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**

**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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Type II Shell Evolution

$^{96}$Zr – Type II Shell Evolution

Electron Scattering at the S-DALINAC

C. Kremer, PRL 117, 172503 (2016)

Well-separated spherical and deformed minima
$\Rightarrow$ weakly mixing structures
Zr Isotopes: Systematics

- $d_{5/2}$ neutron sub-shell closed at $A=96 \rightarrow$ sphericity
- strong ground-state deformation from $A=100$
- deformed excited structure known at $A=94,96$
- $0_{1,2}^+$ states closest at $A=100 \rightarrow$ 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

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**GRETINA & CHICO2**

$(\epsilon_\gamma = 6.5\%, \Delta E/E \sim 1\%, \Delta \theta \sim 1^\circ)$

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

**CHICO2:**
PPAC chamber for particle-track reconstruction

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Figures from www.phy.anl.gov
Analysis → little $^{98}$Zr in-beam

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

Beam dominated by $^{98}$Mo

$^{98}$Zr $2^+_1 \rightarrow 0^+_\text{g.s.}$ – transition observed

$^{98}$Mo $3^+_1 \rightarrow 2^+_1$

1230 keV

1223 keV
Analysis → little $^{98}$Zr in-beam

- Beam composition analysis at beam dump!

\[
\text{(no) } ^{98}\text{Zr } 2^+_1 \rightarrow 0^+_{\text{g.s.}} \\
\text{1223 keV}
\]

\[
^{98}\text{Mo } 3^-_1 \rightarrow 2^+_1 \\
\text{1230 keV}
\]

\[
\text{No} \\
^{98}\text{Zr } 2^+_1 \rightarrow 0^+_{\text{g.s.}} \text{ – transition observed}
\]
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

$B(E2) < 11 \text{ W.u.}$

$11 \text{ W.u.} > B_{Zr-98}(E2; 2^+_1 \rightarrow 0^+_{\text{g.s.}}) > 0.7 \text{ W.u.}$ (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 $\tau$-curve
- 2n – transfer: ~60 mb
**Lifetime Curve \( \frac{2_{1}^{+}}{98\text{Zr}} \)**

- Feeding from observed states subtracted
- Feeder lifetimes (limits) known → feeding uncertainties excluded
- \( v_{\text{recoil}} \) calculated 0.5-1 %
- Verified from coinc. data summed over all distances
- Statistics too low to disentangle shifted peak from bg
- Singles-analysis, stop peak only

\( \tau = 2.8 - 0.7 + 1.1 \, \text{ps} \)
$2_{1}^{+}$ B(E2) Fixed!

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- 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)
P. Singh et al., PRL 121, 192501 (2018)
W. Witt, V.W. et al., in preparation
Consequences:

- Spherical ground state and more collective excited $0^+$ state in $^{98}$Zr
- $2_1^+$ in $^{98}$Zr: built on collective $0^+$! $\rightarrow 2^+$ sph./coll. Swap before $0^+$'s
Consequences:

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

MCSM Wave Functions

- Occupation numbers and ESPE change
- More protons in $g_{9/2}$ $\rightarrow$ bunched neutron SPE
New Interpretation of Zr Quantum Phase Transition(s)


- 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

![Graphs and data](image_url)
New Interpretation of Zr Quantum Phase Transition(s)


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- 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)
  → 1st order type I QPT

- What happens to A at N>58, 2_2^+?
  how certain are we at N=56?
"doubly-magic" $^{96}\text{Zr}$

From W. Witt et al., submitted to EPJA

Really collective vibration, Or Q-deformed/γ-soft?

some levels quite uncertain, from one transfer exp. only

From W. Witt et al., submitted to EPJA

Volker Werner | TU Darmstadt | AG Pietralla | NSD 2019, Venice | 16 May 2019 | Shape transitions between and within Zr isotopes
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
  - $1^{\text{st}}$ order type II (swap of sph./coll. Structures)
  - $1^{\text{st}}$ order type I (sph.$\rightarrow$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!

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