Shape evolution in neutron-rich Zr isotopes; Lifetime measurements in ^{98}Zr

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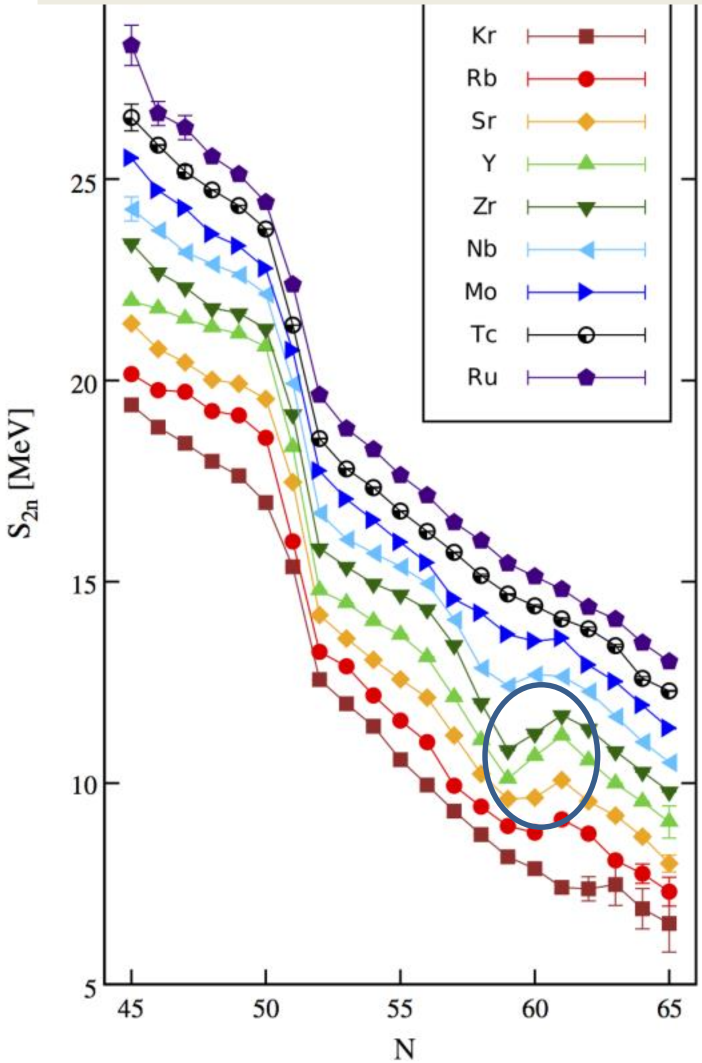
Outline
Motivation
Method
Findings
Interpretation

Supported by European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant

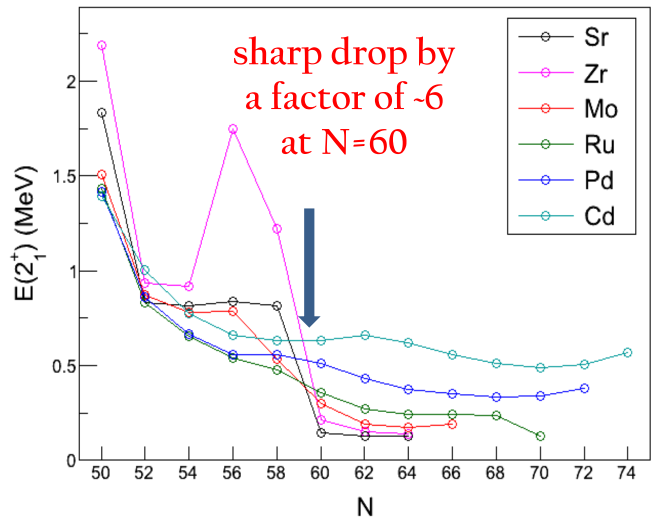
Evidence for abrupt shape changes at N=60

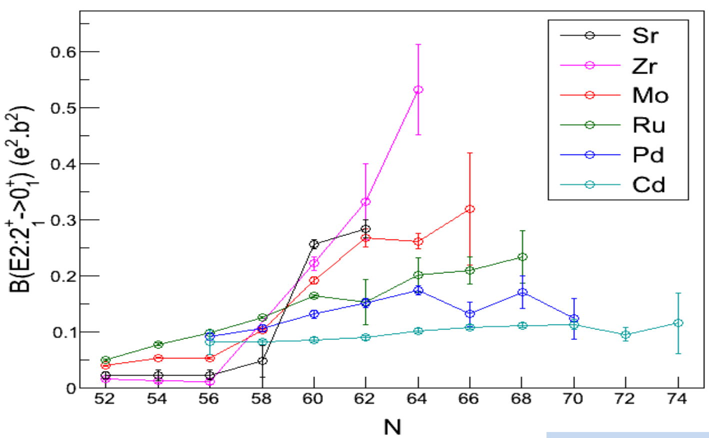
Two-neutron separation energies



P. Campbell et al., Prog. Part. Nucl. Phy. 86, 127 (2016)

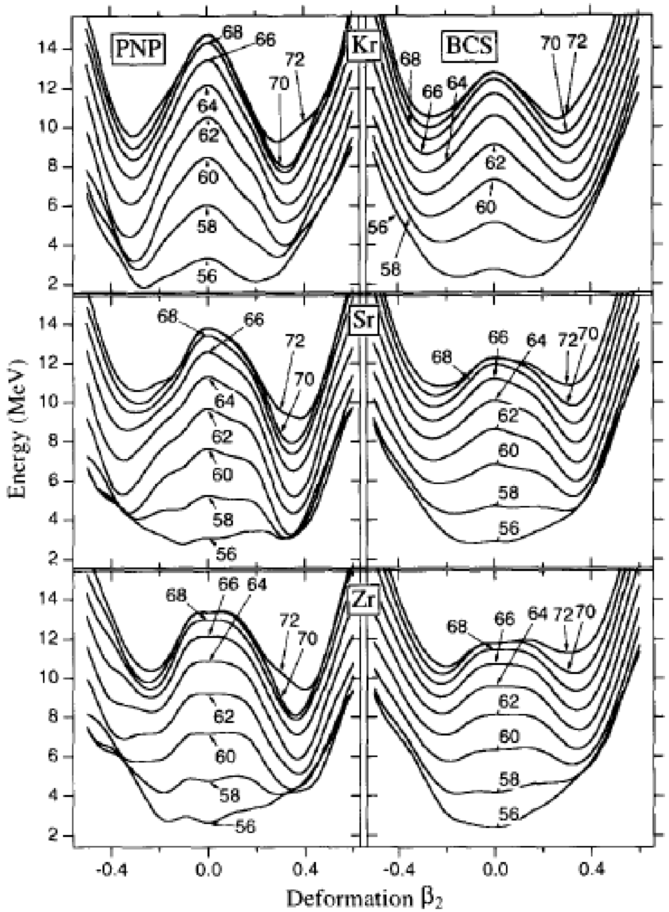
Excitation energies and transition probabilities of first 2^+ state





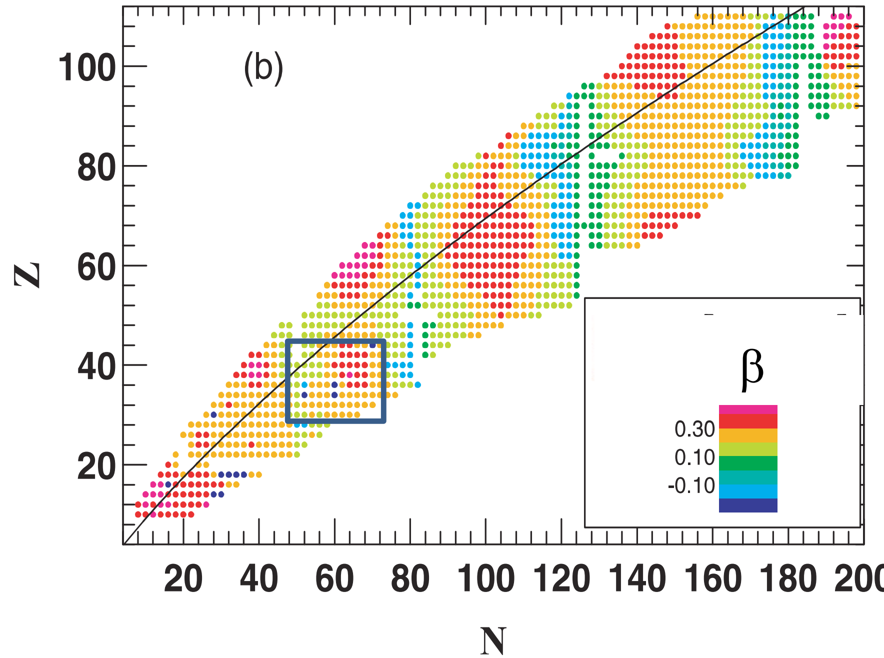
NNDC Database

Shape coexistence and evolution in A~100 region



Oblate and prolate minima, varying with Z,N

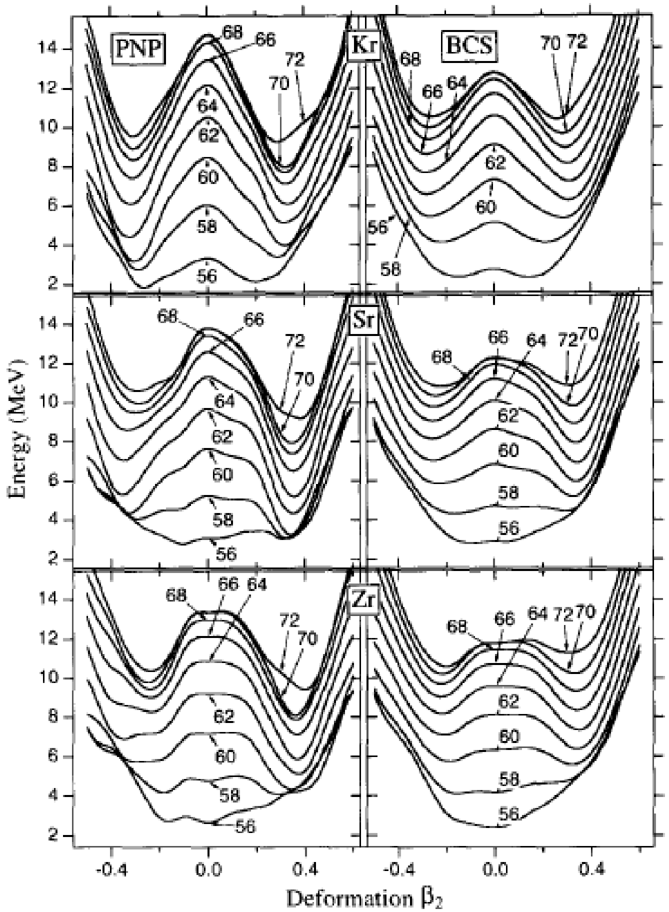
HF-BCS mean field calculations
J. Skalski et al., NPA617, 282(1997)



HFB+5DCH calculations
with Gogny D1S force,
J.P. Delaroche et al., PRC 81, 014303 (2008)

- Considerably sensitivity to Z,N
- Shape coexistence; low-lying 0+
- Crossing between coexisting shapes → rapid shape evolution

