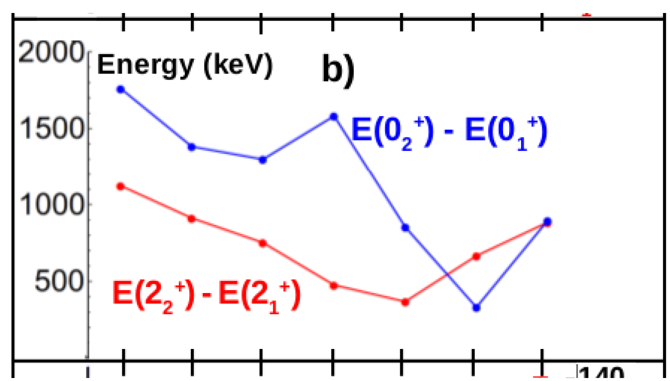




Consequences:

- Spherical ground state and more collective excited 0^+ state in ^{98}Zr
- 2_1^+ in ^{98}Zr: built on collective 0^+ !

  → 2^+ sph./coll. Swap before 0^+'s



(2016)

change

SPE

MCSM Wave Functions

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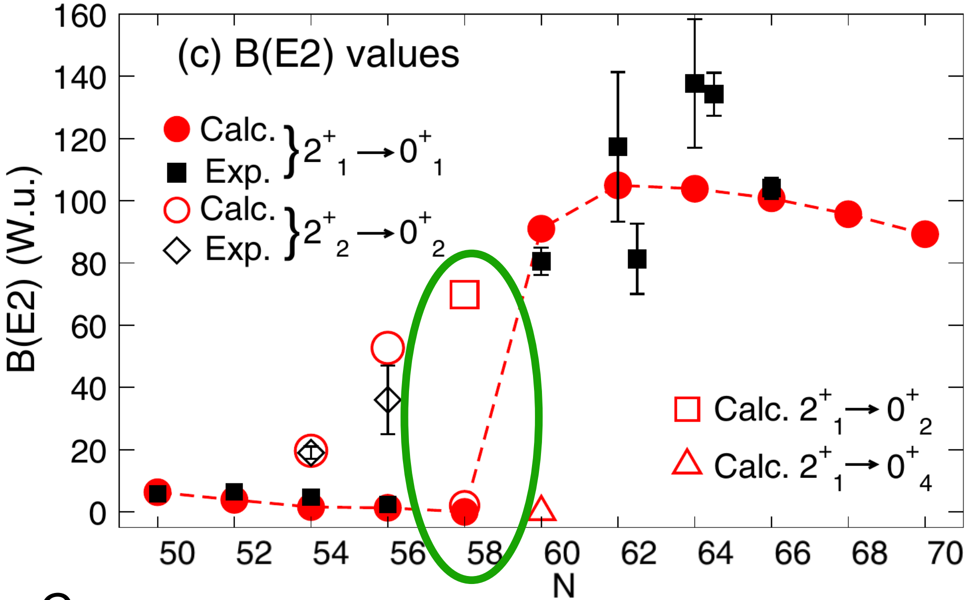

