In-beam spectroscopy of neutron-rich Mg isotopes

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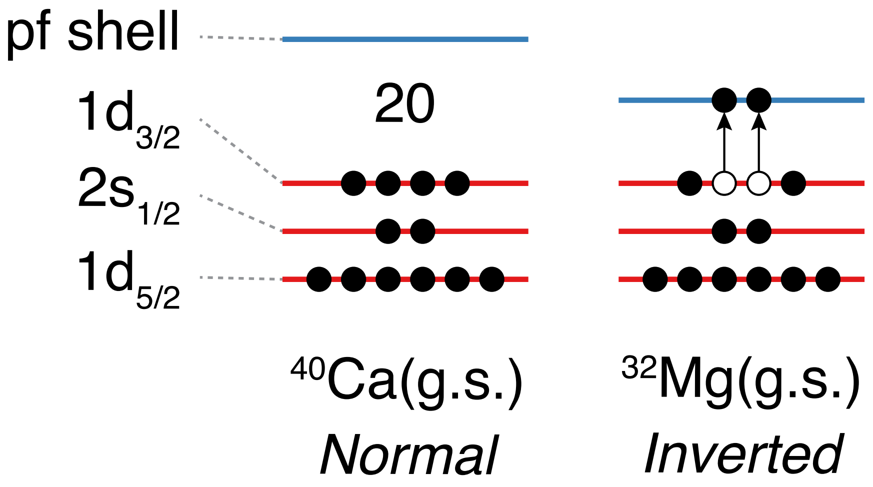
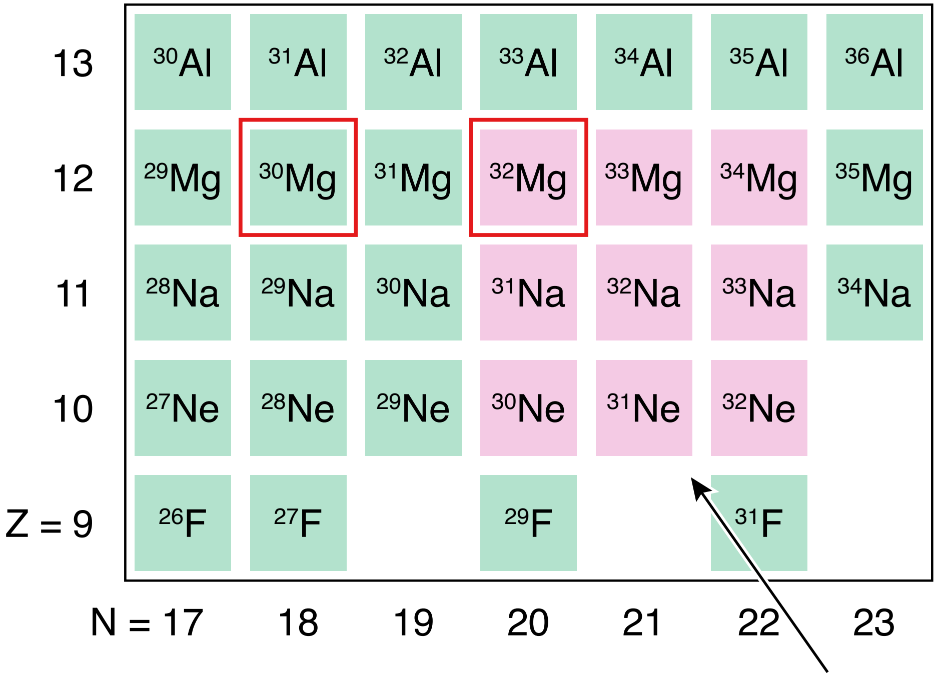
The island of inversion

Simplified neutron configurations
in N = 20 nuclei





	N = 17	18	19	20	21	22	23
13	^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al
12	^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg
11	^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na
10	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne	
Z = 9	^{26}F	^{27}F		^{29}F		^{31}F	

Original island of inversion proposed in
E. K. Warburton et al., PRC **41**, 1147 (1990)

Neutron-rich nuclei around ^{32}Mg are characterized by intruder-dominated ground states

- Dominance of cross-shell excitations, 2p2h etc.
- Disappearance of the N = 20 magic number

Spectroscopy of neutron-rich Mg isotopes enables us to track structural evolution approaching the island

Present understanding of the transition into the island

^{30}Mg (N = 18): outside

- Dominance of 0p0h (normal) configuration in the ground state
- Mixing of 0p0h and 2p2h leads to shape coexistence