Shape coexistence and evolution in A~100 region



Oblate and prolate minima, varying with Z,N

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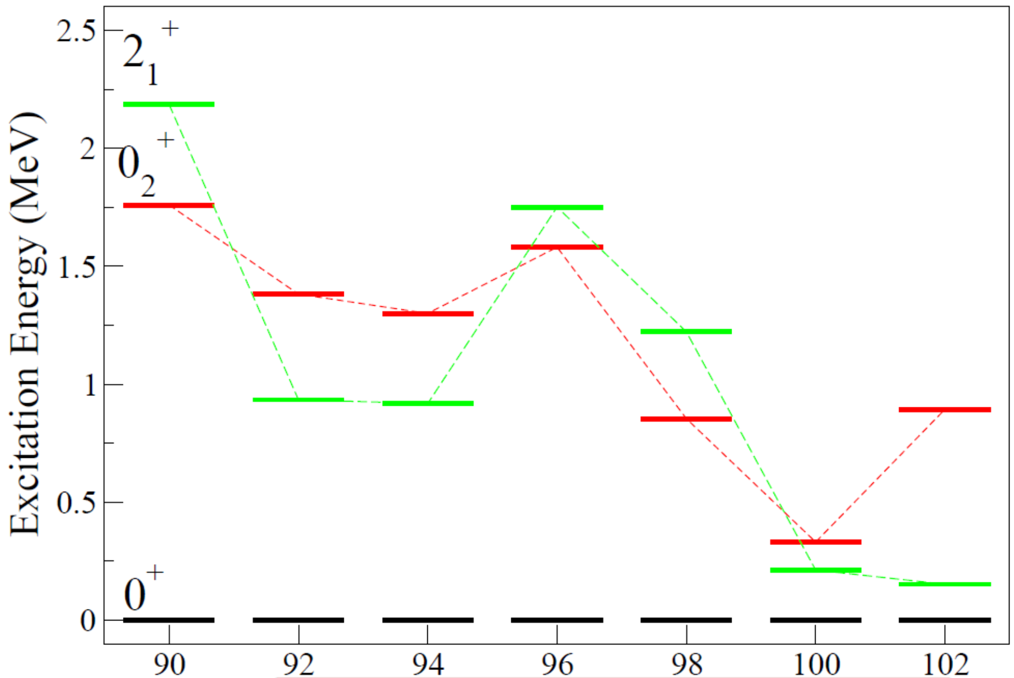
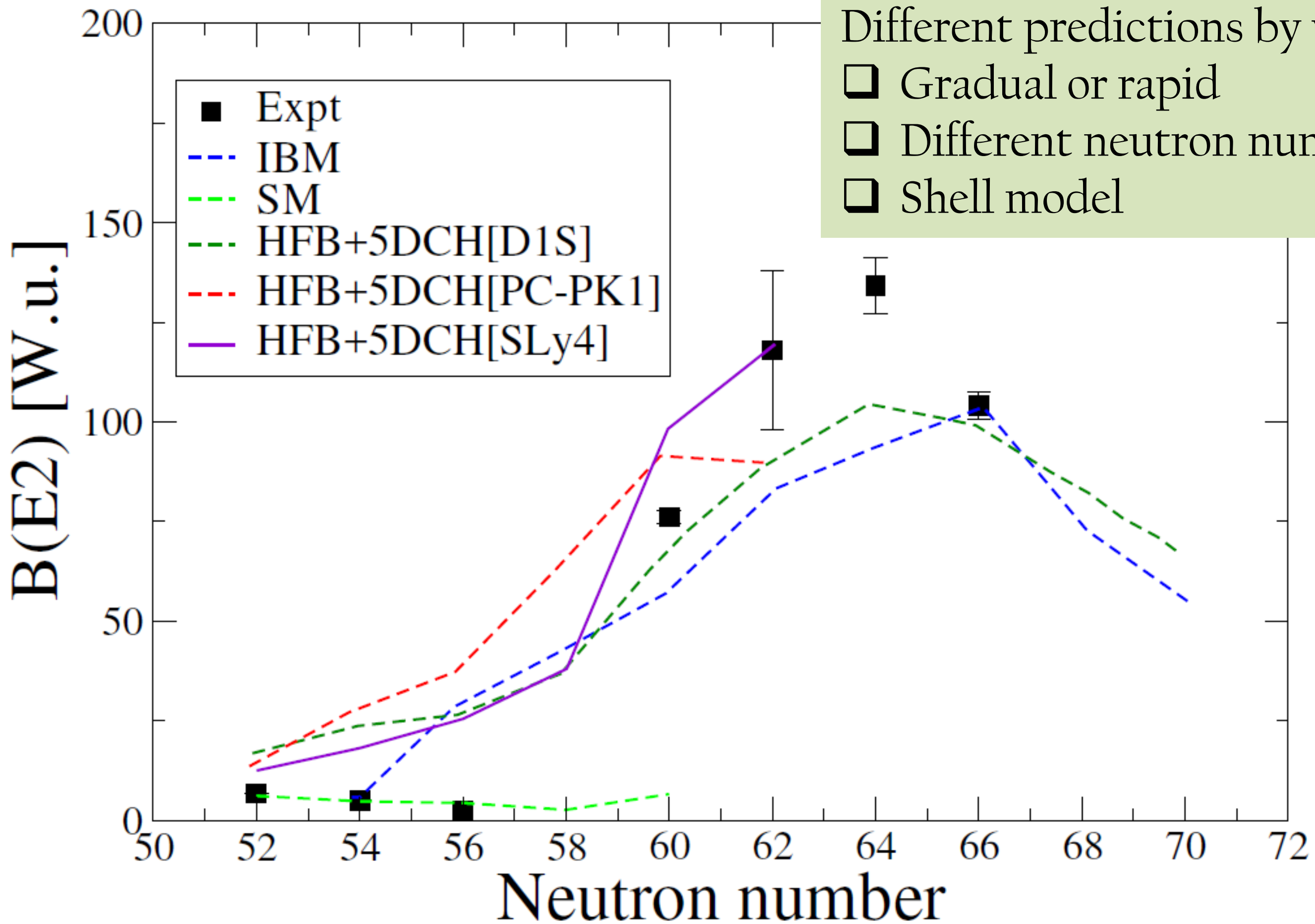


Systematics of excitation energy in Zr isotopes (NNDC database)

- ❑ Considerably sensitivity to Z,N
- ❑ Shape coexistence; low-lying 0+
- ❑ Crossing between coexisting shapes → rapid shape evolution

How do we interpret this?

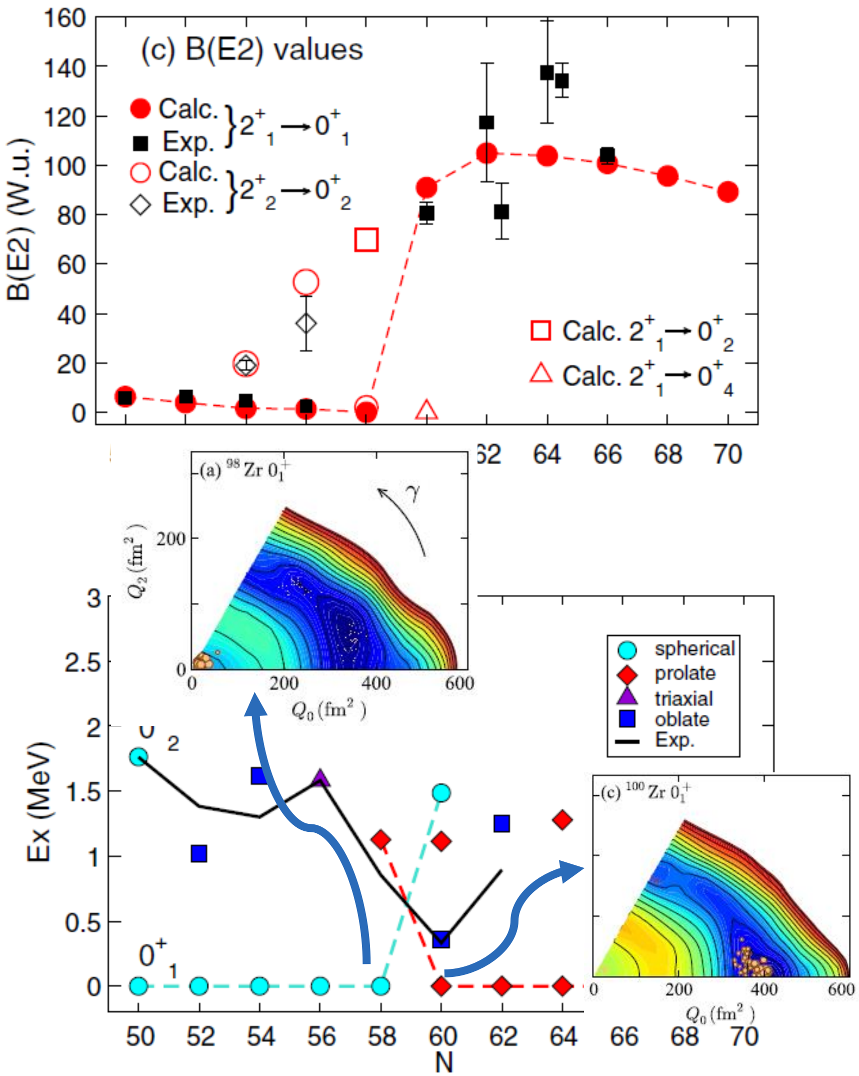


Different predictions by various models

- Gradual or rapid
- Different neutron number
- Shell model

J.-P. Delaroche et al., Phys. Rev.C 81, 014303 (2010) and private communication
H. Mei et al., Phys. Rev. C 85, 034321 (2012)
K. Nomura et al., Phys. Rev. C 94, 044314 (2016).
K. Sieja et al., Phys. Rev. C 79, 064310 (2009)
ENSDF/NNDC database

Where do we stand ?

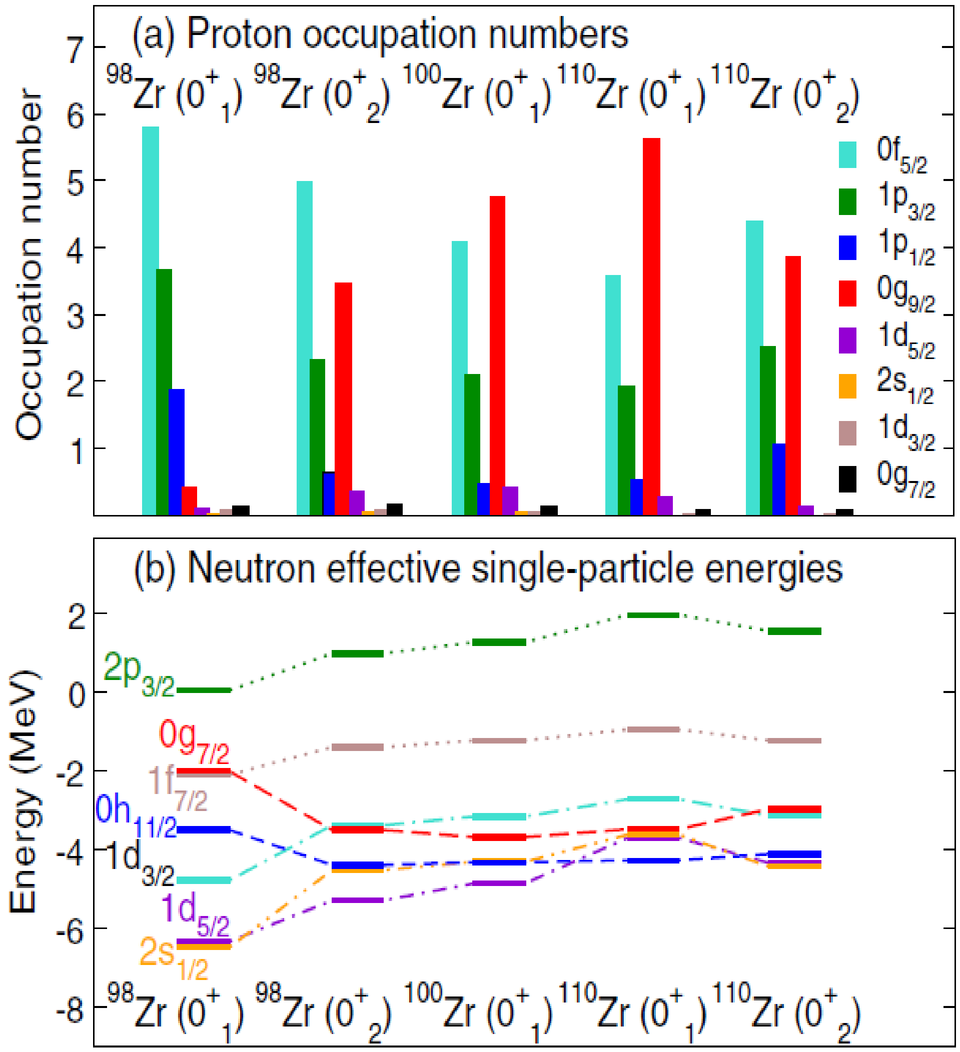


MCSM calculations by Togashi et al.

