E2 rates from Electron Scattering Reveal Shell Evolution to Shape Coexistence in ^{96}Zr

Norbert Pietralla, Institut für Kernphysik, TU Darmstadt

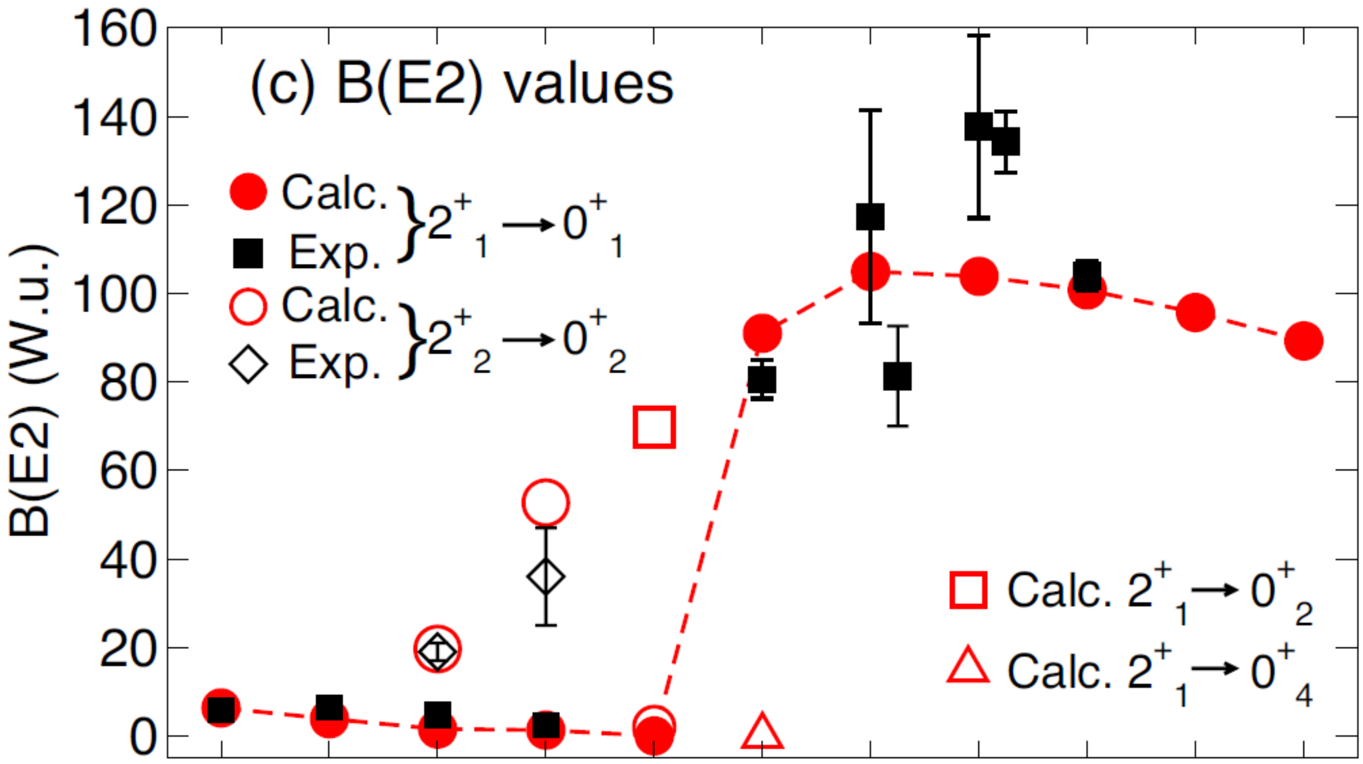
- **Evidence for shape coexistence from EM transition rates: ^{96}Zr**
- **Interpretation in Terms of Type II Shell Evolution**