  W. Schwerdtfeger et al., PRL **103**, 012501 (2009)

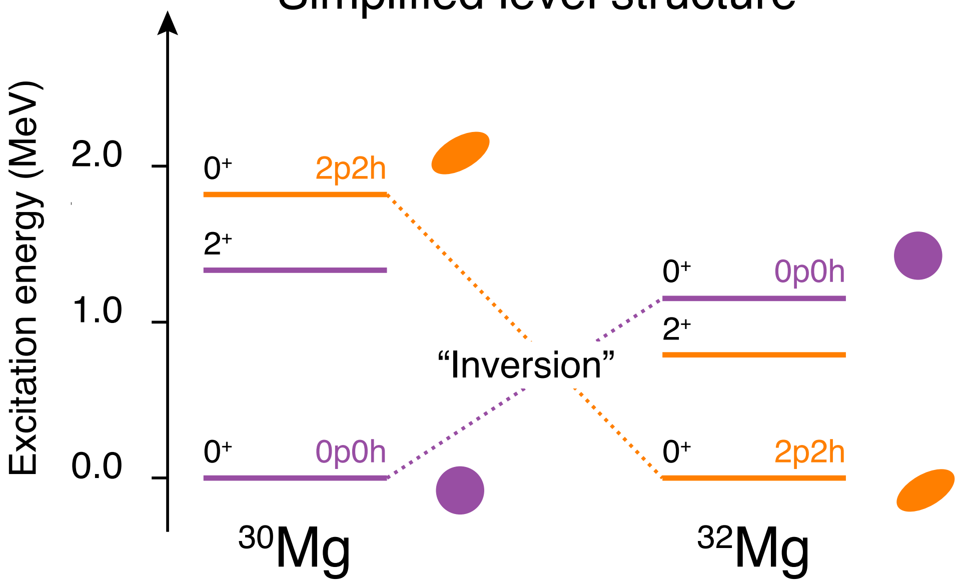
^{32}Mg (N = 20): inside

T. Motobayashi et al., PLB **346**, 9 (1995)

- Coexisting shapes, but the two 0^+ are reversed as compared to ^{30}Mg

  K. Wimmer et al., PRL **105**, 252501 (2010)

Simplified level structure



This picture is intuitive. But, how accurate is this?

N. Hinohara et al., PRC **84**, 061302(R) (2011)

A. O. Macchiavelli et al., PRC **94**, 051303 (2016)

Is ^{30}Mg normal?

Recent in-beam γ-ray measurements

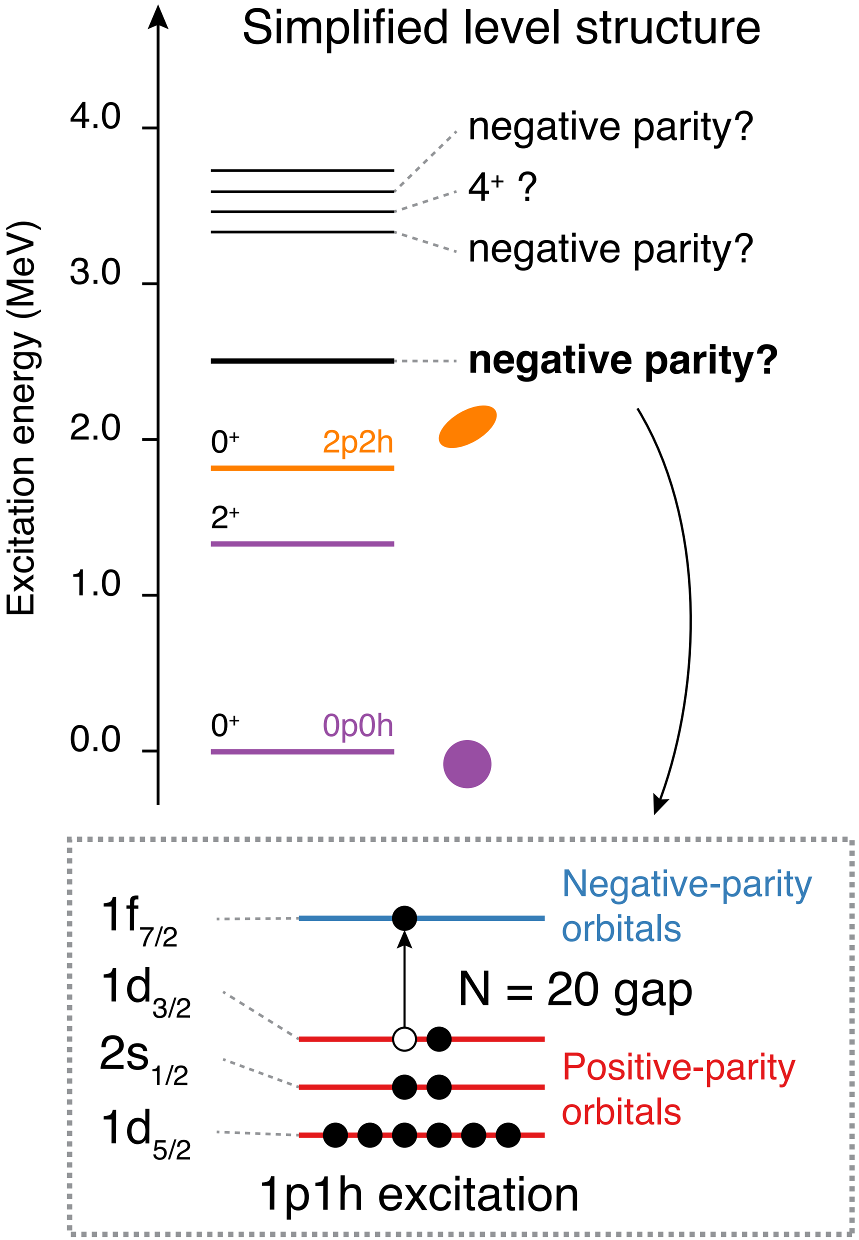
- $^{14}C(^{18}O,2p)^{30}Mg$ fusion-evaporation