- ❑ Low-lying 0+ states
- ❑ Crossing of the two 0+ states

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

Shape-coexistence and type-II shell evolution in Zr

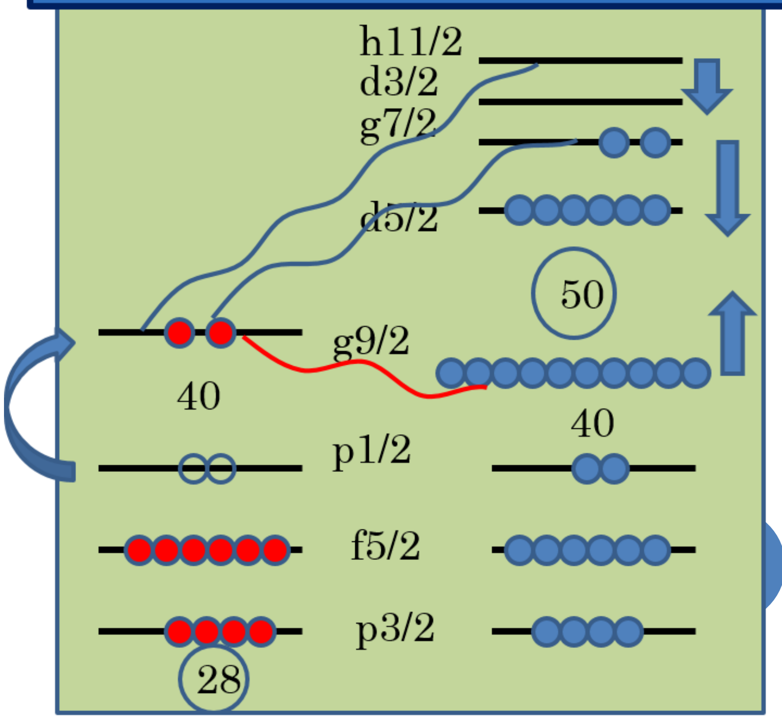


T. Togashi et al. PRL. 117, 172502 (2016).

MCSM calculations by Togashi et al.

- ❑ Shape coexistence
- ❑ Type II shell evolution
- ❑ Deformation of states-test the interpretation

The Z~40, N~60 region

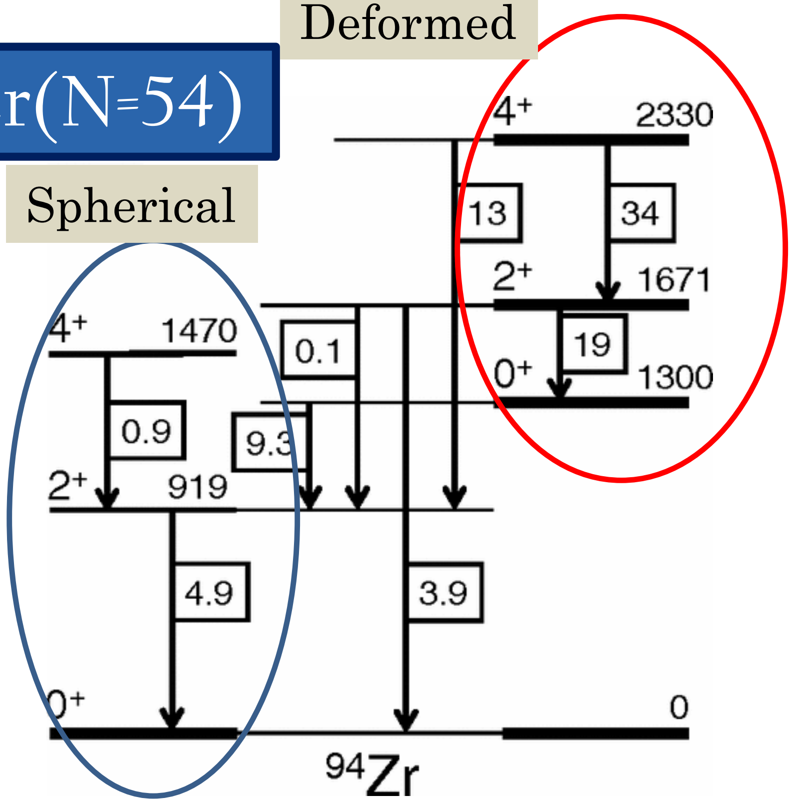


Shape-coexistence in Zr isotopes: ^{94,96}Zr

^{94}Zr(N=54)

Deformed

Spherical

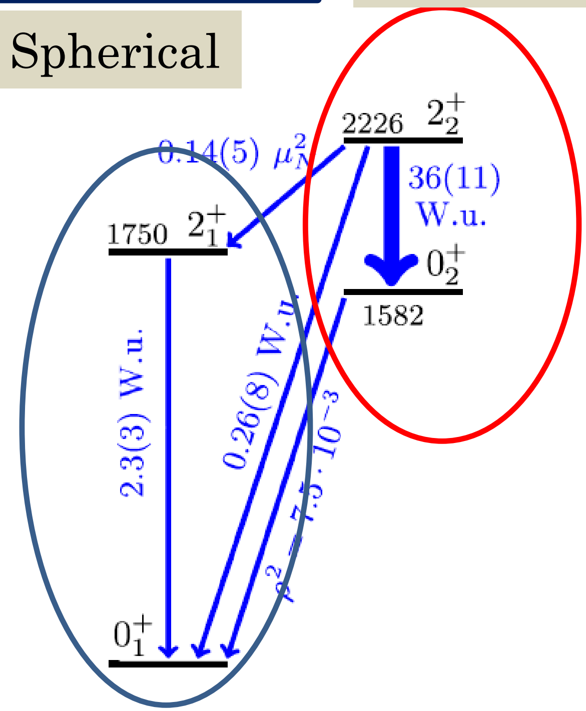


A. Chakraborty et al. PRL 110, 022504 (2013).

^{96}Zr(N=56)

Deformed

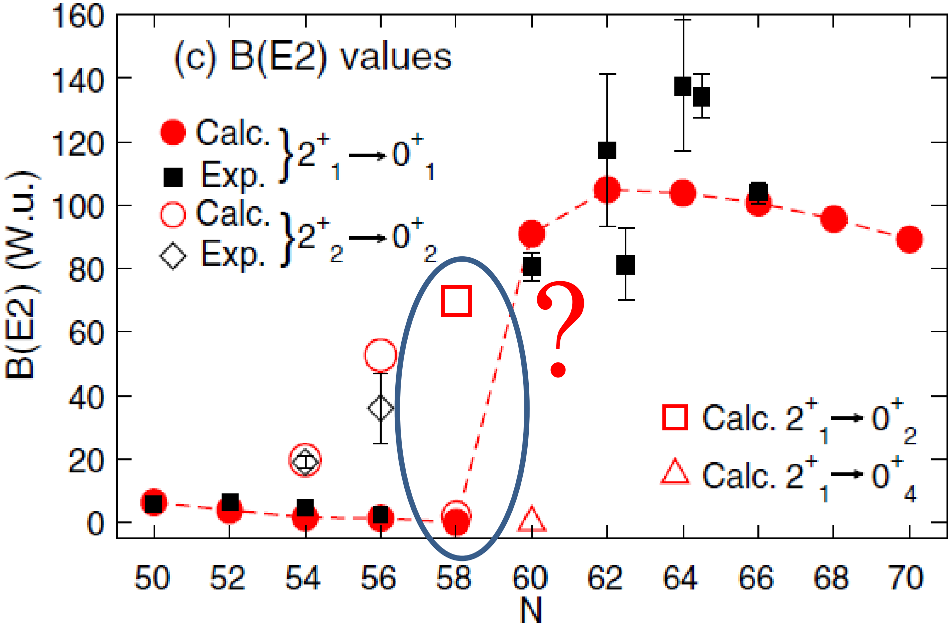
Spherical



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

Coexisting spherical and well deformed structure

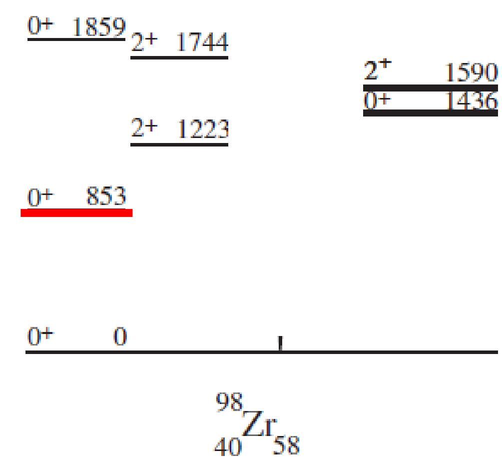
Shape-coexistence in Zr isotopes: ^{98}Zr (N=58)



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

B(E2 $2_1^+ \rightarrow 0_1^+$)≥1.83 W.u
Ansari et al., Phys. Rev. C 96, 054323 (2017).
B(E2 $2_1^+ \rightarrow 0_1^+$) <11 W.u
W. Witt et al.,Phys. Rev. C98, 041302(2018)

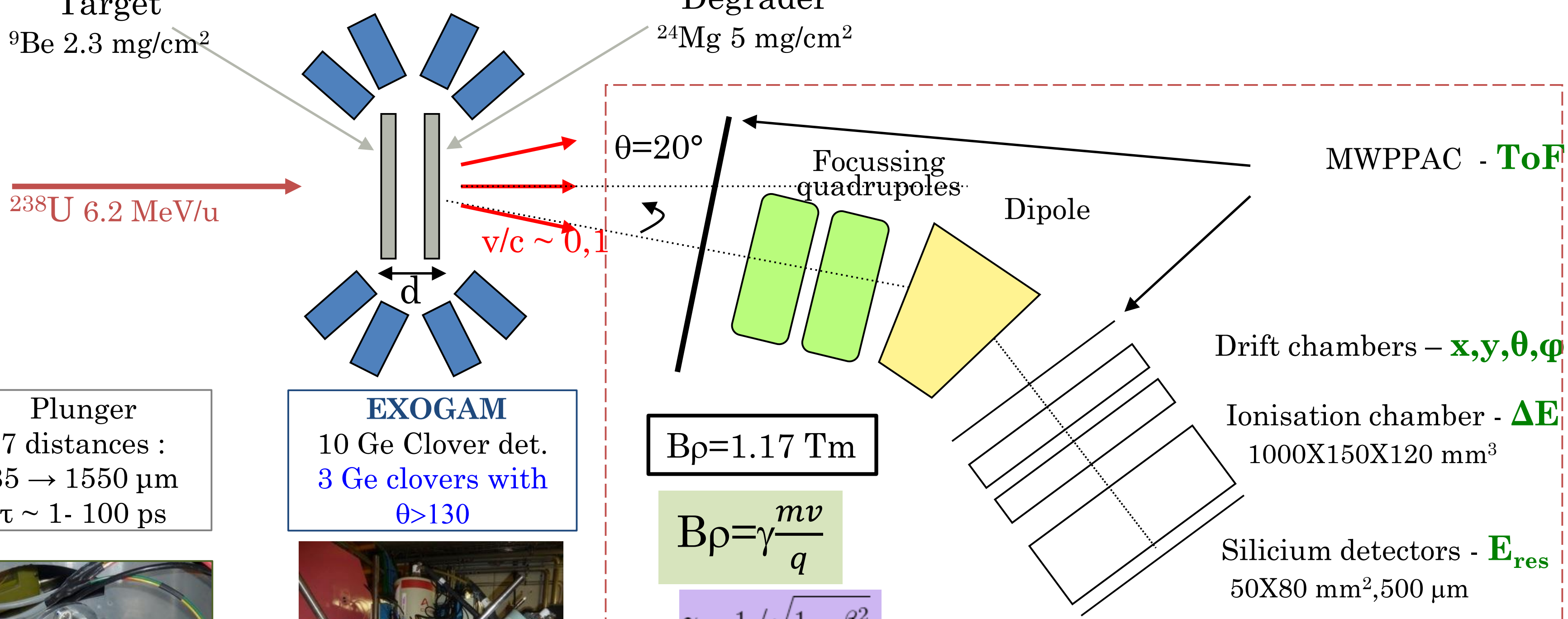
- Suggestions for Shape-coexistence in ^{98}Zr
- Observation of low-lying 0^+ states
- Absence of precise B(E2) values/deformation



K. Hyde and J. L. Wood, Rev. Mod. Phys.83, 1467 (2011)

In-flight studies of fission fragments at GANIL

- **Fission** reaction $^{238}U + {}^{9}Be$ in inverse kinematics ($E^* \approx 45$ MeV)
- **VAMOS** to identify fission fragments in **(Z,A)**
- Spectroscopy with **EXOGAM & RDDS lifetimes** from plunger set-up