Funded by the German Research Council, DFG

Structural Evolution in Zirconium Isotopes

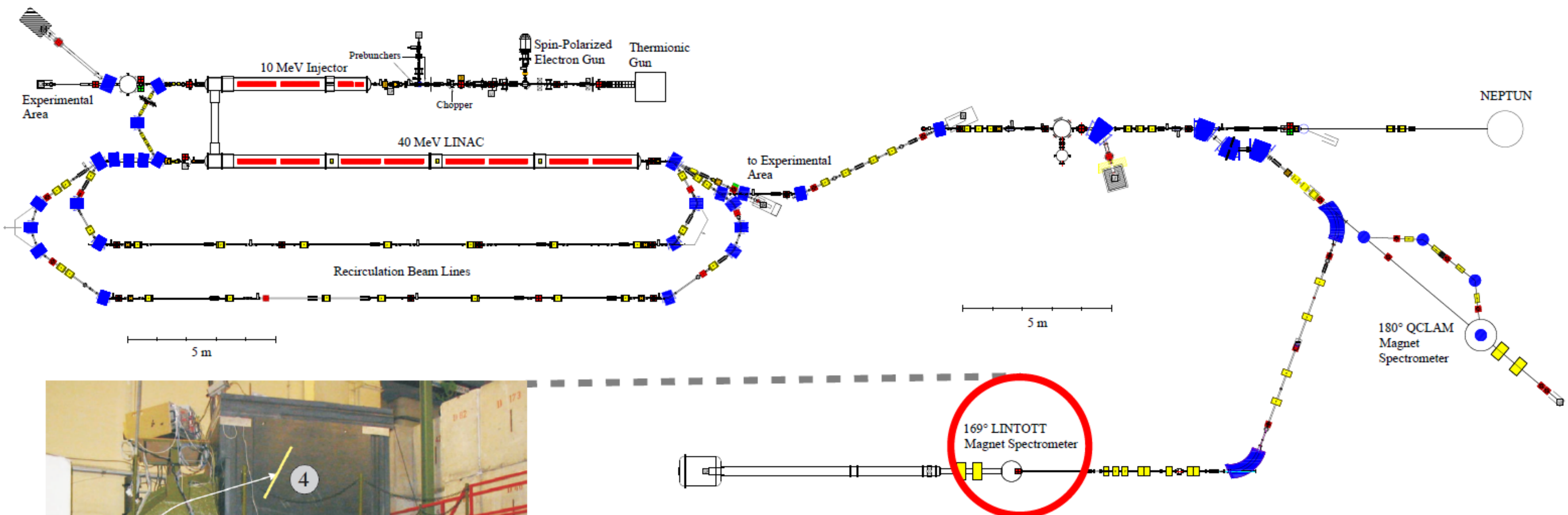
$^{90-110}Zr$

Neutron Number →



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

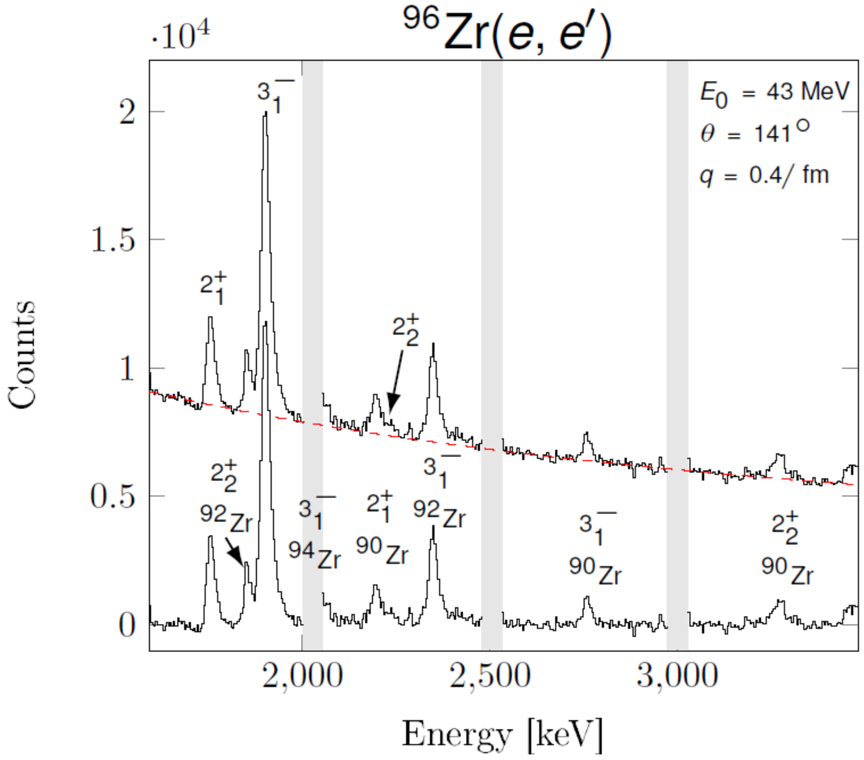
Electron Scattering on ^{96}Zr Experiment



Four measurements (E_0, θ, q)

- 69 MeV, 117°, 0.59 fm^{-1}
- 43 MeV, 141°, 0.40 fm^{-1}
- 43 MeV, 93°, 0.31 fm^{-1}
- 43 MeV, 81°, 0.28 fm^{-1}

Electron Scattering on ^{96}Zr
Data



natural abundance ^{96}Zr 2.8 %

Isotope	Enrichment
^{90}Zr	9.2 %
^{91}Zr	2.0 %
^{92}Zr	27.2 %
^{94}Zr	4.3 %
^{96}Zr	57.36 %

C. Kremer, PhD Thesis, TU Darmstadt (2016)

Electron Scattering on ^{96}Zr
Data

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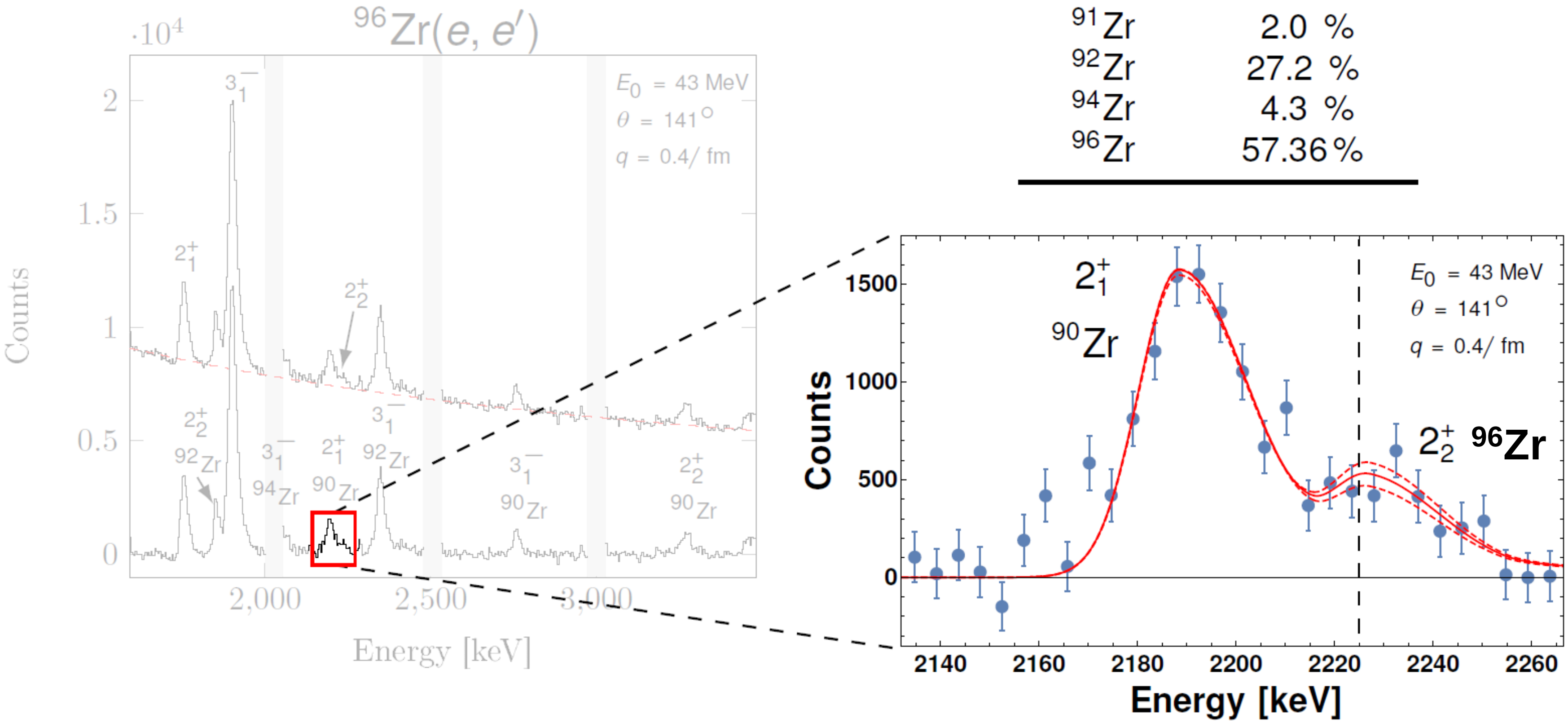
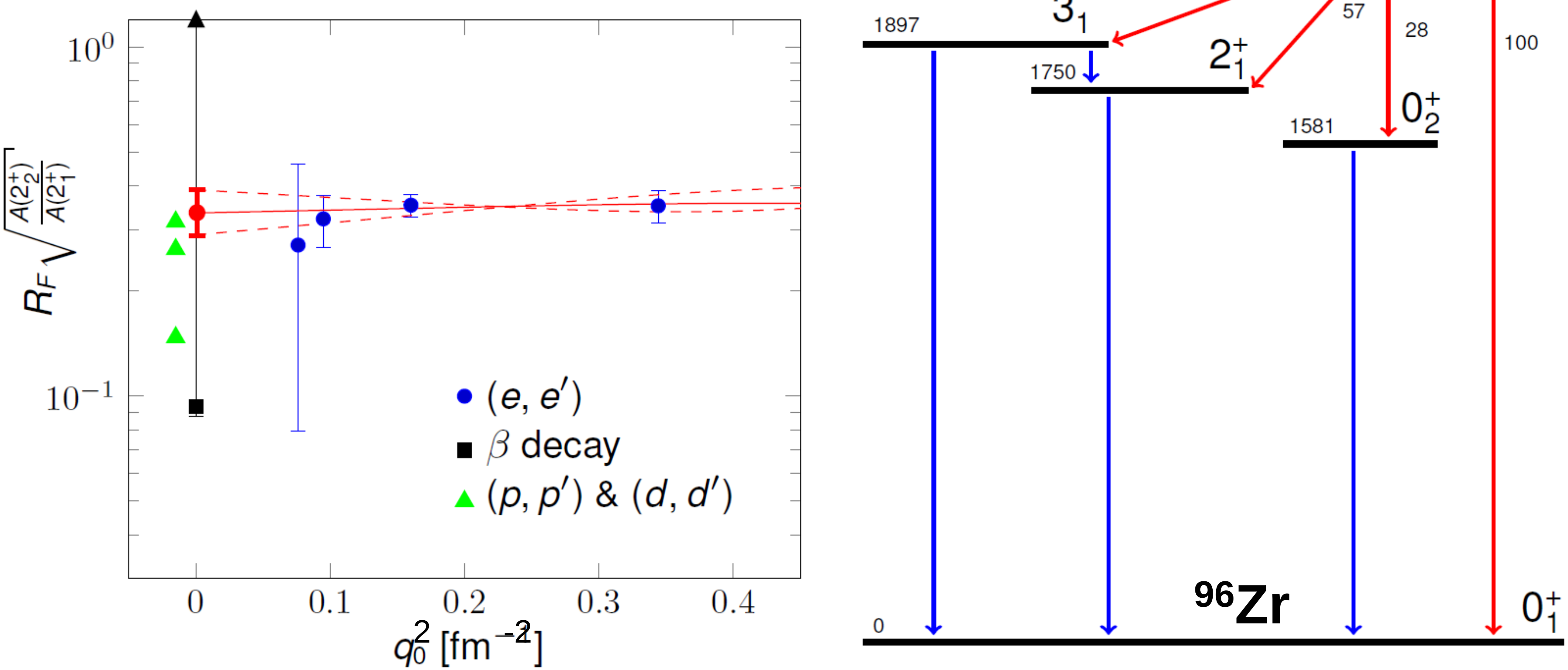