  A. N. Deacon et al., PRC **82**, 034305 (2010)
- One-neutron knockout from ^{31}Mg

  B. Fernández-Domínguez et al., PLB **779**, 124 (2018)

These two experiments questioned the present understanding of ^{30}Mg

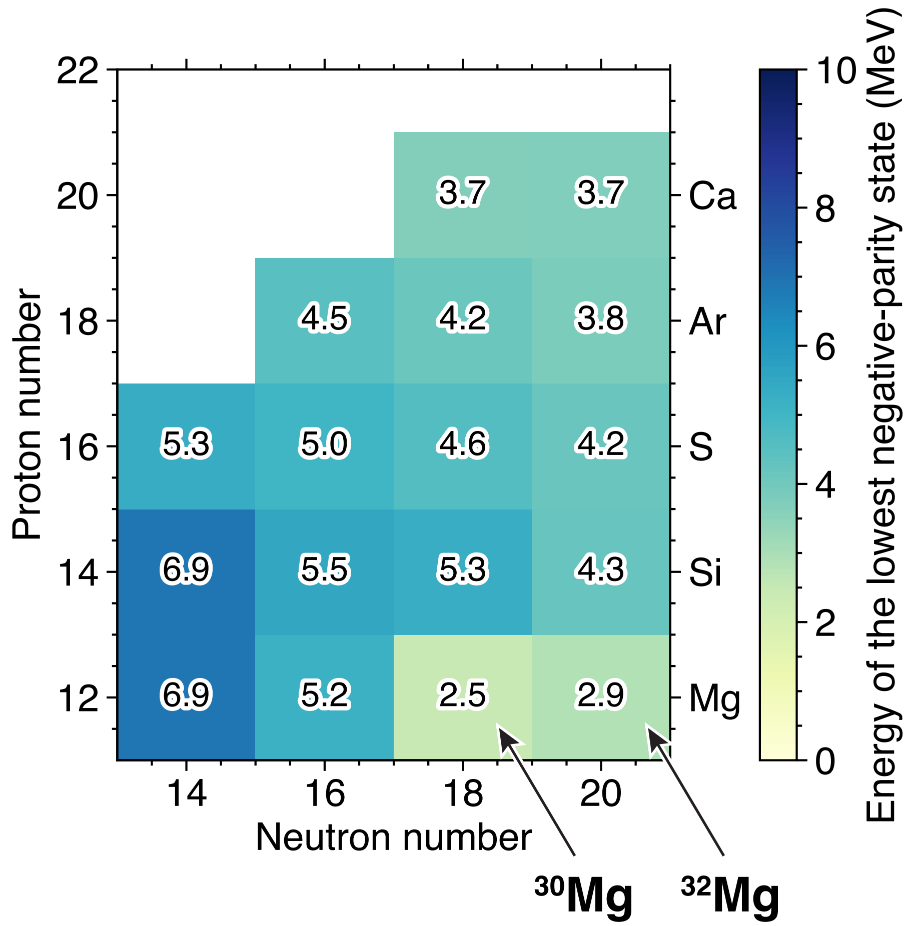
- Unusual negative-parity state at 2.5 MeV



Negative-parity states

Systematics of the lowest negative-parity states in sd-shell nuclei

- Excitation energies of negative-parity states reflect the N = 20 gap size
- Negative-parity state at 2.5 MeV cannot be reproduced by shell model
- Even lower than the negative-parity candidate in ^{32}Mg at 2.9 MeV

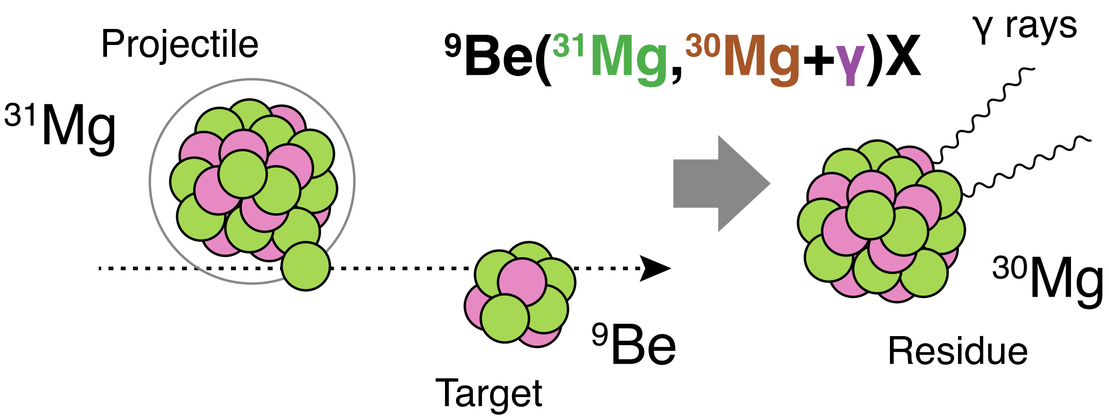


More detailed spectroscopic study for ^{30}Mg (and ^{32}Mg) for conclusive spin-parity assignments is needed