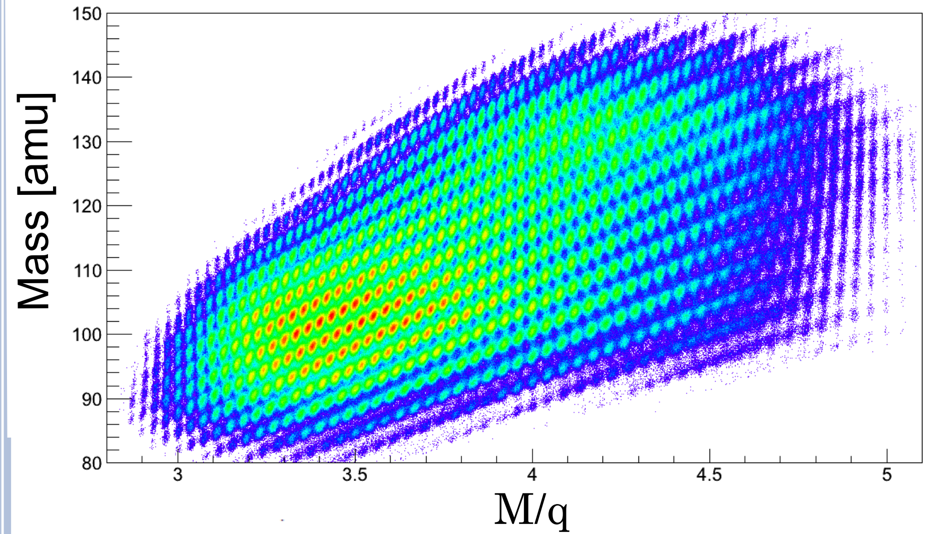
$$B\rho = \gamma \frac{mv}{q}$$

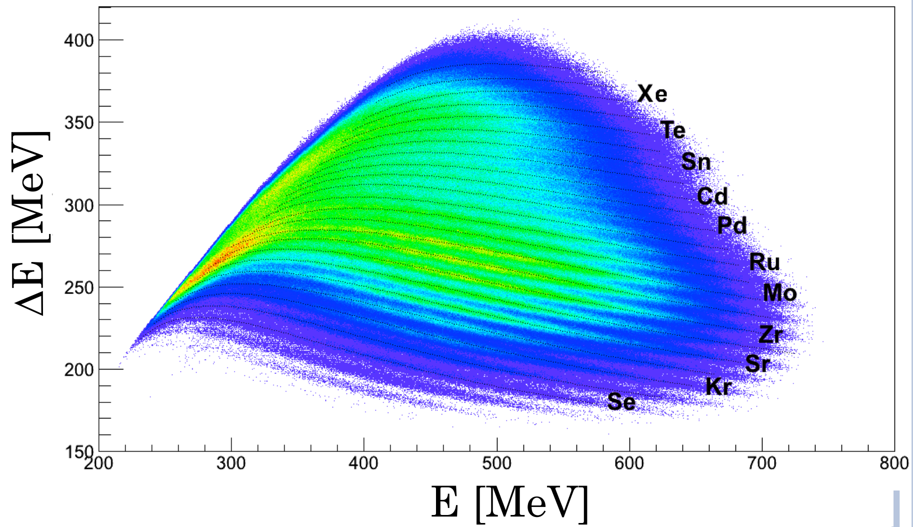
$$\gamma = 1./\sqrt{1-\beta^2}$$

VAMOS spectrometer

Fission fragment identification in q, M and Z

Fission fragment identification with VAMOS

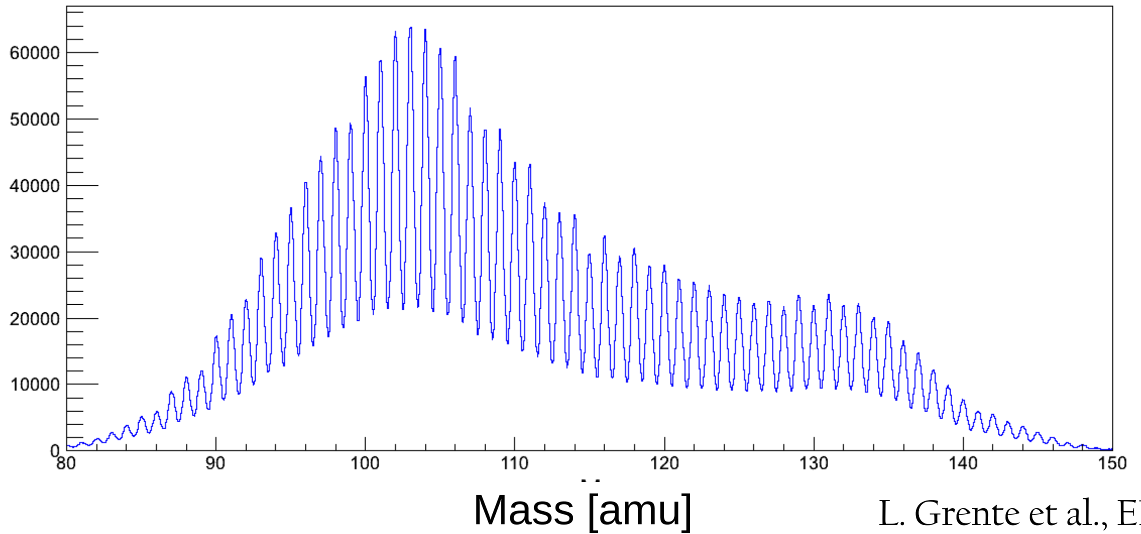




$$\frac{M}{Q} = \frac{B_\rho}{3.105 \times \gamma \times \beta}$$

$$M_0 = \frac{E}{931.5016 \times (\gamma - 1)}$$

$$\Delta E \sim MZ^2/E$$



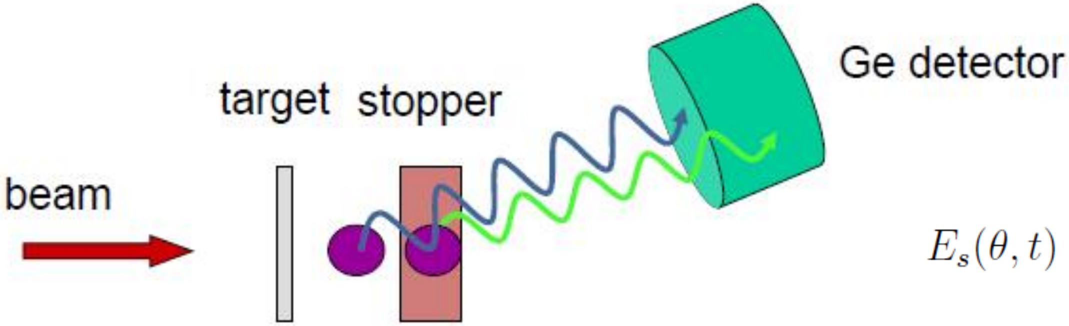
Z and A resolution

$$\frac{\Delta Z}{Z} = \frac{1}{60}$$

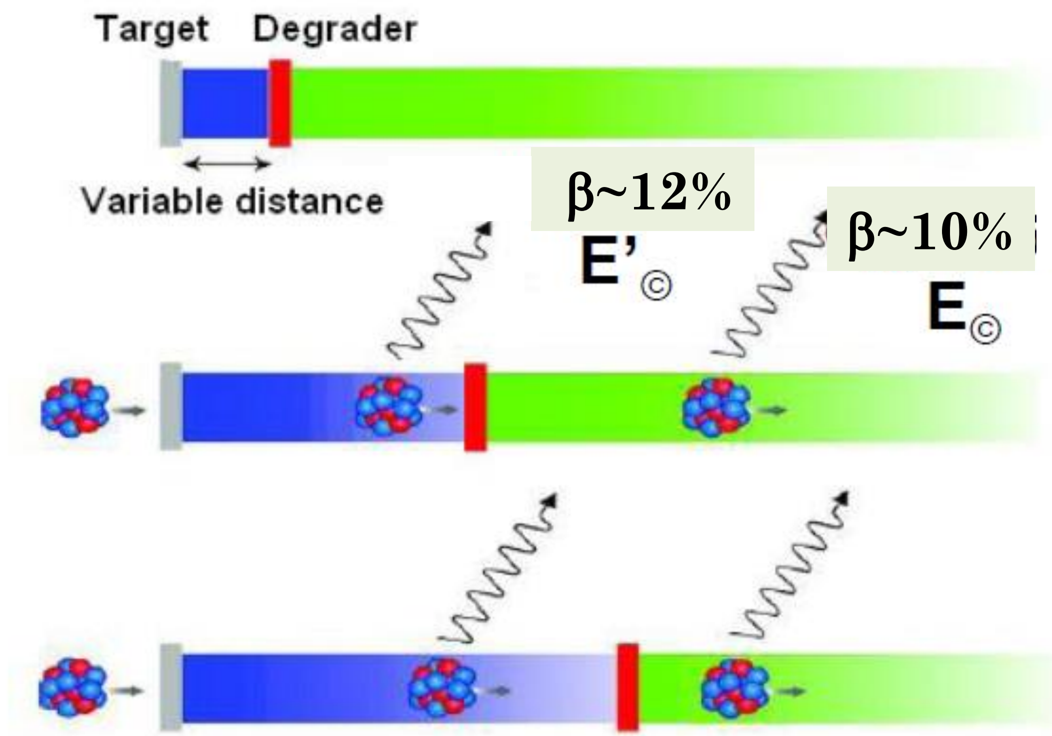
$$\frac{\Delta M}{M} = \frac{1}{200}$$

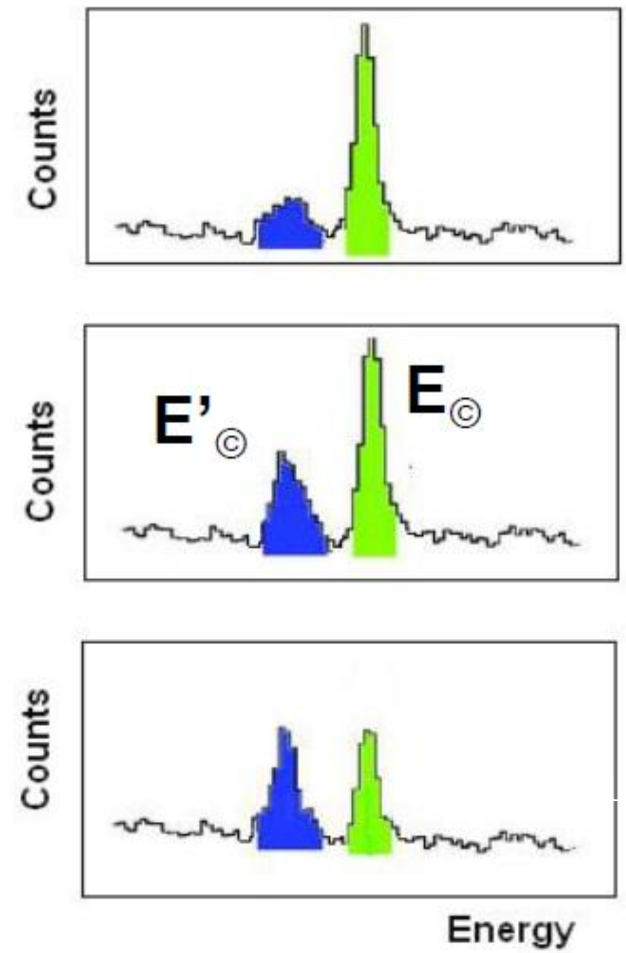
L. Grente et al., EPJ Web of Conferences **62**, 01002 (2013)

The Recoil-Distance Doppler-Shift technique



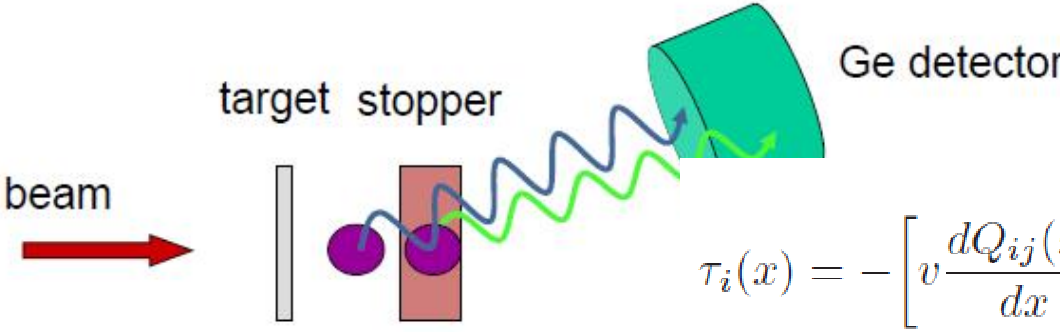
$$E_s(\theta,t) = E_o\frac{\sqrt{1-\frac{v}{c}}}{1-\frac{v}{c}\cos\theta} \approx E_o\left(1+\frac{v}{c}\cos\theta\right)$$