C. Kremer, PhD Thesis, TU Darmstadt (2016)

Electron Scattering on ^{96}Zr
Data

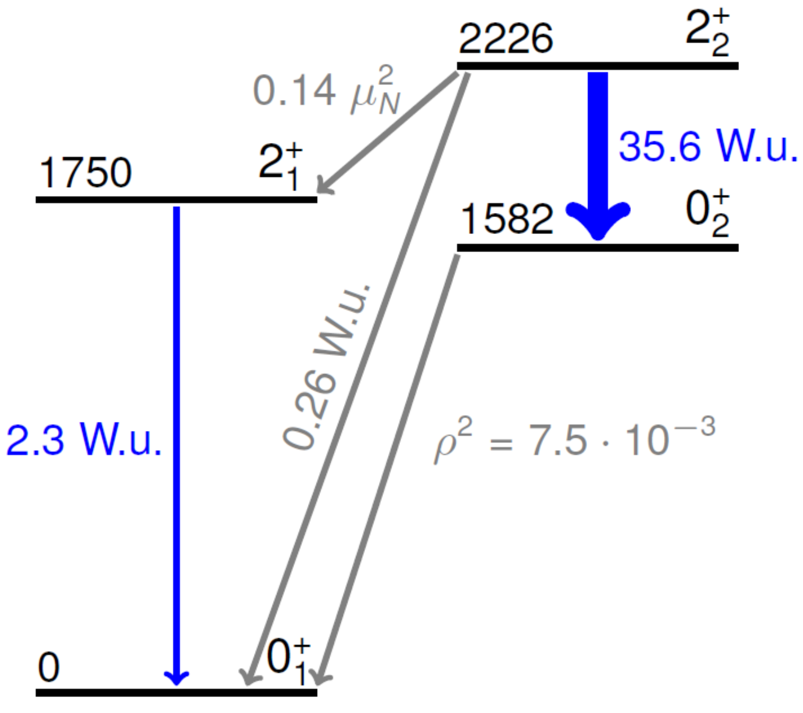
$$R_F(q)\sqrt{\frac{A_2}{A_1}} \approx \sqrt{\frac{B(E2;2_2^+\to0_1^+)}{B(E2;2_1^+\to0_1^+)}}\cdot\left(\frac{1-\frac{q_2^2}{14}(R_{tr,1}+\Delta R)^2}{1-\frac{q_1^2}{14}(R_{tr,1})^2}\right)$$