^{30}Mg spectroscopy

- ^{30}Mg is located at the boundary of the island of inversion
  - Structural evolution approaching the island
- Spin-parity assignments for states in ^{30}Mg have yet to be established
  - Negative-parity states are particularly important

- Direct one-neutron removal reaction from ^{31}Mg
  - Highly selective spectroscopic tool
  - Spin-parity determinations via momentum distributions
  - Additional structural information comes from cross sections populating each final state—spectroscopic factors

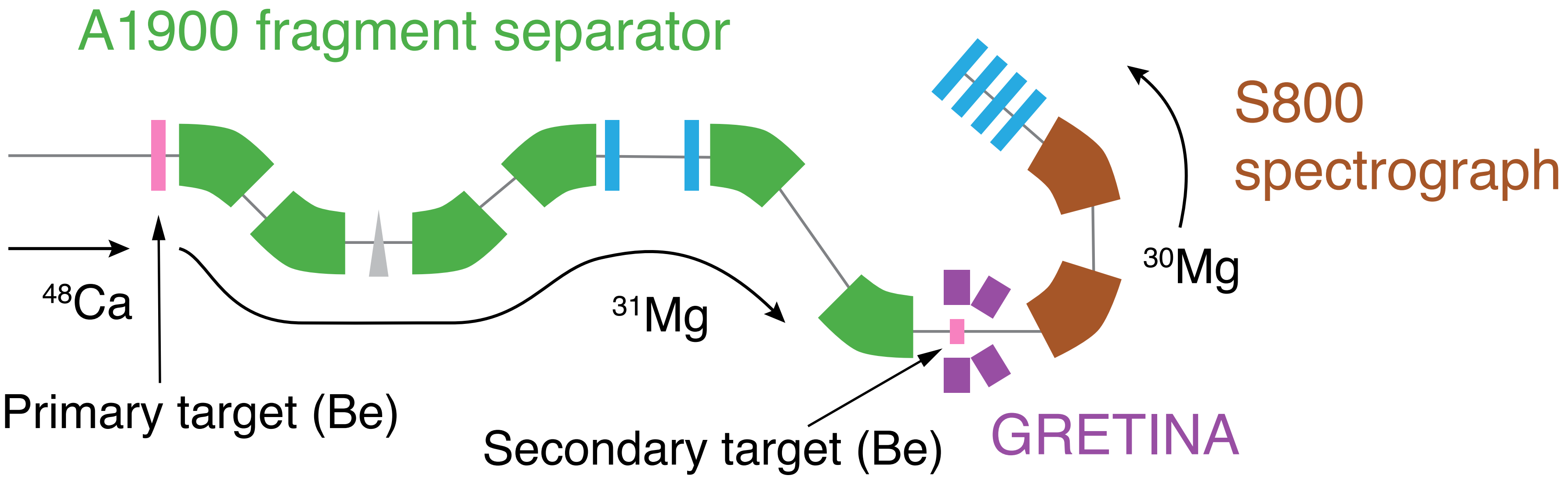


Experimental setup overview

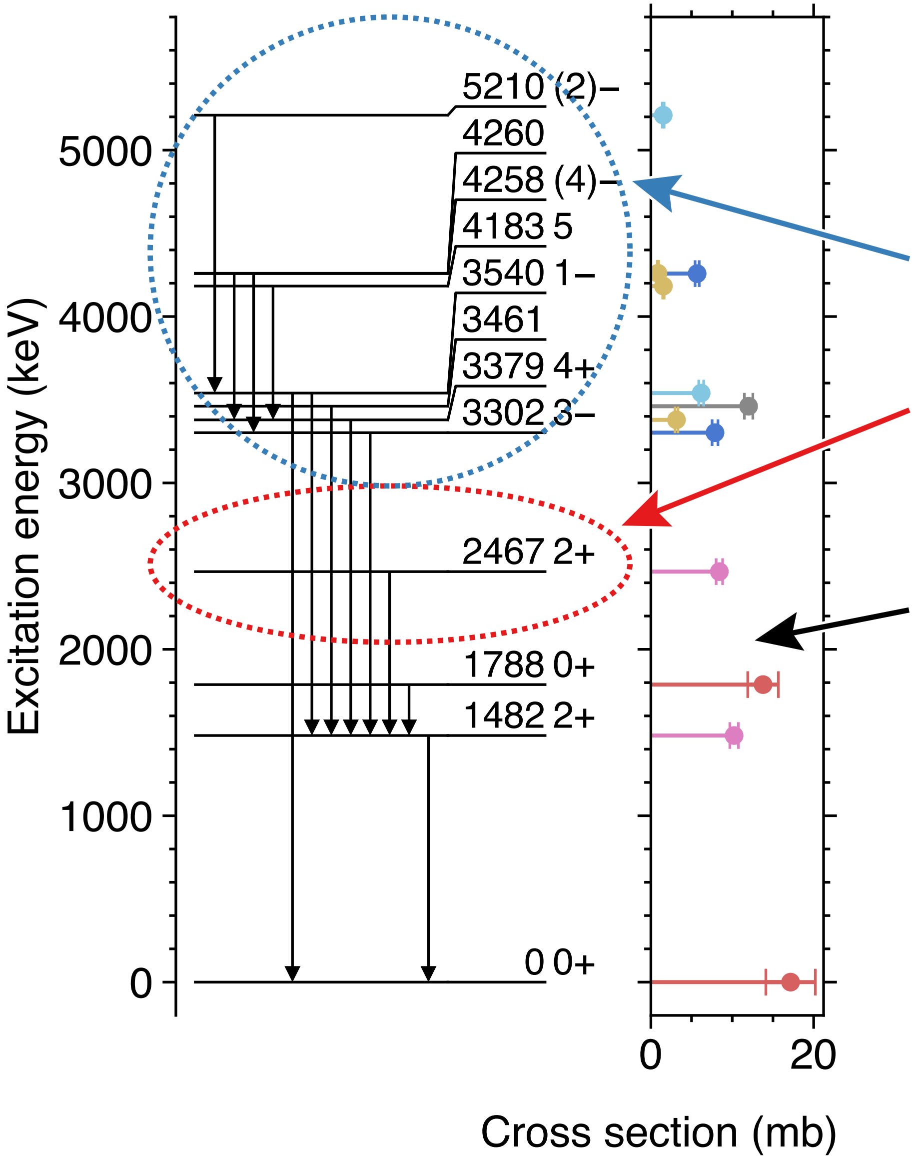
The experiment was performed at National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University

Key devices

- **A1900 fragment separator:** production of radioactive beams
- **S800 spectrograph:** momentum analysis of reaction products
- **GRETINA:** detection of γ rays with hit-position sensitivity



^{30}Mg main results



N. Kitamura et al., PRC **102**, 054318 (2020)

Reliable spin-parity assignments have been made by momentum distribution analysis

- Firm identification of negative-parity states
- **The controversial 2.5-MeV state turned out to be 2^+**

Experimental cross sections populating each final state

- To be compared with theoretical predictions by shell model combined with reaction theory

Shell-model interactions for island-of-inversion nuclei

SDPF-M

Y. Utsuno et al., PRC **60**, 054315(R) (1999)

- Developed in 1999, traditional interaction
- Full sd shell and $f_{7/2}p_{3/2}$ orbitals
- SPEs and TBMEs are empirically adjusted

SDPF-U-MIX

E. Caurier et al., PRC **90**, 014302 (2014)

- Full sdpf degree of freedom, state-of-the-art interaction
- SPEs and TBMEs are empirically adjusted

EEdf1

Y. Tsunoda et al., PRC **95**, 021304(R) (2017)

- Microscopically derived using the EKK method
- Full sdpf degree of freedom, state-of-the-art interaction
- No TBME adjustments