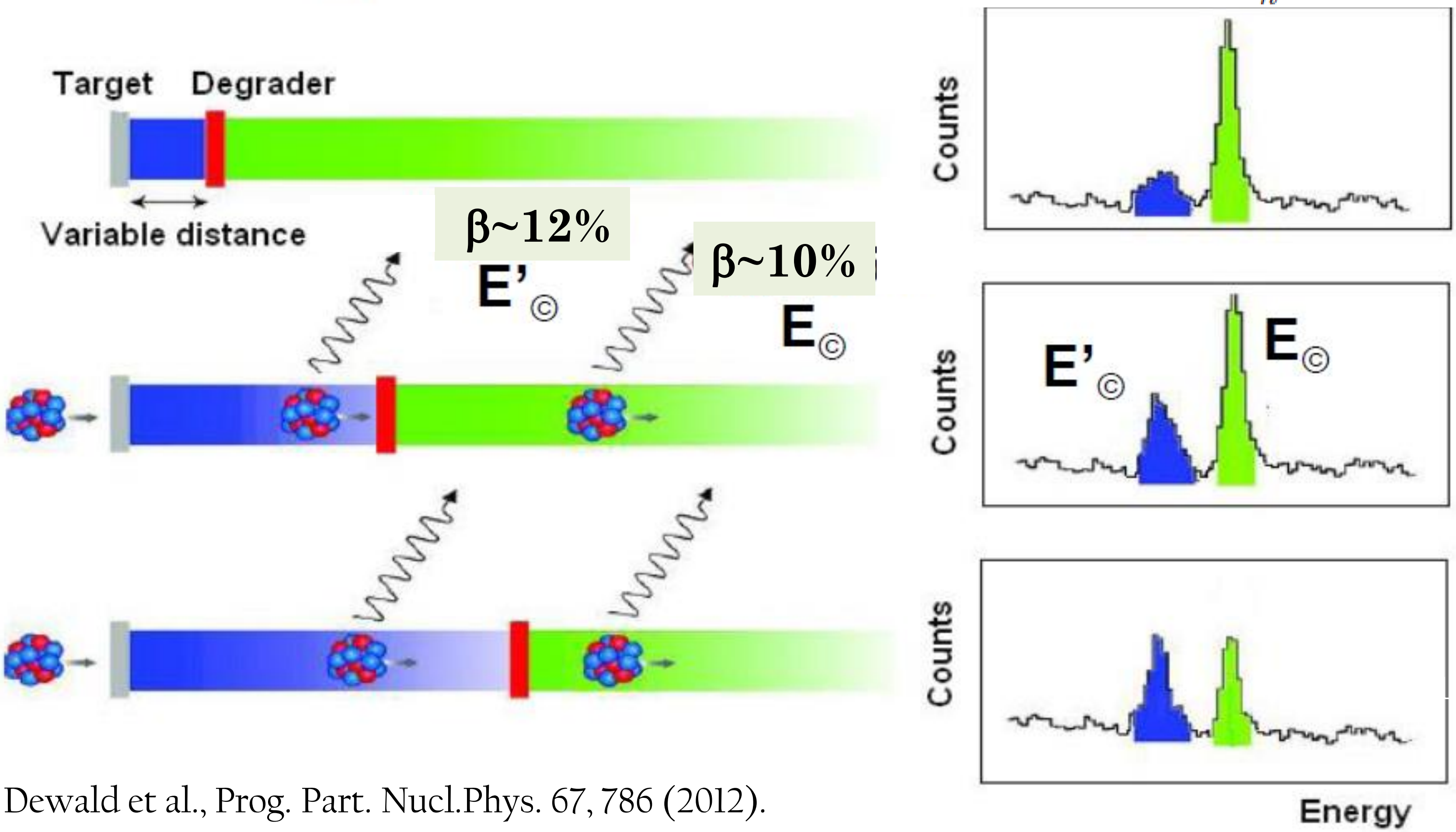
A. Dewald et al., Prog. Part. Nucl.Phys. 67, 786 (2012).

The Recoil-Distance Doppler-Shift technique



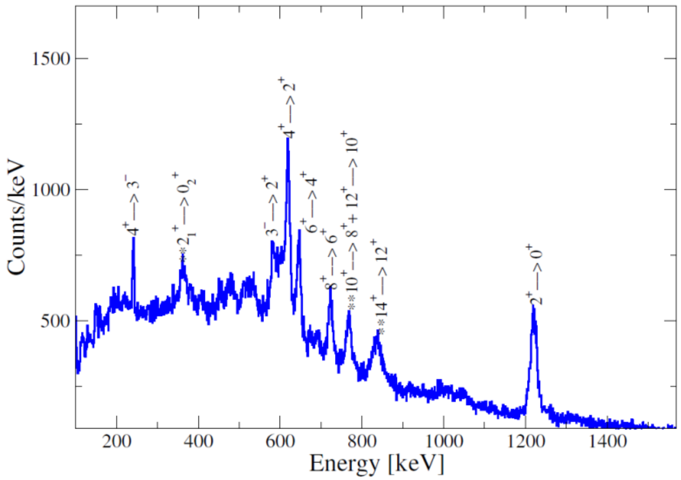
$$Q_{ij}(x) = \frac{I^u_{ij}(x)}{I^u_{ij}(x) + I^s_{ij}(x)}$$

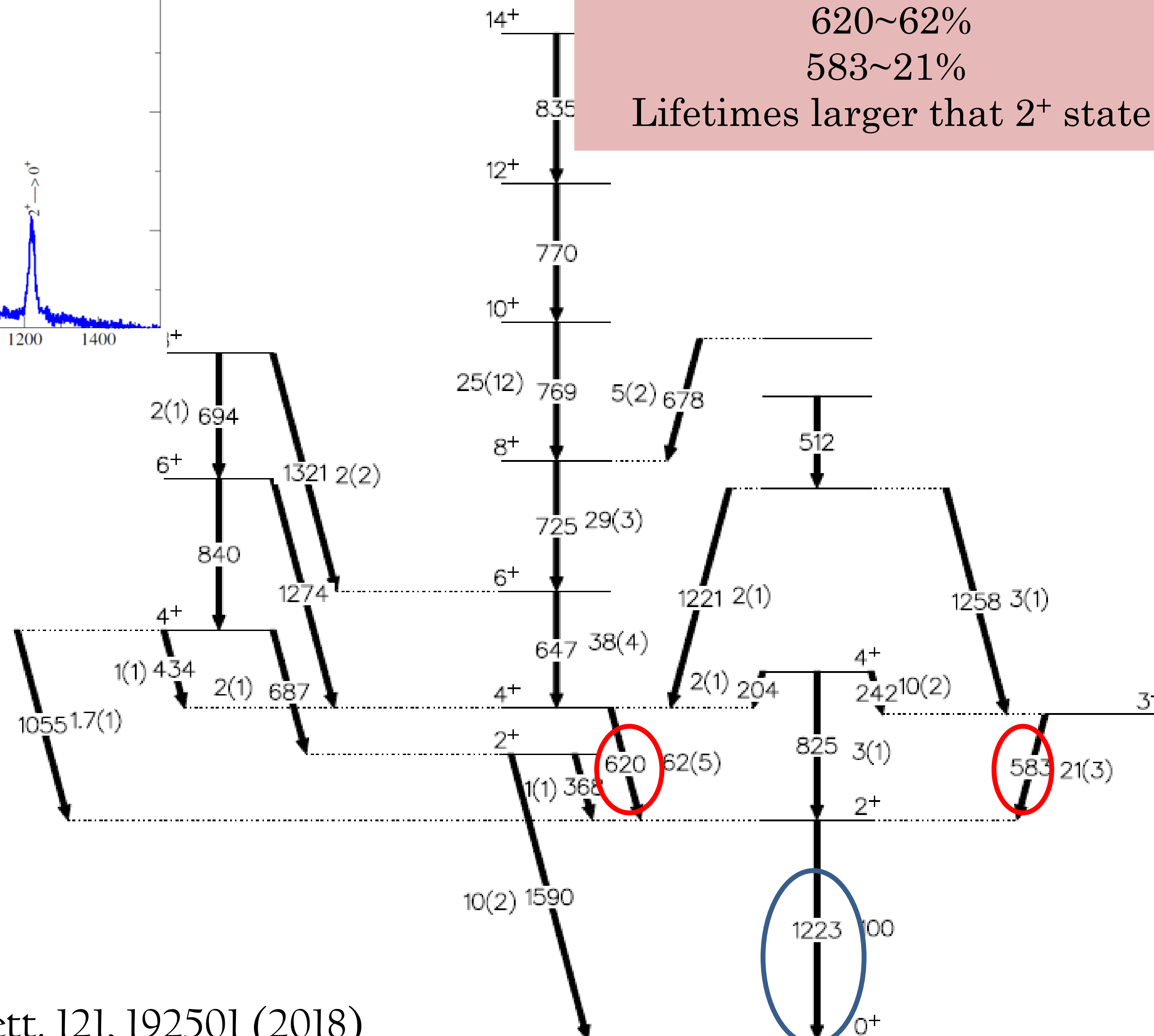
$$\tau_i(x) = -\left[v\frac{dQ_{ij}(x)}{dx}\right]^{-1}\left[Q_{ij}(x) - b_{ij}\sum_h \alpha_{hi}Q_{hi}(x)\right]$$