$$B(E2;2_2^+\to0_1^+) = 0.26^{+0.09}_{-0.07}\ \text{W.u.}$$

C. Kremer, PhD Thesis, TU Darmstadt (2016)

Electron Scattering on ^{96}Zr
Data



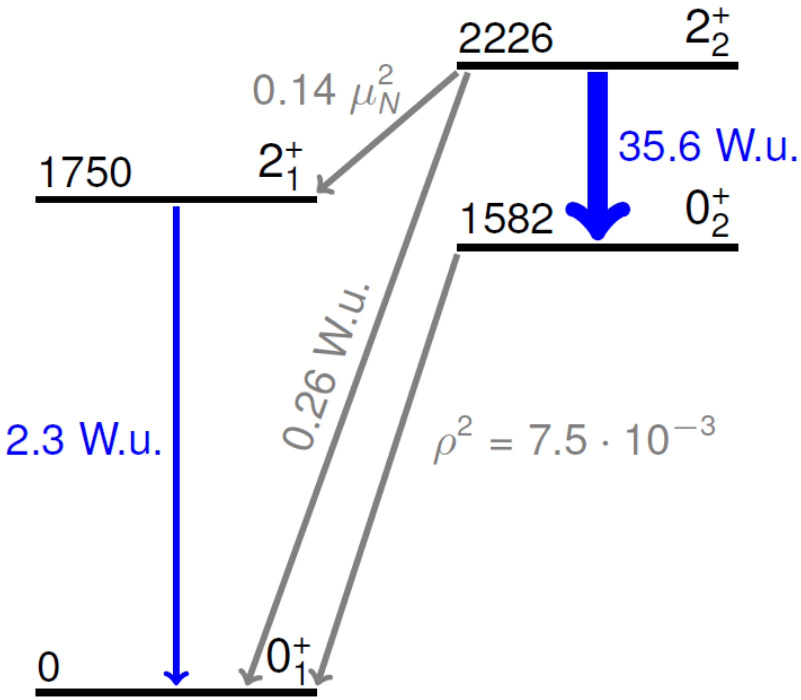
Observed transition strengths

- strong for $2_2^+ \to 0_2^+$
- weakly collective for $2_1^+ \to 0_1^+$

➡ mixing of two distinct structures

C. Kremer, PhD Thesis, TU Darmstadt (2016)

Type II Shell Evolution in ^{96}Zr
Two-State Mixing Calculation



$$|0_1^+\rangle = \alpha\,|0_s^+\rangle + \beta\,|0_d^+\rangle$$
$$|0_2^+\rangle = -\beta\,|0_s^+\rangle + \alpha\,|0_d^+\rangle$$
$$|2_1^+\rangle = \gamma\,|2_s^+\rangle + \delta\,|2_d^+\rangle$$
$$|2_2^+\rangle = -\delta\,|2_s^+\rangle + \gamma\,|2_d^+\rangle$$

Observed transition strengths

- strong for $2_2^+ \rightarrow 0_2^+$
- weakly collective for $2_1^+ \rightarrow 0_1^+$

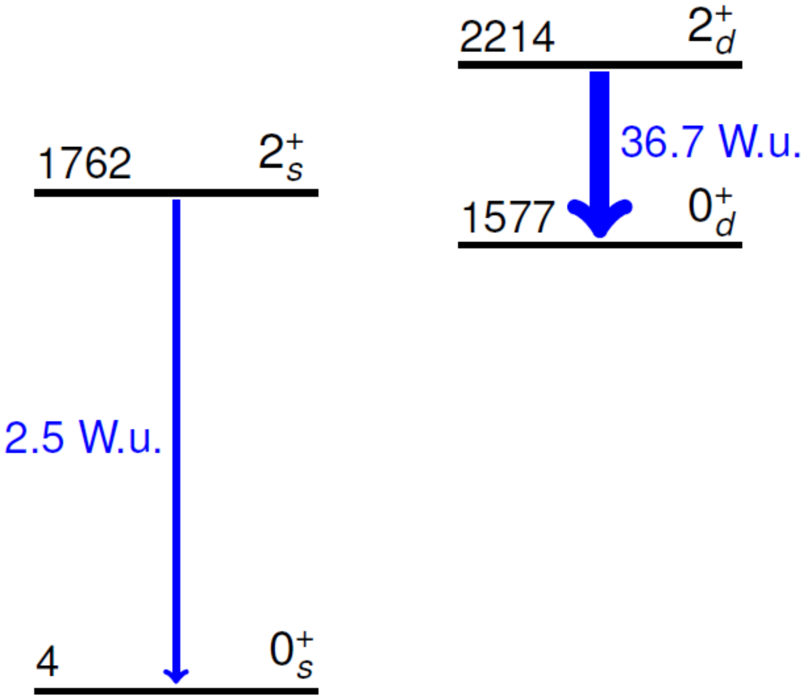
➡ mixing of two distinct structures

Underlying structures

- spherical ground-state band
- deformed band
- $V_{\mathrm{mix}}(J)$ = const.

C. Kremer, PhD Thesis, TU Darmstadt (2016)

Shape Coexistence in ^{96}Zr



$$|0^+_1\rangle = \alpha\,|0^+_s\rangle + \beta\,|0^+_d\rangle$$
$$|0^+_2\rangle = -\beta\,|0^+_s\rangle + \alpha\,|0^+_d\rangle$$
$$|2^+_1\rangle = \gamma\,|2^+_s\rangle + \delta\,|2^+_d\rangle$$
$$|2^+_2\rangle = -\delta\,|2^+_s\rangle + \gamma\,|2^+_d\rangle$$

Observed transition strengths

- strong for $2^+_2 \rightarrow 0^+_2$
- weakly collective for $2^+_1 \rightarrow 0^+_1$

➡ mixing of two distinct structures

Underlying structures

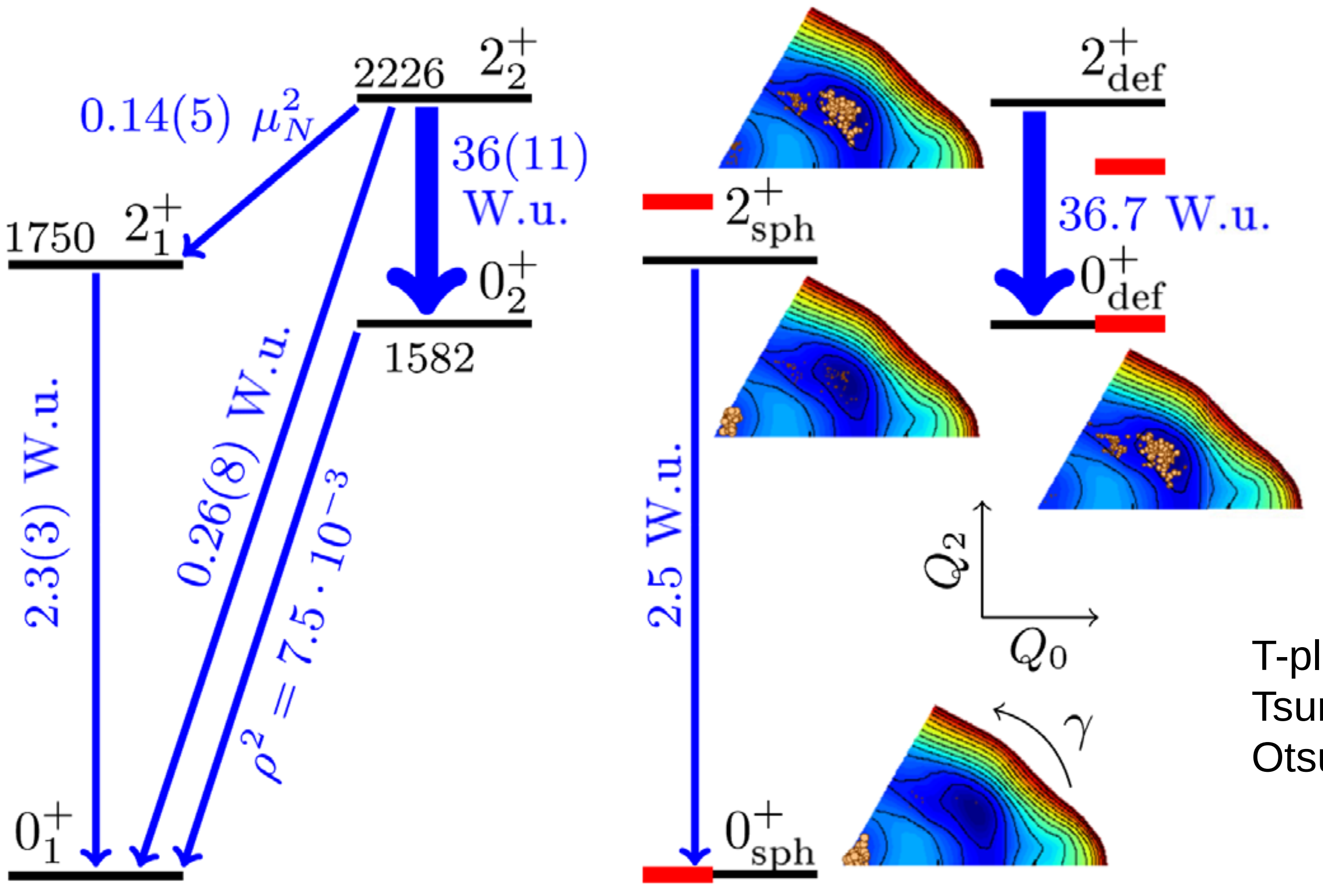
- spherical ground-state band
- deformed band
- weak mixing $V_{mix} = 76$ keV