Comparison with shell-model calculations

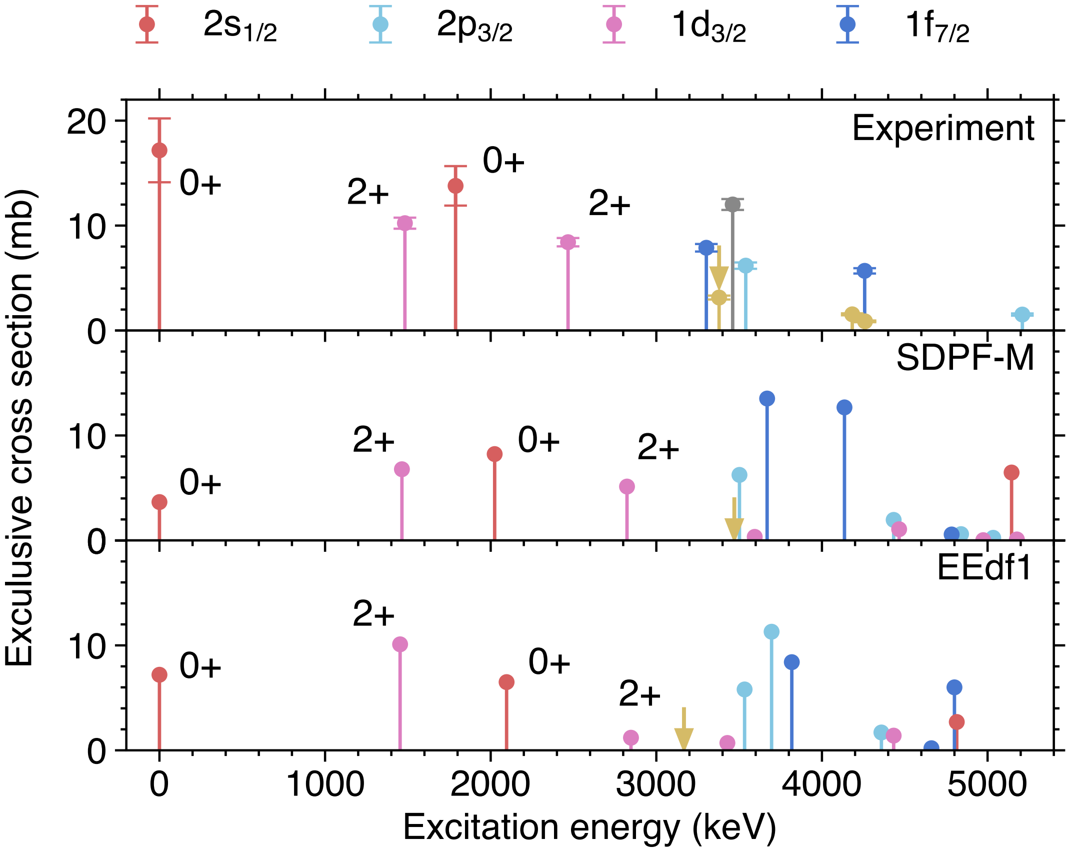
- Level energies are very well reproduced by shell model
- However, theoretical cross sections show a large variation despite the similarity in level structure

Negative-parity states

- EEdf1 shows very good agreement with experiment
- SDPF-M tends to overestimate the $1f_{7/2}$ component

Positive-parity states

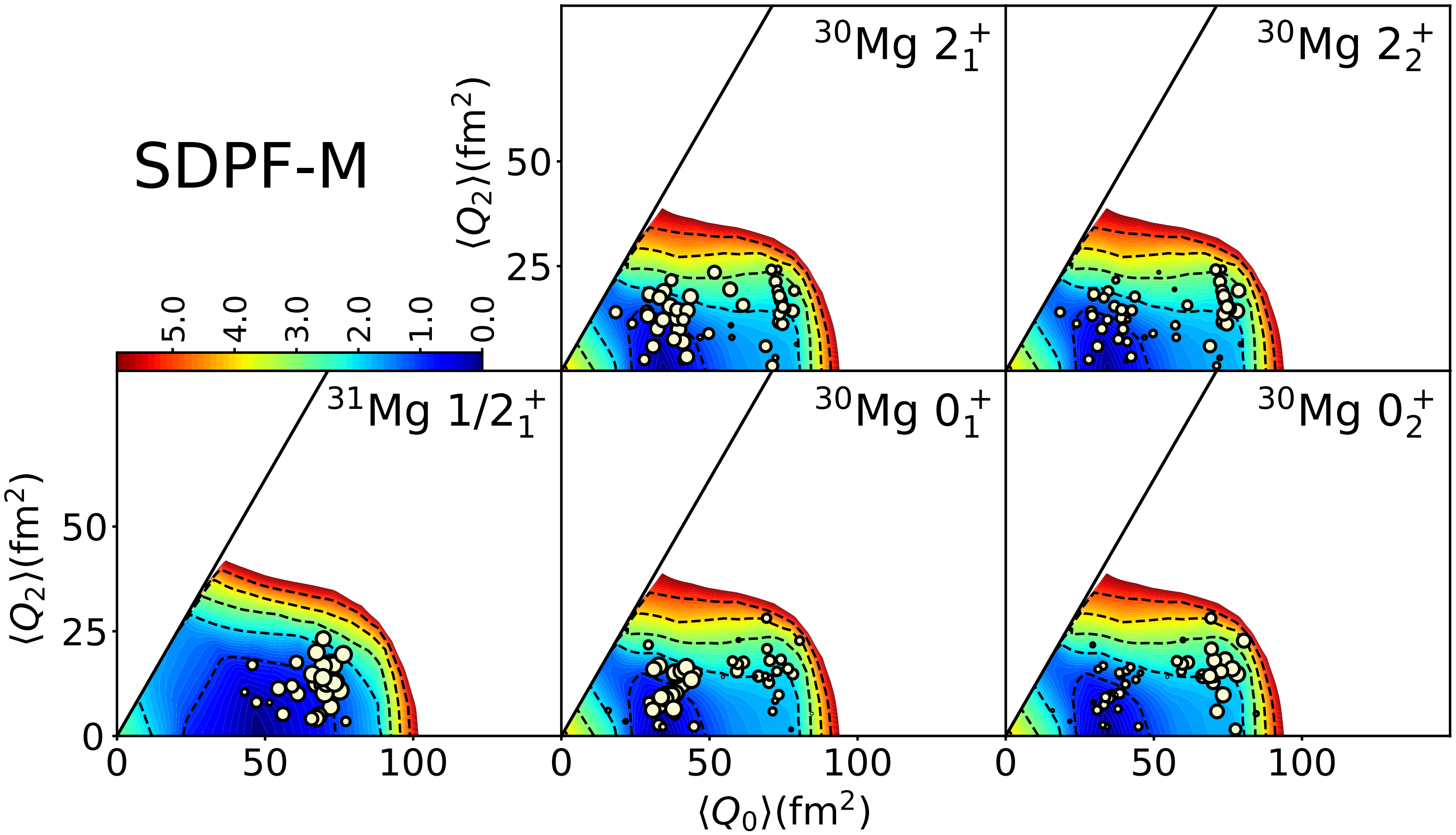
- EEdf1 is not perfect
- Somewhat closer to SDPF-M