A. Dewald et al., Prog. Part. Nucl.Phys. 67, 786 (2012).

Results

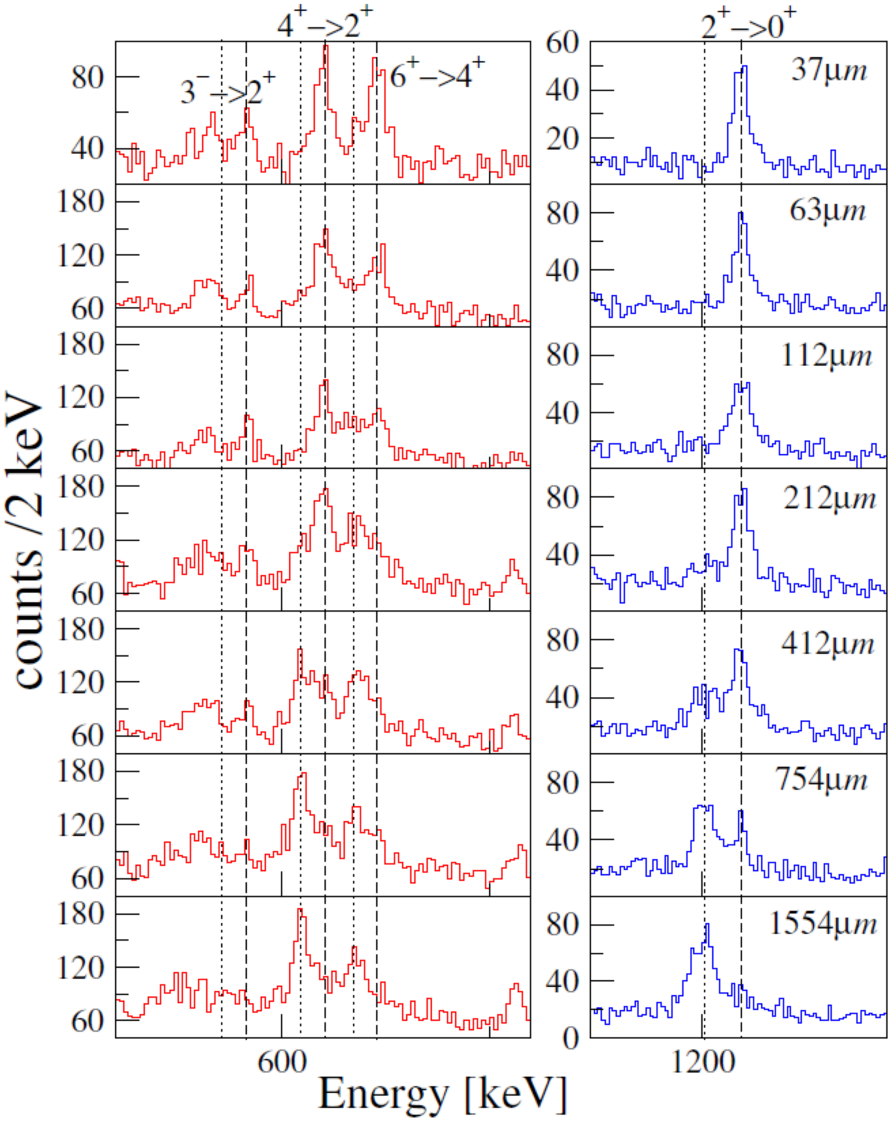


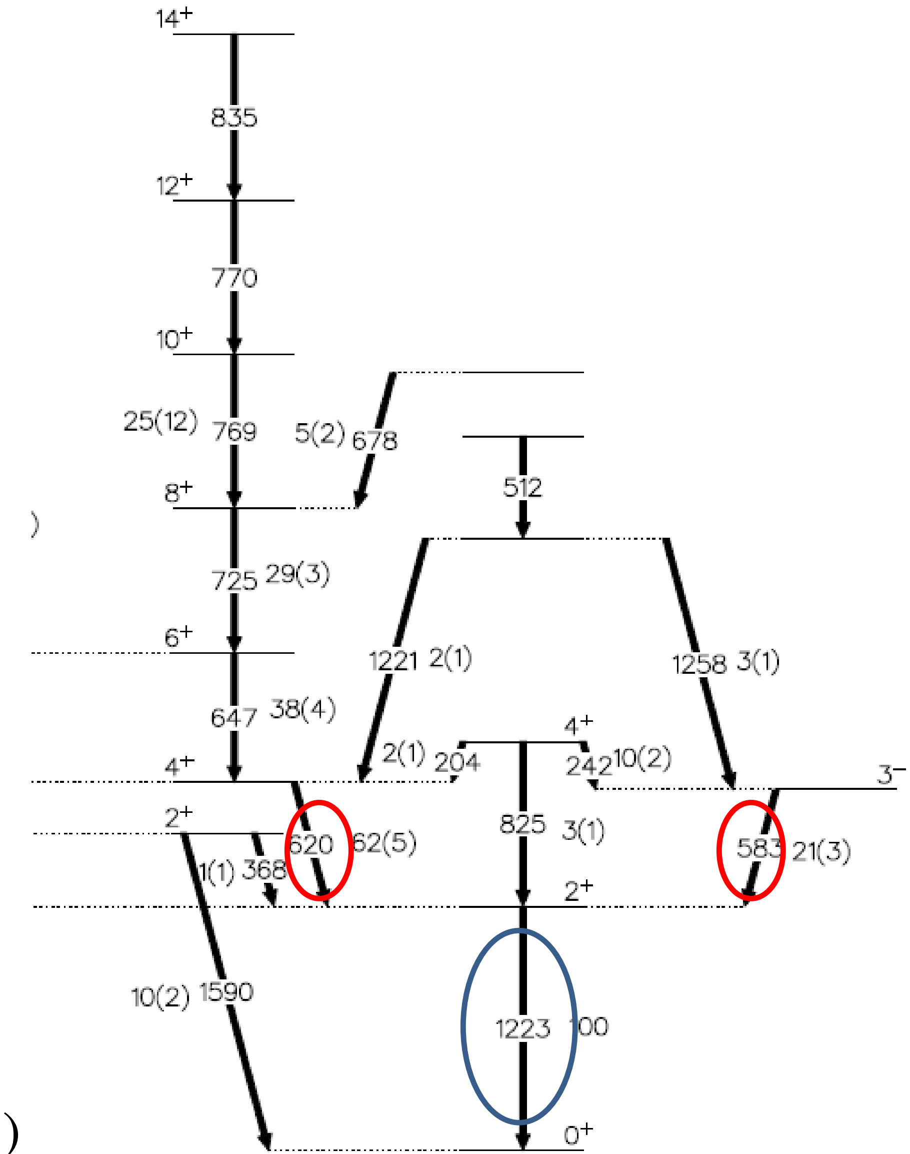


2+ level fed by several transitions
620~62%
583~21%
Lifetimes larger that 2+ state

P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

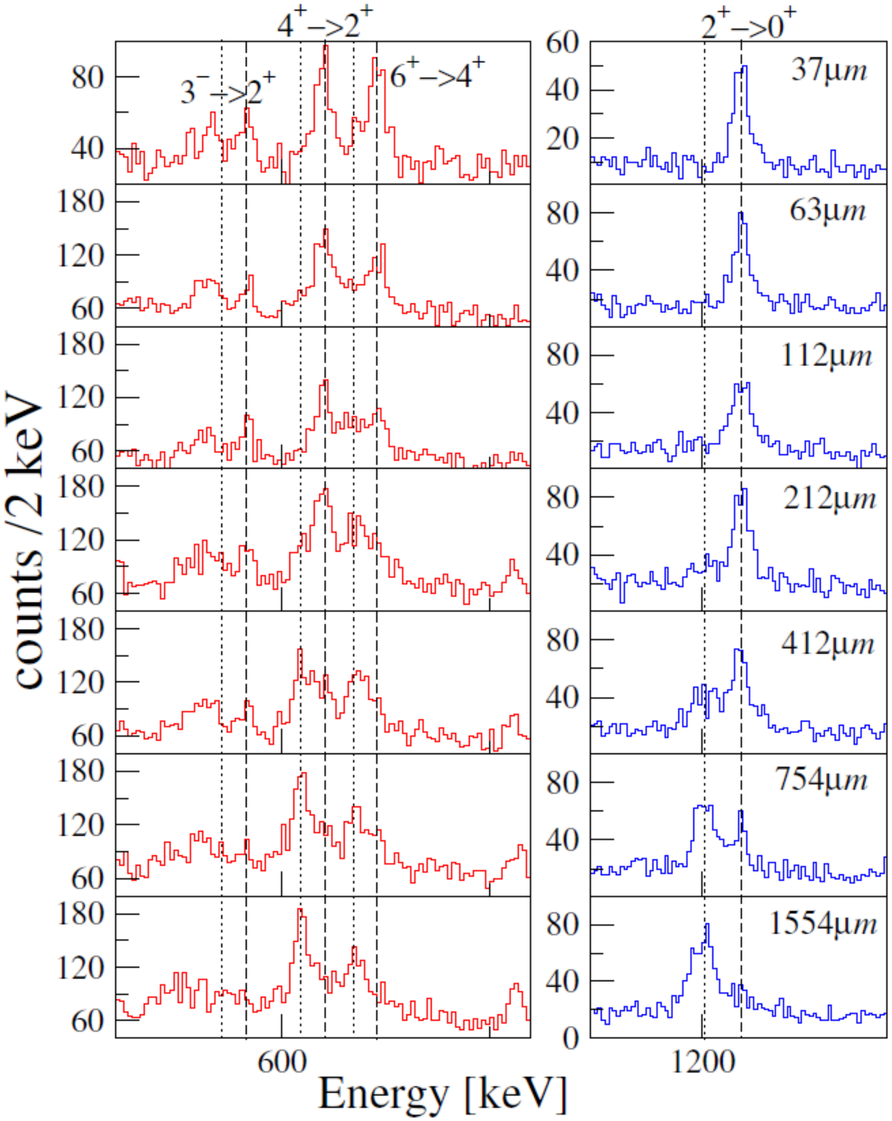
Results

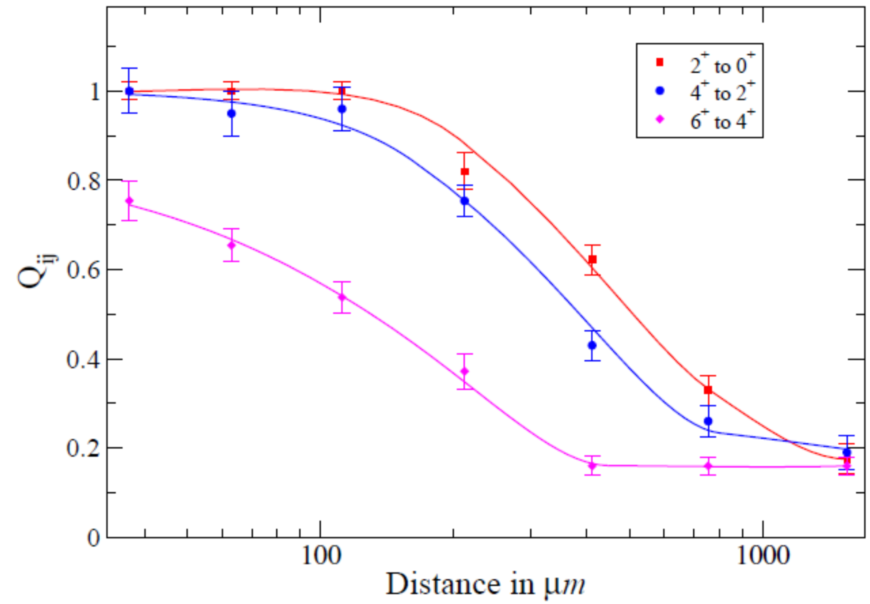


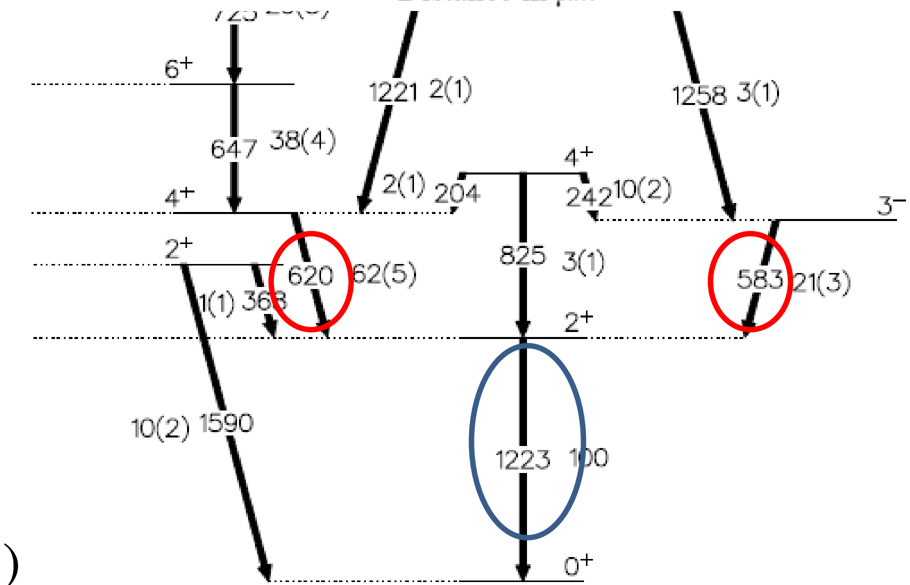


P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

Results

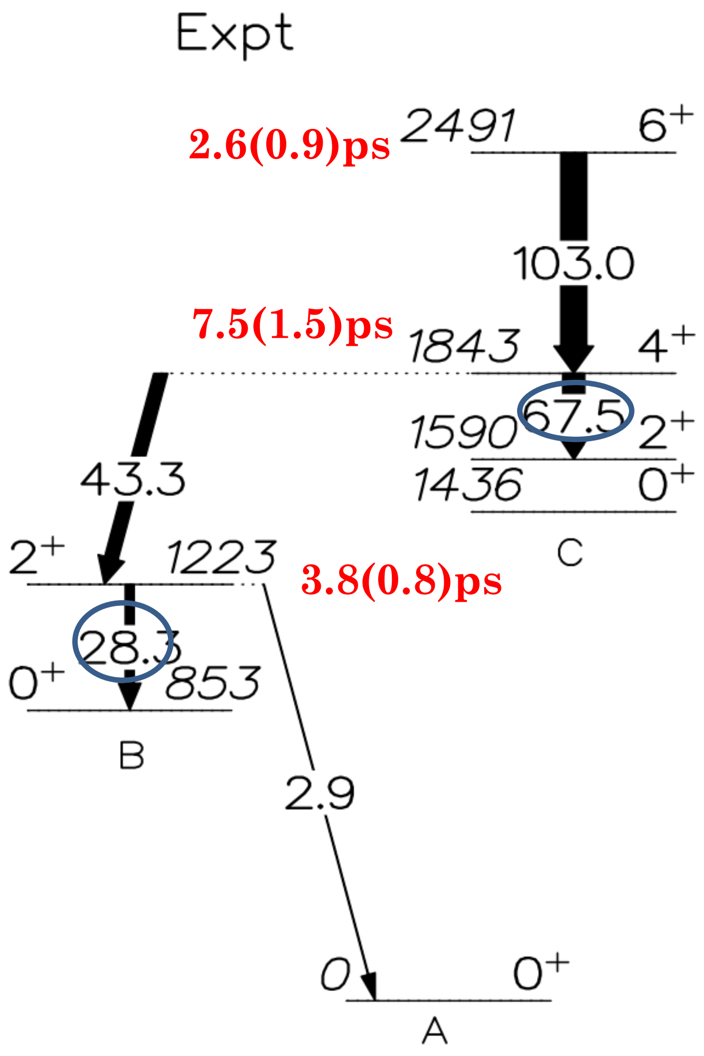






P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

Results



Determination of B(E2) from RDDS lifetime measurements

$B(E2\ 2_1^+ \rightarrow 0_1^+)=2.9(6)$

$B(E2\ 4_1^+ \rightarrow 2_1^+)=43.3(7.5)$

$B(E2\ 6_1^+ \rightarrow 4_1^+)=103.0(36)$

Extraction of B(E2) using known branching ratios (Urban et al.)