$\alpha^2 = 0.998$ $\beta^2 = 0.002$

$\gamma^2 = 0.975$ $\delta^2 = 0.025$

C. Kremer, PhD Thesis, TU Darmstadt (2016)

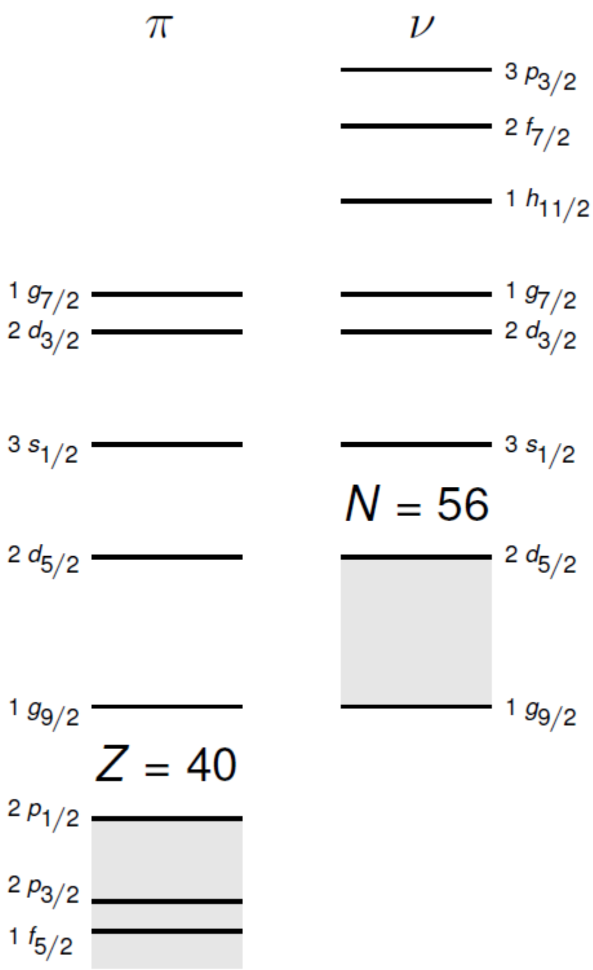
Comparison to Large-Scale Shell Model



T-plots:
Tsunoda,
Otsuka et al.

C.Kremer et al., PRL 117, 172503 (2016)

Comparison to Large-Scale Shell Model



	Experim ent	SM	TSM$_u$	TSM$_m$
$B(E2; 2_1^+ \to 0_1^+)$ [W.u.]	2.3(3)	1.28	2.5	2.3
$B(E2; 2_2^+ \to 0_2^+)$ [W.u.]	36(11)*	52.7	36.7	36
$B(E2; 2_2^+ \to 0_1^+)$ [W.u.]	0.26(8)*	0.00	0.00	0.26
$B(M1; 2_2^+ \to 2_1^+)$ $[\mu_N^2]$	0.14(5)*	0.01	0.00	0.07
$B(E3; 3_1^- \to 0_1^+)$ [W.u.]	57(4)	46.6[a]	...	...
$B(E1; 2_2^+ \to 3_1^-)$ [W.u.]	$28(9) \times 10^{-3*}$	0.00	...	...

Interpretation in terms of Type II Shell Evolution*

*Tokyo group: T.Otsuka et al.