Differentiating between SDPF-M and EEdf1

T-plots visualize intrinsic deformation of shell-model eigenstates

Y. Tsunoda et al., PRC **89**, 031301 (2014)



These two interactions paint different pictures of shape coexistence and mixing for ^{30}Mg

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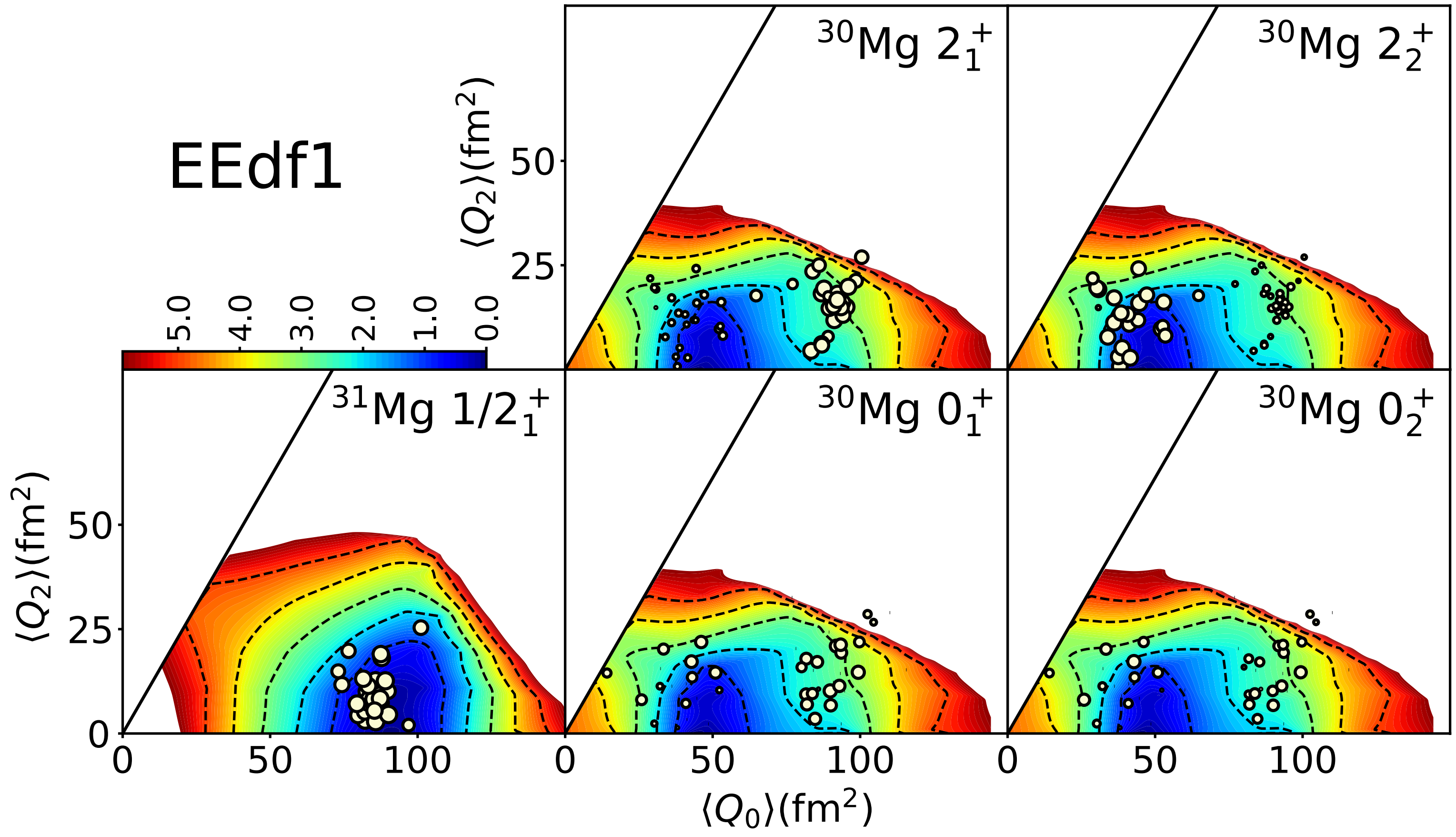