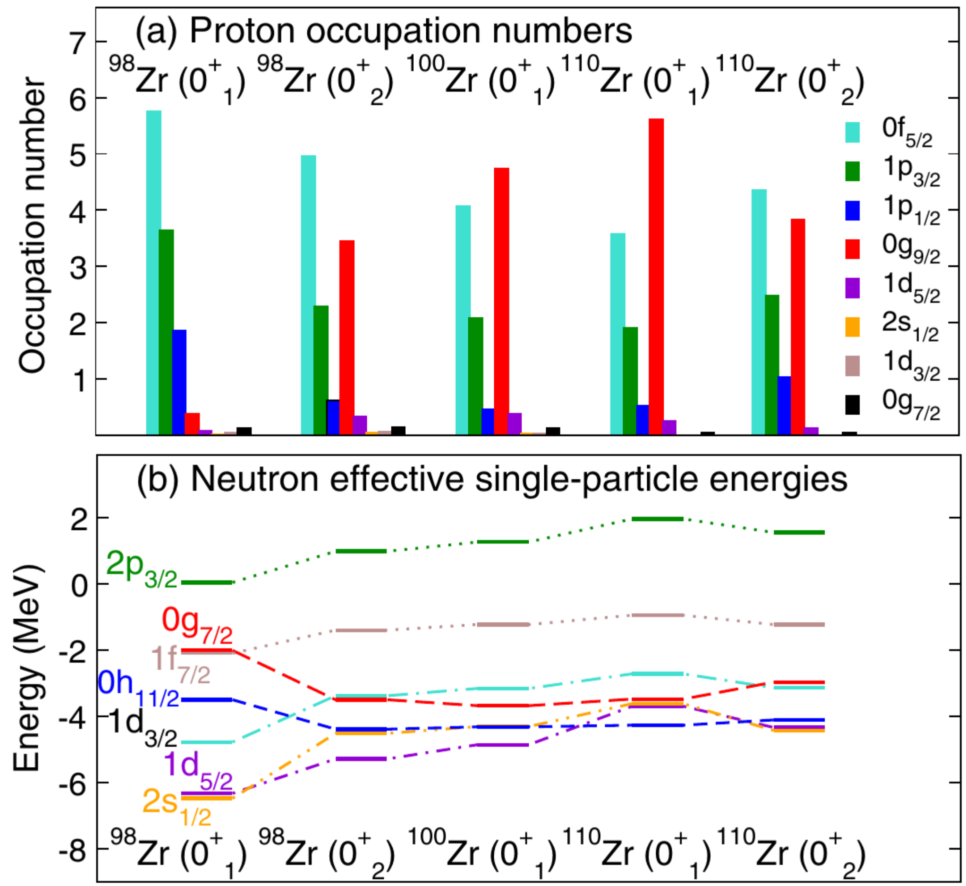

Togashi, PRL 117, 172502 (2016)

Consequences:

- Spherical ground state and more collective excited 0^+ state in ^{98}Zr
- 2_1^+ in ^{98}Zr: built on collective 0^+ !

  → 2^+ sph./coll. Swap before 0^+'s
- **Is 2_2^+ the spherical state?**
- Switch-over in ^{100}Zr: deformed becomes ground state
- Where does the spherical 0^+ go?

- Occupation numbers and ESPE change
- More protons in $g_{9/2}$

  → bunched neutron SPE

New Interpretation of Zr Quantum Phase Transition(s)