Nuclear Shell Evolution

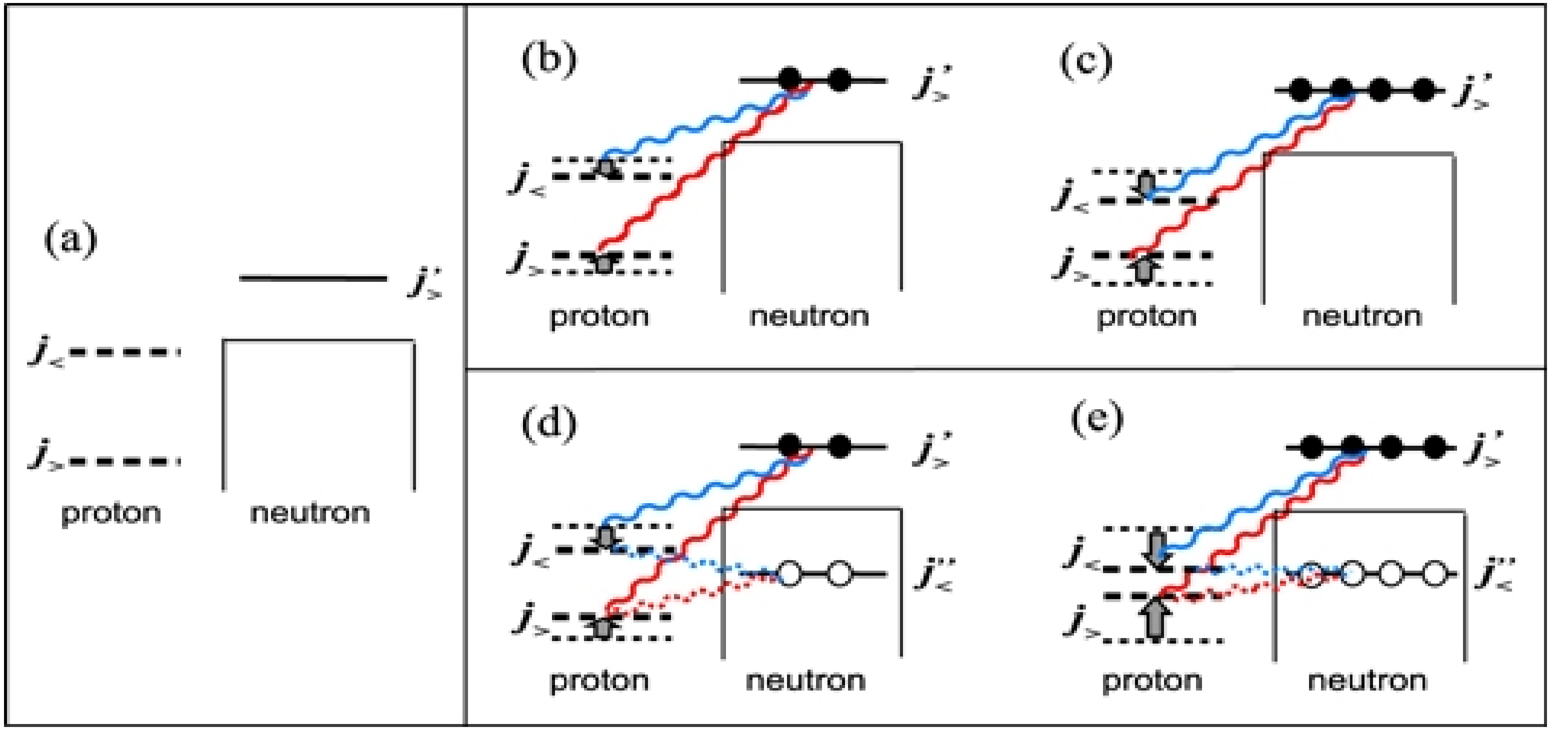
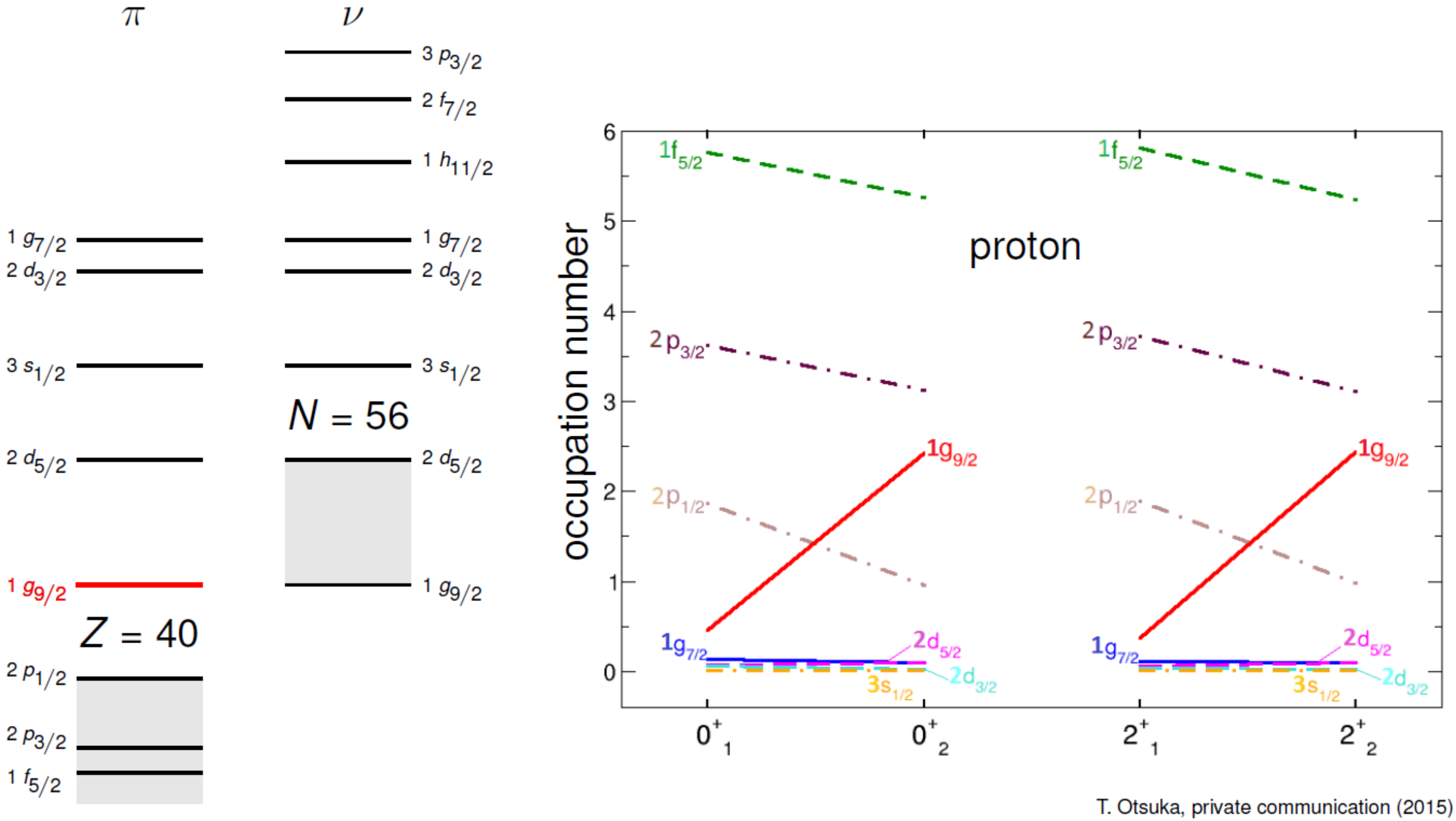


Figure 1 from “*The role of shell evolution in shape coexistence*”
T Otsuka and Y Tsunoda 2016 J. Phys. G: Nucl. Part. Phys. 43 024009