$B(E2\ 2_1^+ \rightarrow 0_2^+)=28.3(6.5)$ ($\beta\sim0.21$)

$B(E2\ 4_1^+ \rightarrow 2_2^+)=67.5(16.2)$

W. Urban et al., Phys. Rev. C 96, 044333 (2017)

$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L\left((2L+1)!!\right)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \rightarrow J_f)$$

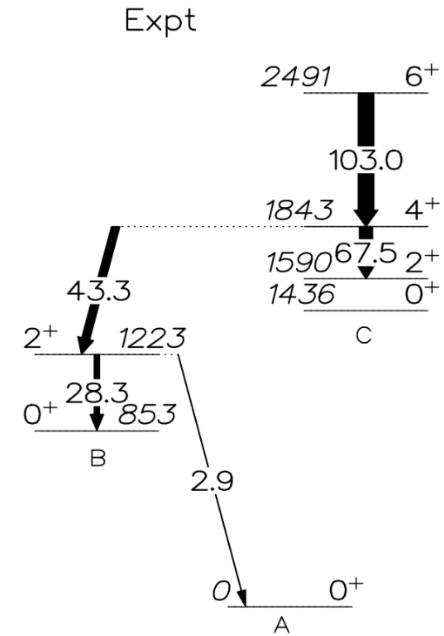
$$T(E2) = 1.223 \times 10^9 E_\gamma^5 B(E2)$$

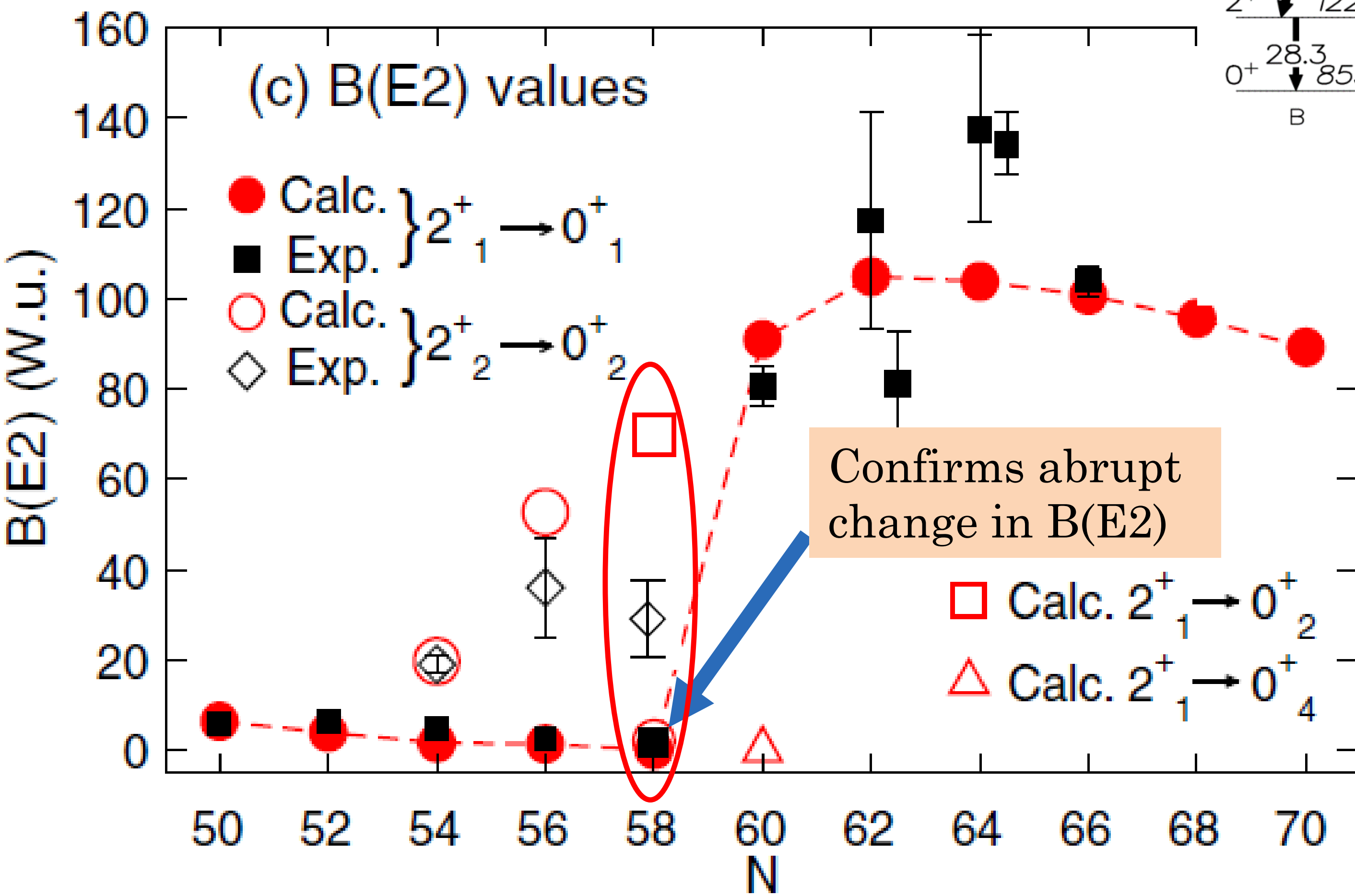
$$e^2 \cdot b^2 = (5.94\times10^{-6})A^{4/3} \text{ w.u.}$$

P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

Results

B(E2 $2_1^+ \rightarrow 0_1^+$)=2.9(6)
B(E2 $2_1^+ \rightarrow 0_2^+$)=28.3(6.5) ($\beta \sim 0.21$)



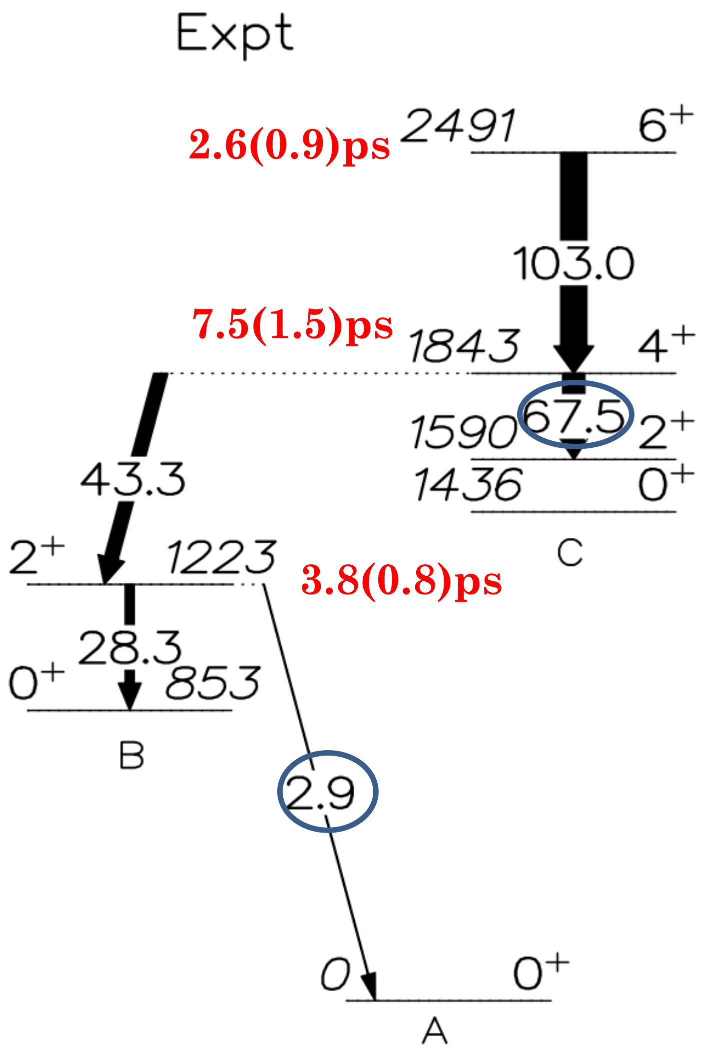


Confirms abrupt change in B(E2)

Togashi et al. Phys.Rev.Lett. 117, 172502 (2016).
T. Otsuka priv comm.

P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

Results



Coexistence of three structures at low spin

0_1^+

B(E2 $2_1^+ \rightarrow 0_1^+$)=2.9(6)

0_2^+

B(E2 $2_1^+ \rightarrow 0_2^+$)=28.3(6.5) ($\beta \sim 0.21$)

0_3^+

B(E2 $4_1^+ \rightarrow 2_2^+$)=67.5(16.2)

B(E2 $6_1^+ \rightarrow 4_1^+$)=103.0(36)

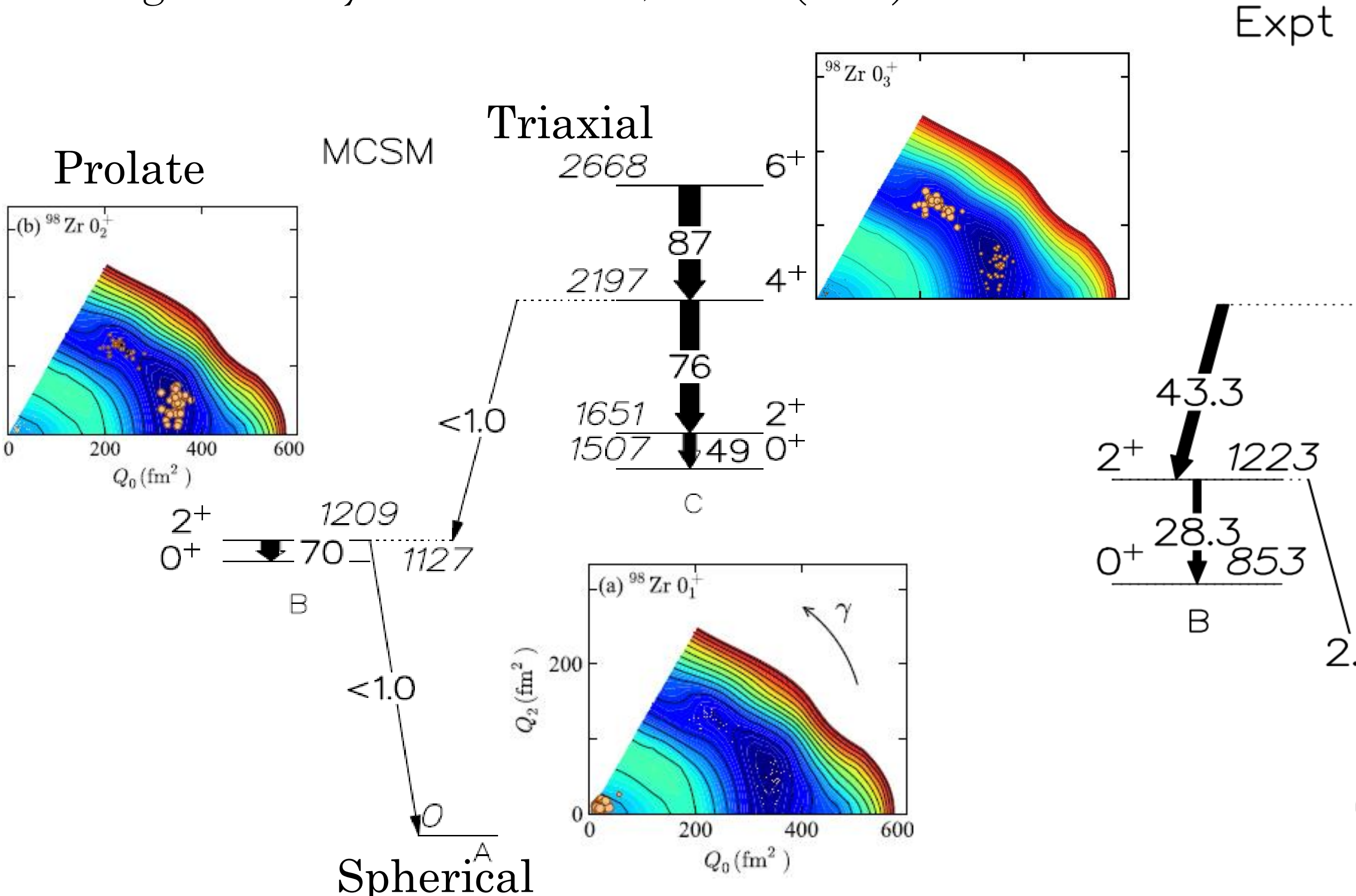
Large mixing

B(E2 $4_1^+ \rightarrow 2_1^+$)=43.3(7.5)