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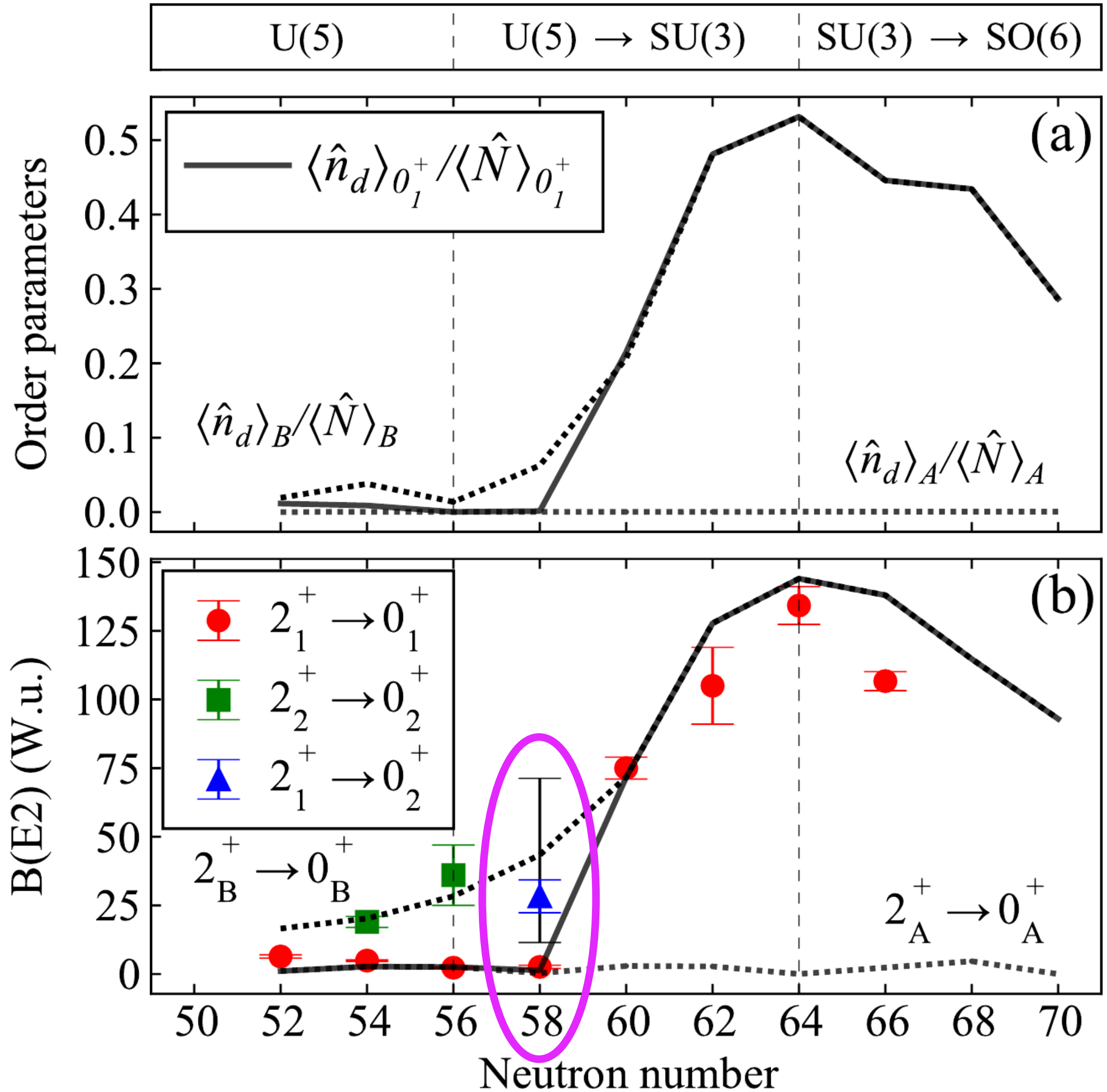
N. Gavrielov, A. Leviatan, F. Iachello, arXiv:1904.09919v1 [nucl-th] 22 Apr 2019

- Two configurations:
  - A: spherical, "normal"
  - B: deformed, "intruder"

- At N=60: A and B switch
  → onset of g.s. deformation
  → 1st order type II QPT



