Overview

- Shape (Phase) Transitions ...
- ... and Coexistence
- Spherical and Deformed Shape in Zr Isotopes
  - G.S. Collectivity in the transitional $^{98}$Zr
  - Experiment: GRETINA & CHICO2 @ ATLAS / CARIBU
  - New, more stringent Limits on B(E2)
Shape (Phase) Transitions

Shape Transition 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 with Weak Mixing / High Barrier

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

A. Leviathan, PRC 74 (2006)
Type II Shell Evolution

**E(2⁺₁) Systematics at N=56-60**

Weak coupling (p-n) was shown for Z~40, N<56 in prev. works

Assume it here -> E(2⁺₁) depends mainly on SPEs

![Graph showing systematics for E(2⁺₁) at N=56-60](image)

**Ru:** smooth drop

**Mo:** small peak at 56, moderate drop

**Zr:** clear peak at N=56,58 in Zr

**Sr:** „peak“ N=56, drop past 58

**Kr:** small peak at 56, smooth after

For Z>40 νg⁷/₂ fills and is lowered because of πg⁹/₂ -> gaps disappear
$^{96}\text{Zr}$ – Type II Shell Evolution

Electron Scattering at the S-DALINAC

C. Kremer, PRL 117, 172503 (2016)
96Zr – 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
Shape Transition in Zr Isotopes

- Closed $d_{5/2}$-shell in $^{96}$Zr $\rightarrow$ Spherical ground state
- Deformation in $^{100}$Zr $\rightarrow$ Deformed ground state
Shape Transition in Zr Isotopes

- Closed $d_{5/2}$-shell in $^{96}\text{Zr} \rightarrow$ Spherical ground state
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$R_{4/2} = \frac{E(4^+_1)}{E(2^-_1)}$

$\text{B(E2)} > 0.7 \text{ W. u.}$

(Betterman et al., 2010)
Coulex Experiment

Figure from www.phy.anl.gov
Coulex Experiment

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

GRETINA & CHICO2
($\varepsilon_\gamma = 6.5\%, \Delta E/E \sim 1\%, \Delta \theta \sim 1^\circ$)

Figures from www.phy.anl.gov
Kinematics Reconstruction

- CoulEx of P/T
- Detection of Ejectiles (P/T) with CHICO2
- Calculate γ-angle θ & velocity β
- Correct for Doppler-shift in energy: 
  \[ E' \approx E \left(1 + \beta \right) \cos(\theta) \]

→ use of CHICO2 for Doppler-correction & safe CoulEx
Spectra

Uncorrected Target-CoulEx

$^{98}\text{Mo}$ $2^+_1 \rightarrow 0^+_\text{g.s.}$

Doppler-Correction for $A=98$

Beam dominated by $^{98}\text{Mo}$
Analysis $\rightarrow$ no $^{98}$Zr in-beam

- Beam composition analysis
- Calibration with standard sources
- Reaction partner selection
- Doppler-correction using CHICO2

$(\text{no})^{98}$Zr

$2^+_1 \rightarrow 0^+_{\text{g.s.}}$

1223 keV

$^{98}$Mo

$3^-_1 \rightarrow 2^+_1$

1230 keV

$^{98}$Zr $2^+_1 \rightarrow 0^+_{\text{g.s.}}$ – transition observed
Analysis → no $^{98}$Zr in-beam

- Beam composition analysis
- Calibration with standard sources
- Reaction partner selection
- Doppler-correction using CHICO2

But we know beam composition

$^{98}$Zr $^{2+} \rightarrow ^{0+}_{\text{g.s.}}$
1223 keV

$^{98}$Mo $^{3-} \rightarrow ^{2+}_{1}$
1230 keV

$^{98}$Zr $^{2+} \rightarrow ^{0+}_{\text{g.s.}}$ – transition observed
New Stringent B(E2) Limits

- Stopped Beam Analysis →152(64) pps $^{98}$Zr in beam
- Transition would have been observed with >40 transition counts
- GOSIA: Expected ~460 counts with B(E2) = 10 W.u. and 2400 pps

$^{98}$Mo only
- With 40 $^{98}$Zr transitions: significant Count difference
- significant FWHM difference

B(E2) < 17 W.u.
$^{98}$Zr Spherical

- $s_{1/2}$ likely low
- $p$-$n$ interaction relatively weak
- Little $n$ scattering from $s_{1/2} \rightarrow d_{3/2} / g_{7/2}$

$^{98}$Zr is spherical, weakly collective
QPT to deformed occurs past $^{98}$Zr
(between $N=58$ and $N=60$)
Comparison to Shell Model

Summary

• Investigated shape transition in Zr
• Determined $17 \text{ W.u.} > B_{Zr-98}(E2; 2^+_1 \rightarrow 0^+_{\text{g.s.}}) > 0.7 \text{ W.u.}$
• Phase transition after $N=58$
• Good agreement with theory

• Precision & higher-lying transitions missing
to proof shape coexistence in $^{98}\text{Zr}$
Thank you!

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