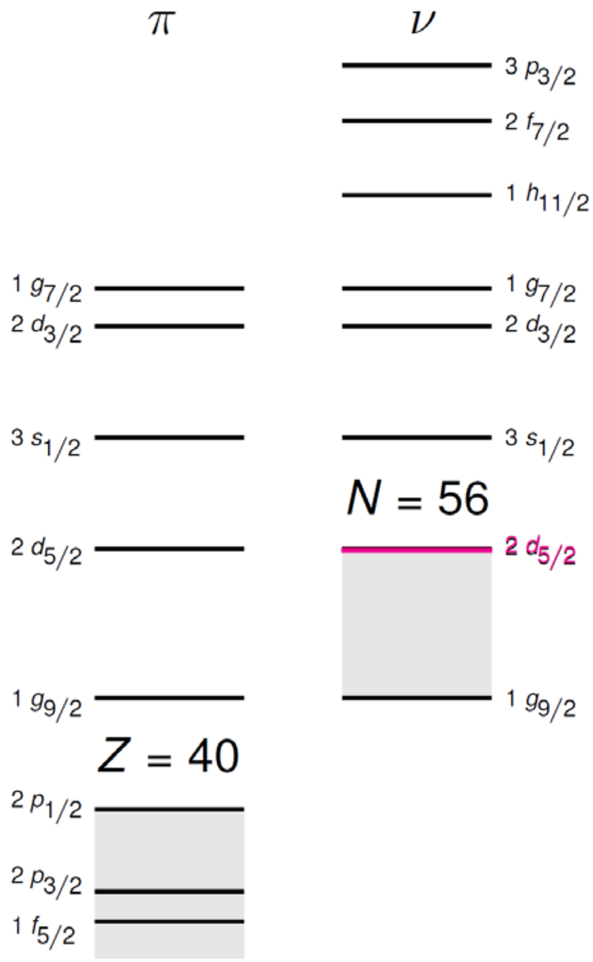
T2SE: Configuration-dependent ESPE‘s

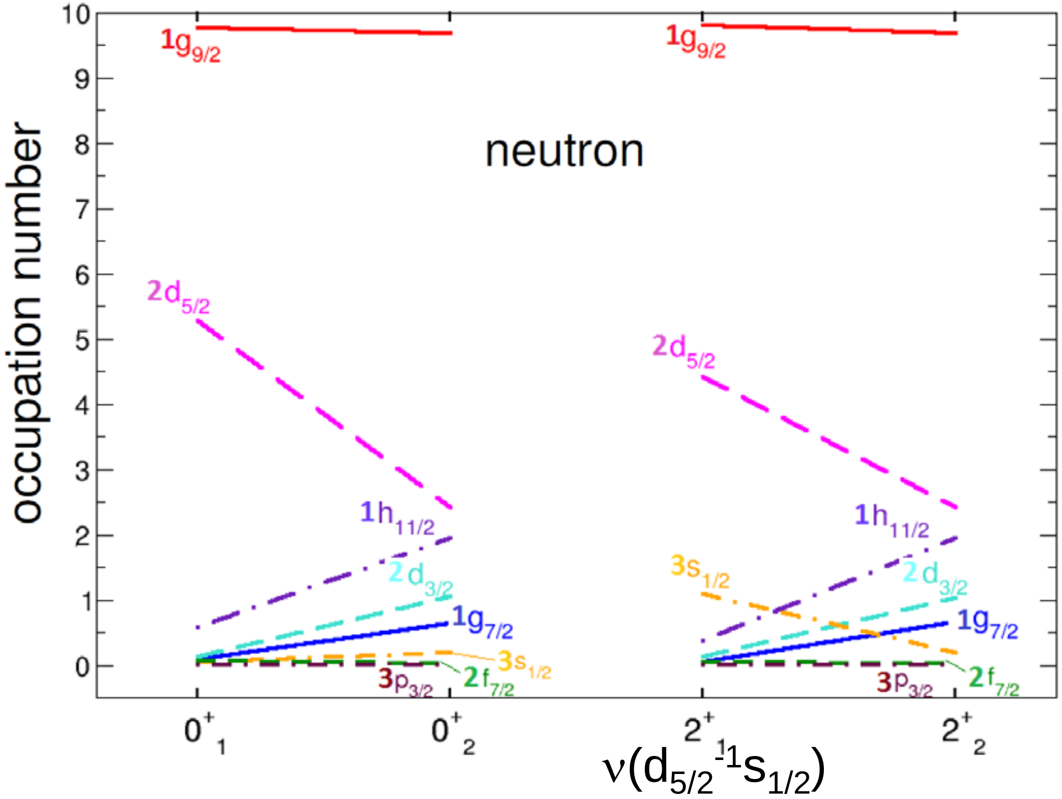
Type II Shell Evolution in ^{96}Zr
Proton Occupation Numbers



T. Otsuka, private communication (2015)

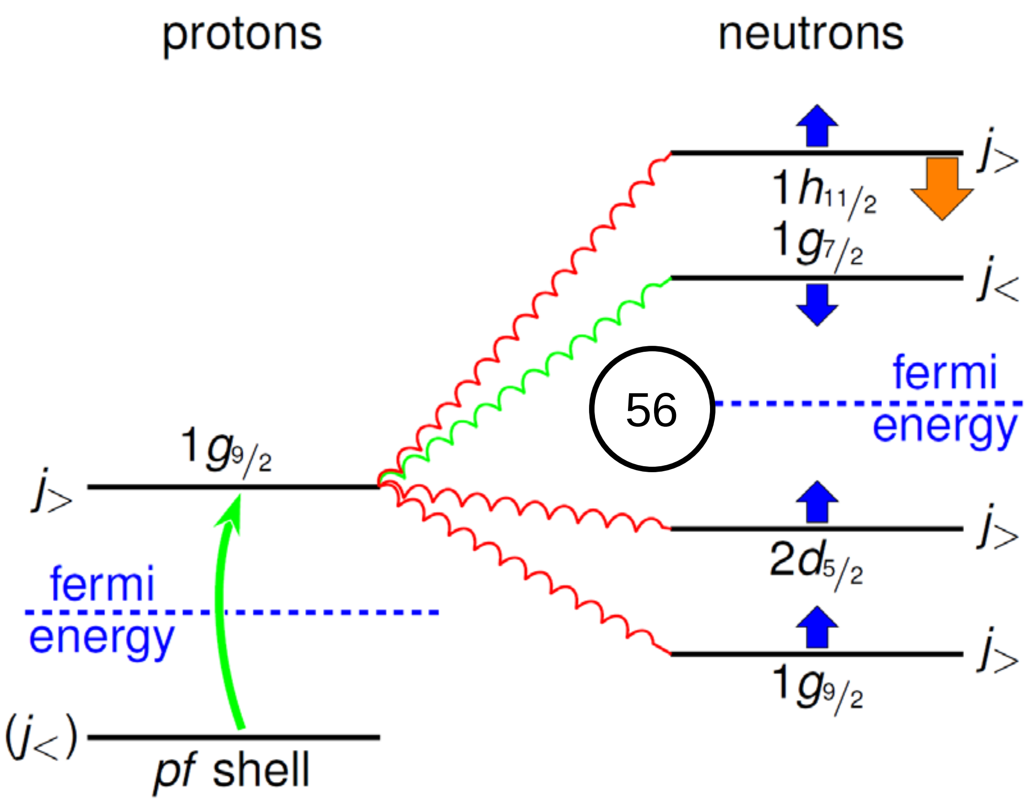
Type II Shell Evolution in ^{96}Zr
Neutron Occupation Numbers