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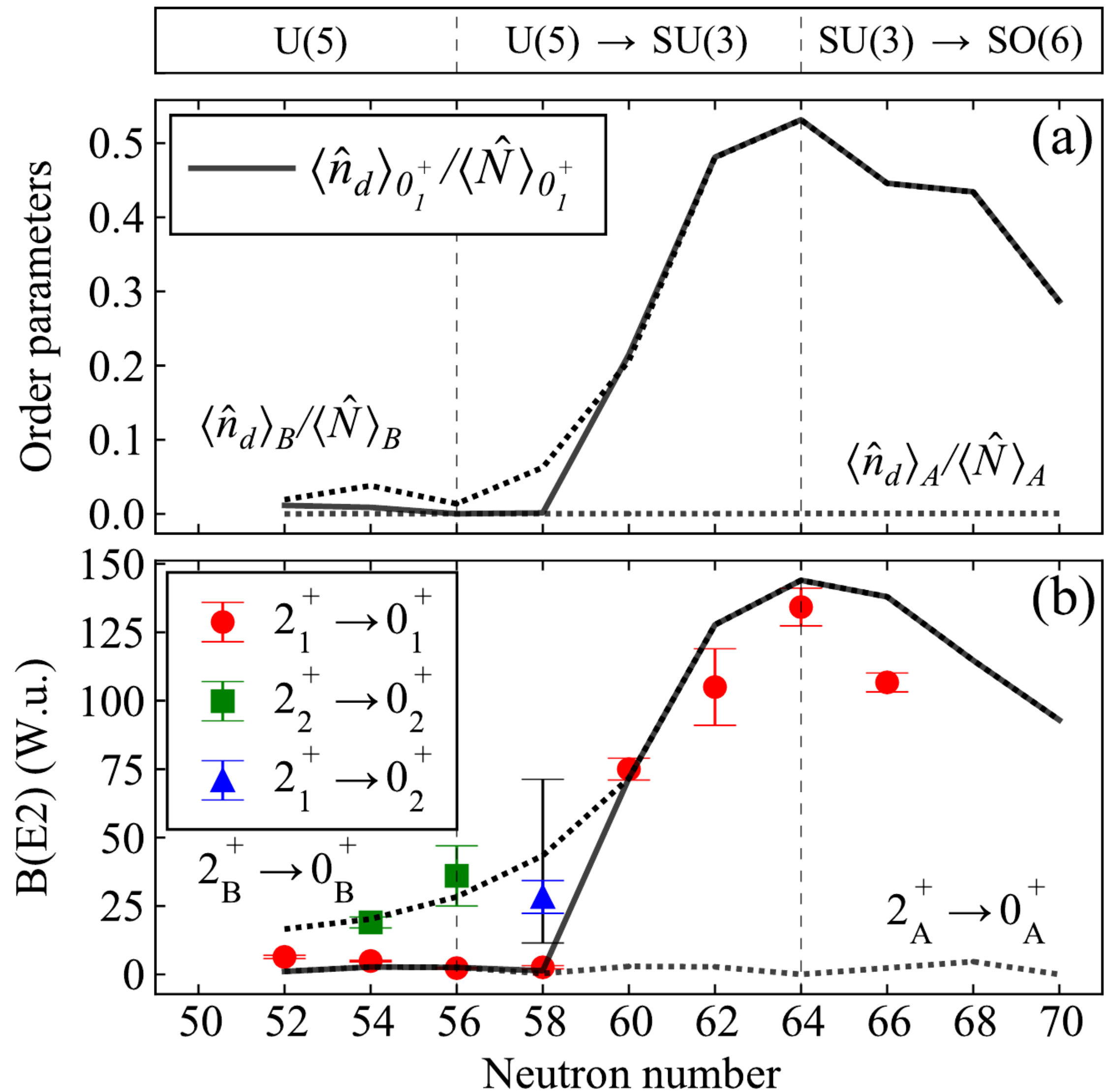
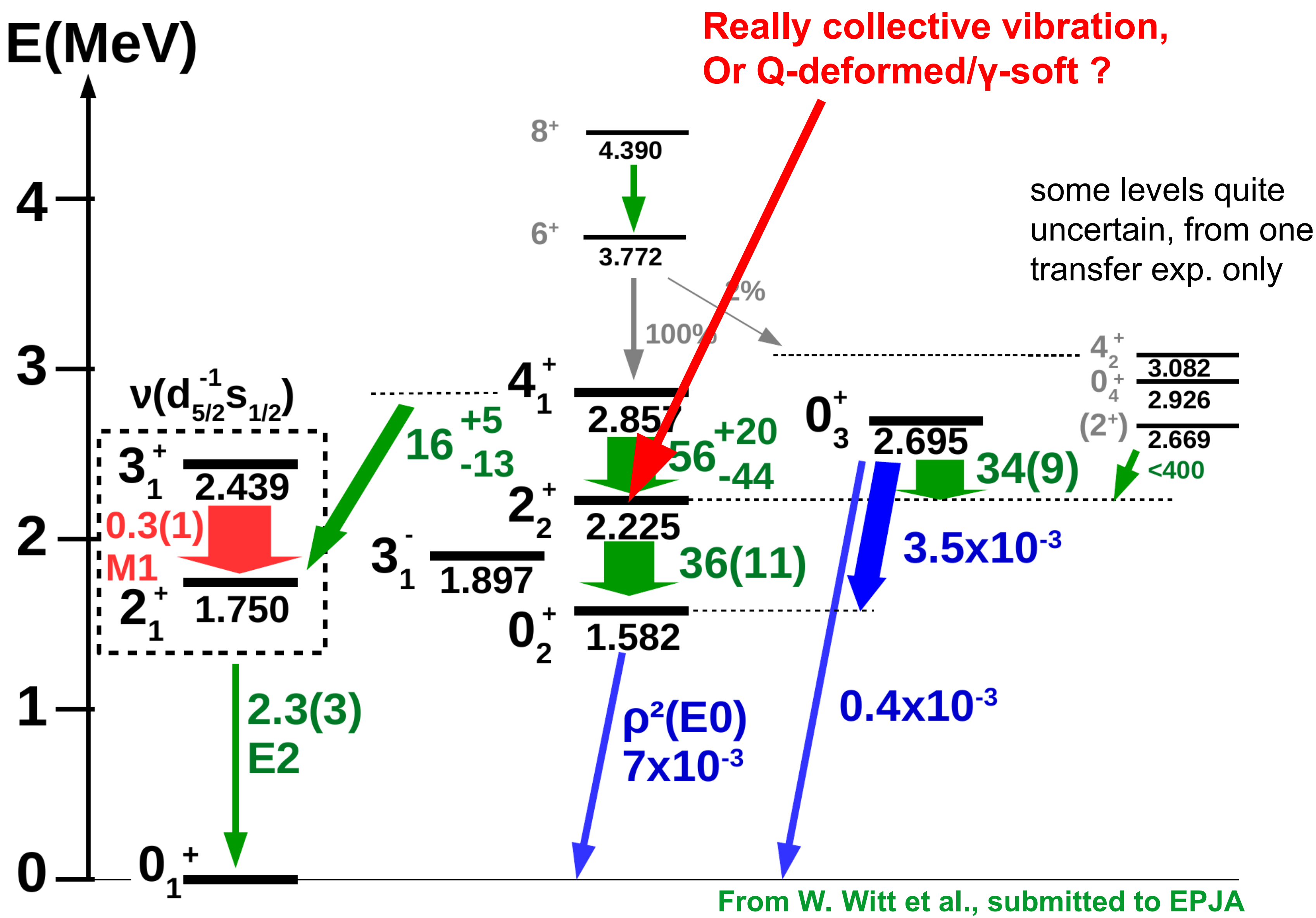
- Two configurations:
  - A: spherical, “normal”
  - B: deformed, “intruder”
- At N=60: A and B switch
  → onset of g.s. deformation
  → 1^{st} order type II QPT
- B dominates g.s. for N>58
- B is a collective vibration [U(5)] up to N=58
- Simultaneously, B undergoes change to SU(3)
  → 1^{st} order type I QPT
- **What happens to A at N>58, 2_2^+?**
  how certain are we at N=56?



“doubly-magic” ^{96}Zr



Summary

- 2_1^+ B(E2) in ^{98}Zr measured to good accuracy
  → ^{98}Zr is still sph./non-collective in its g.s.
  → 2_1^+ is a collective excitation on the "intruder" 0^+
- Type II shape evolution of Togashi/Otsuka confirmed
- Data support interpretation of intertwined QPT
  - 1st order type II (swap of sph./coll. Structures)
  - 1st order type I (sph.→def. Evolution of intruder structure)
- Data base needs to be solidified
  - Structures on ground- and excited bands
    - Need more precise B(E2)s
    - Need Q-moments

Thank you !

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Collaboration:

W. Witt, N. Pietralla, T. Beck
for the local analyses and discussion

M. Carpenter, G. Savard, D. Cline, R.V.F. Janssens, C.-Y. Wu, S. Zhu
for CoulEx @ ATLAS / CARIBU / GRETINA / CHICO2

N. Marginean, C. Mihai, S. Pascu, and the IFIN-HH Team
for RDDS @ IFIN Tandem

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