P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

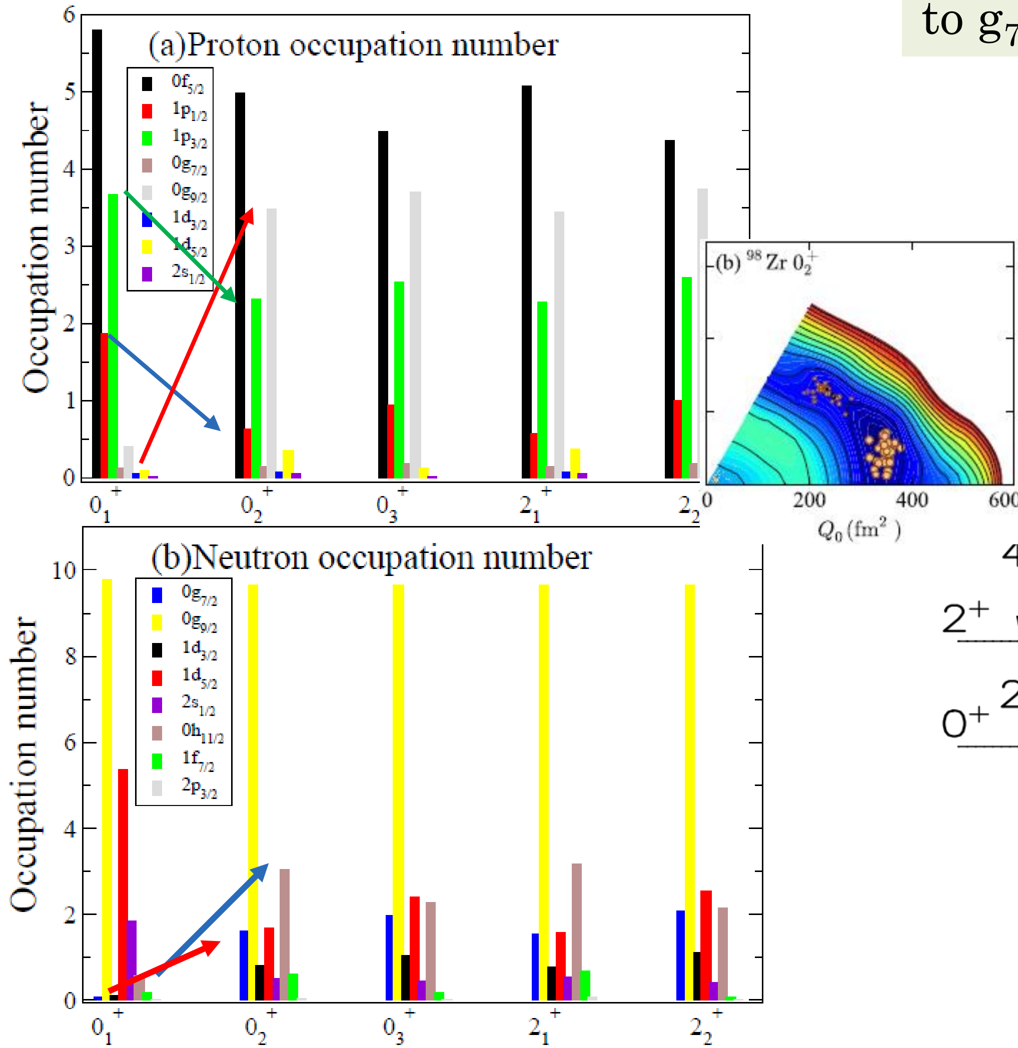
Coexisting shapes: MCSM calculations

Togashi et al. Phys.Rev.Lett. 117, 172502 (2016).
T. Otsuka priv comm.
P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

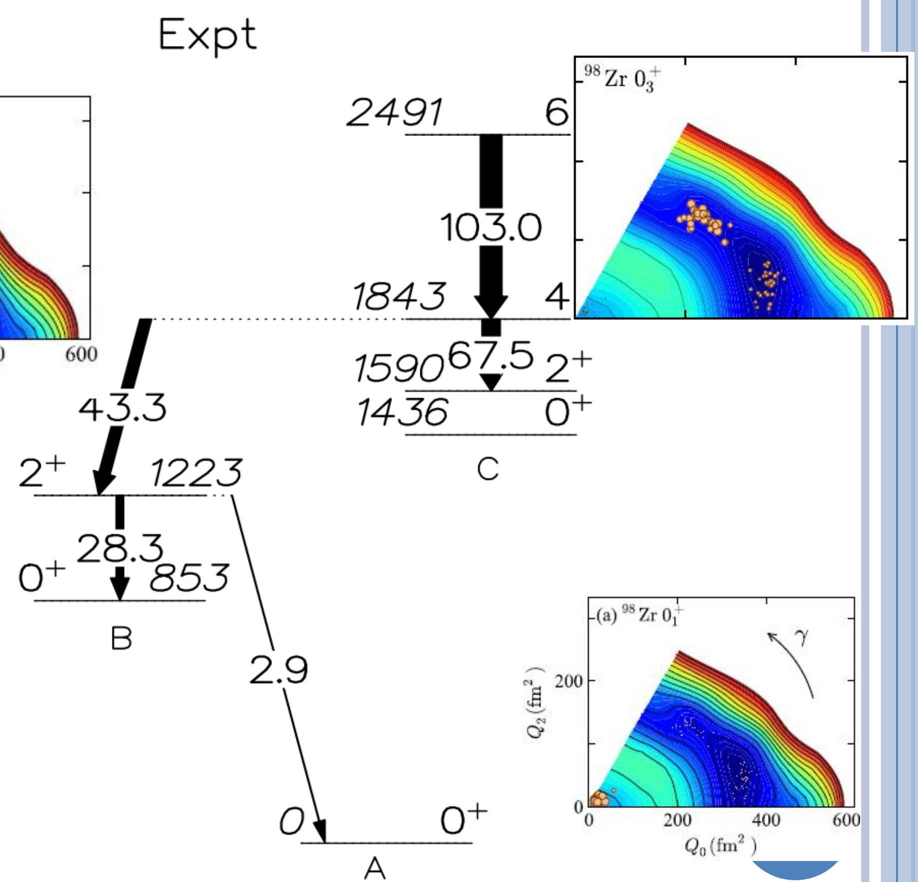


Results

3 proton excitations from pf orbitals to $g_{9/2}$
5 neutron excitations from $d_{5/2}$,$s_{1/2}$ to $g_{7/2}$,$d_{3/2}$ and $h_{11/2}$



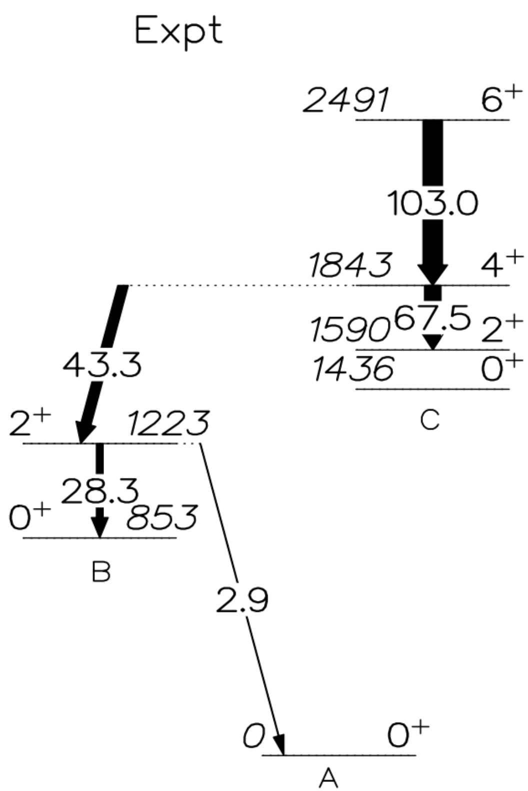
P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)

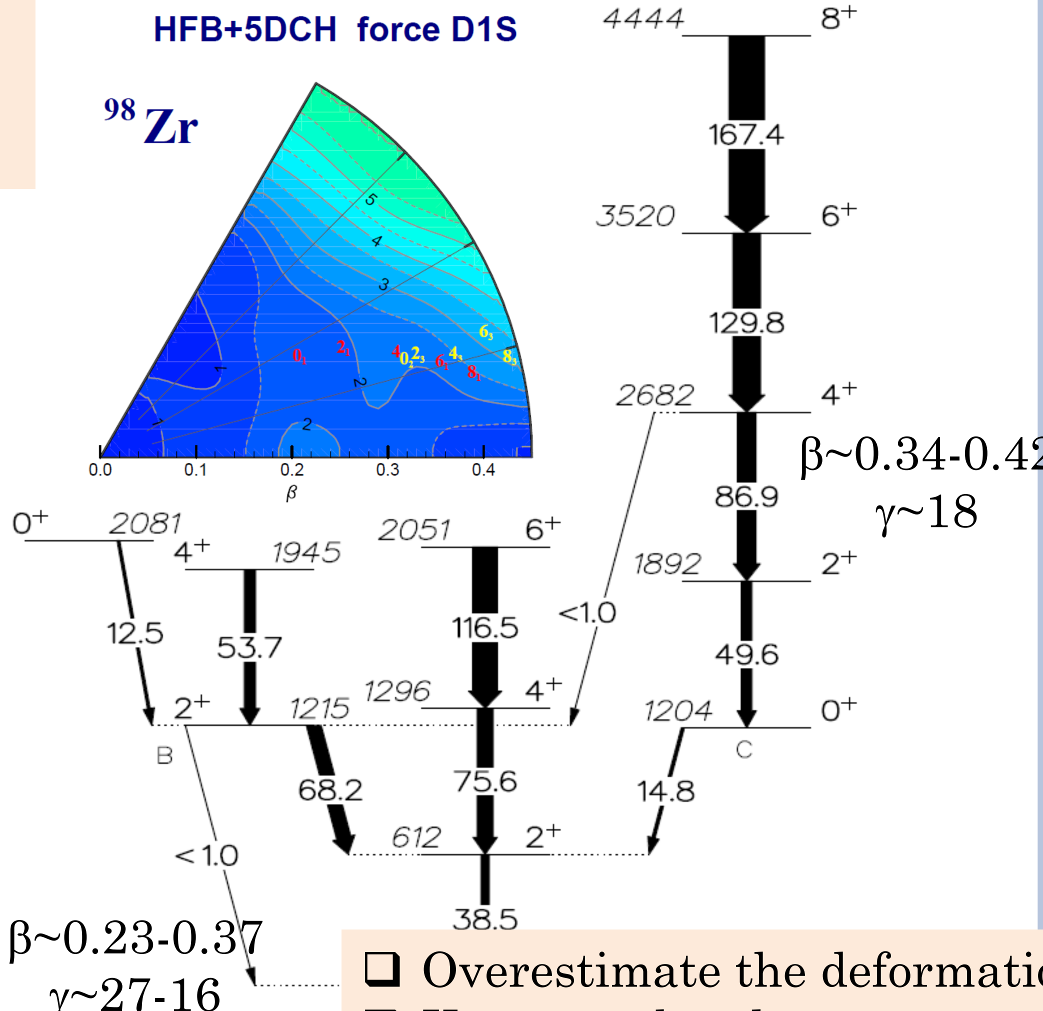


Togashi et al. Phys.Rev.Lett. 117, 172502 (2016).
T. Otsuka priv comm.

Beyond mean field calculations

0$_3$+ calculated too high in energy; No spherical ground state





P. Singh et al. Phys. Rev. Lett. 121, 192501 (2018)
J.-P. Delaroche et al., Phys. Rev.C 81, 014303 (2010) and private communication

- ❑ Overestimate the deformation
- ❑ K=0 yrast band structure
- ❑ Well deformed prolate structure

Summary

- Lifetime measurement in ^{98}Zr using RDDS method on isotopically identified fission fragments.
- B(E2 $2_1^+ \rightarrow 0_1^+$)=2.9 W.u; confirms the sudden onset of collectivity at N=60
- Effect well described by the Monte-Carlo Shell-Model calculations
- Limited success of beyond mean field calculations in explaining the behaviour
- Established two deformed structures coexisting with spherical G.S
- Comparison with state-of-art MCSM calculations indicate spherical-prolate-triaxial shape coexistence

Collaborations

W. Korten, L. Grente, M.-D. Salsac
B. Bruyneel, C. Louchart,
B. Sulignano, Ch. Theisen

T. W. Hagen, A. Gorgen
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M. Hackstein, W. Rother
C. Muller-Gatermann,

T.Otsuka, T. Togashi, Y. Tsunoda

F. Recchia

Thank you