T. Otsuka, private communication (2015)

Type II Shell Evolution in ^{96}Zr



- more protons in $j_>$ lead to lower (higher) ESPE of neutron $j_<$ ($j_>$) orbitals
- more neutrons in $j_<$ lead to lower (higher) ESPE of proton $j_>$ ($j_<$) orbitals

➡ self-reinforcing effect

⬇ monopole part of tensor force

⬇ central force

Type II Shell Evolution in ^{96}Zr

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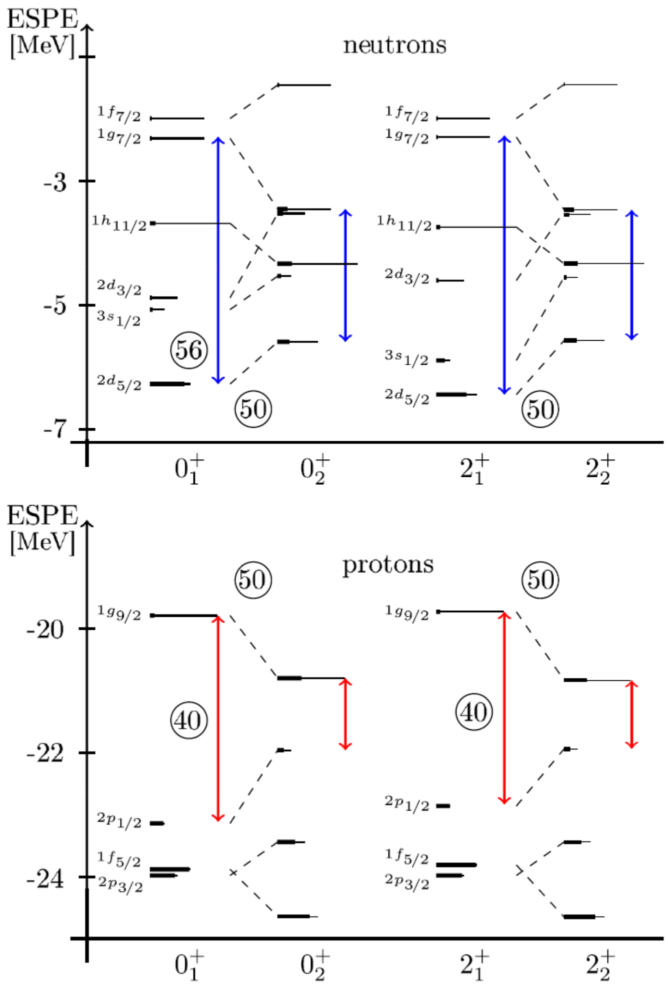

Analysis of excited structure

- Spread of active neutron orbitals is strongly reduced w.r.t. ground state.
- Spread of active proton orbitals is strongly reduced, too.
- Z=40, N=56 subshell closures eliminated
- More uniform occupation of orbitals
- ➢ Deformation!
- Self-reinforcing phenomenon → robust!

PRL 117, 172503 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

First Measurement of Collectivity of Coexisting Shapes Based on Type II Shell Evolution: The Case of ^{96}Zr

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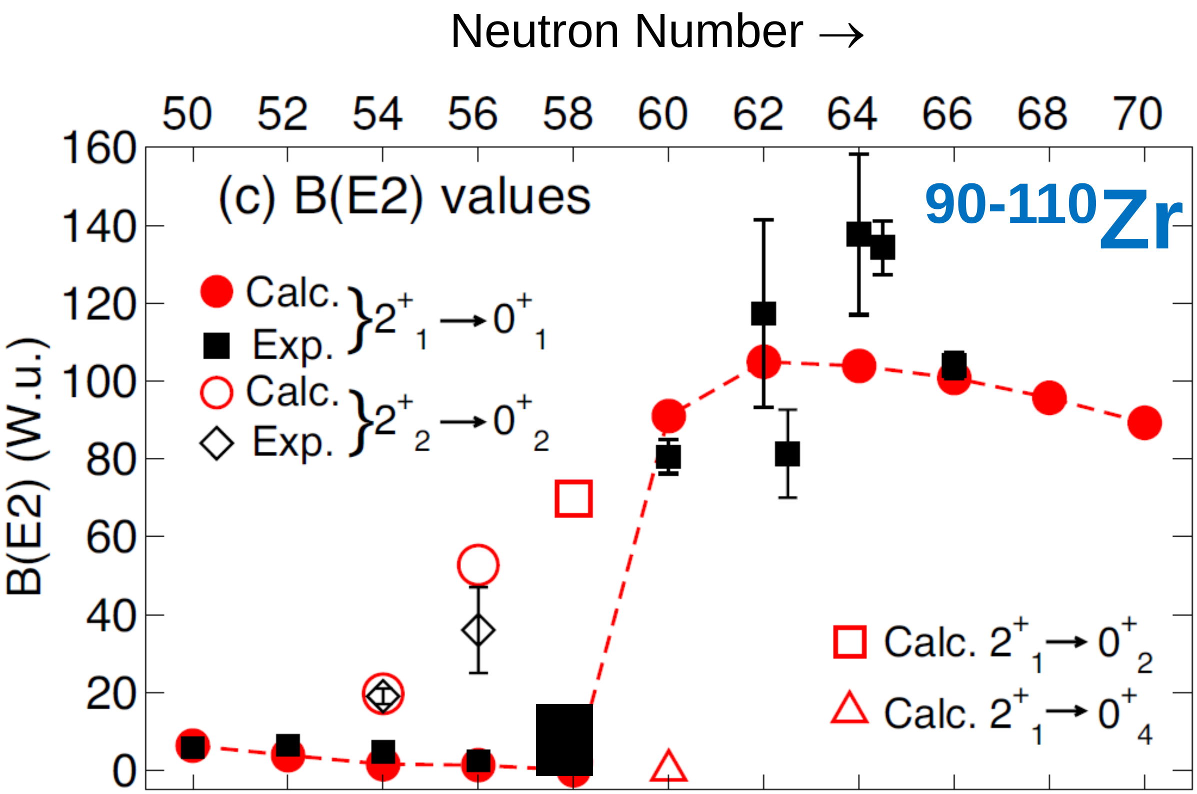
Structural Evolution in Zirconium Isotopes



W.Witt et al., submitted for publication, **next talk**

C.Kremer et al., PRL 117, 172503 (2016)

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

Summary

- Evidence for shape coexistence from EM transition rates: ^{96}Zr
- Interpretation in terms of Type II Shell Evolution

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W. Witt, ^{98}Zr

V. Werner,
P. von Neumann-Cosel

T. Otsuka, T2SE

Thank you very much!