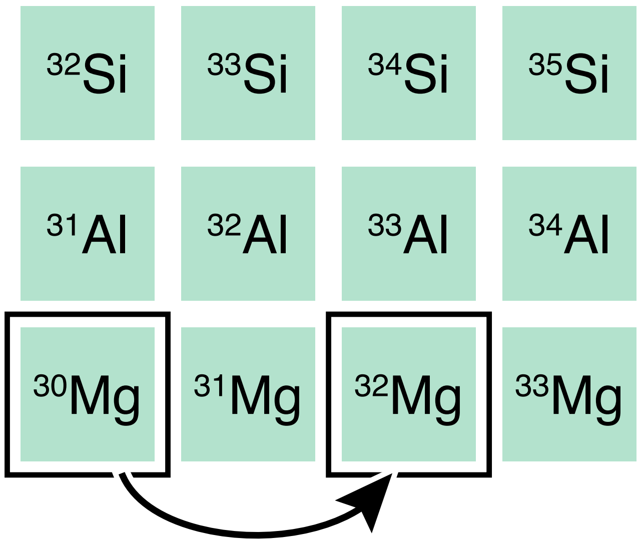
These two interactions paint different pictures of shape coexistence and mixing for ^{30}Mg

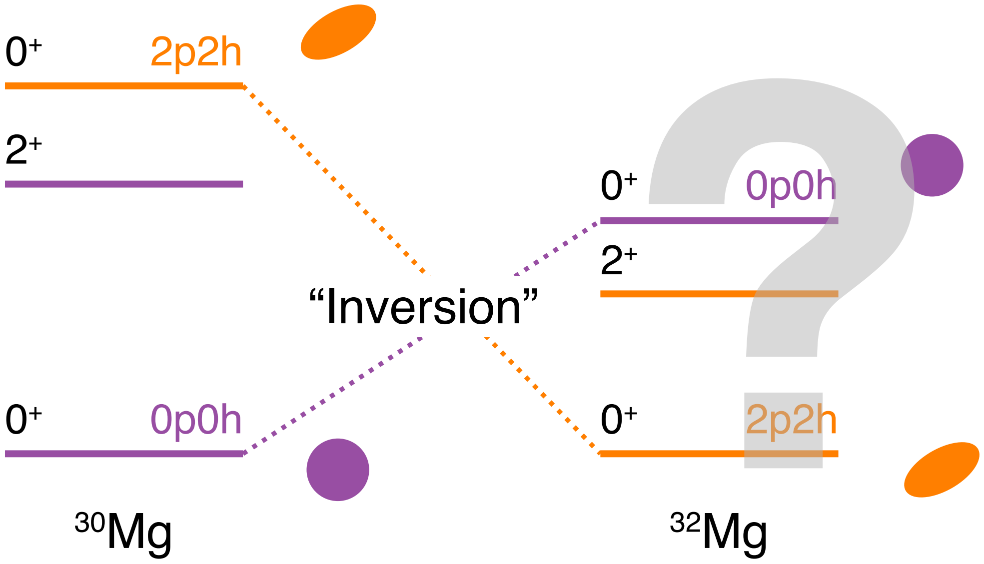
Transition into the island revisited

- The shape-coexistence picture of ^{30}Mg still holds (but oversimplified?)
- Next question: is the description of ^{32}Mg valid?
  - Theory predicts another spherical 0^+ state

    A. O. Macchiavelli et al., PRC **94**, 051303 (2016)

Spectroscopy of ^{32}Mg is an obvious next step

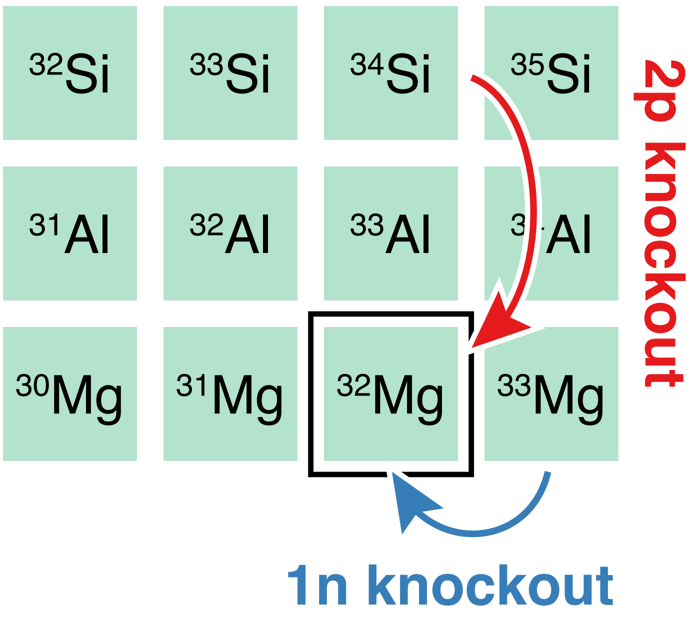


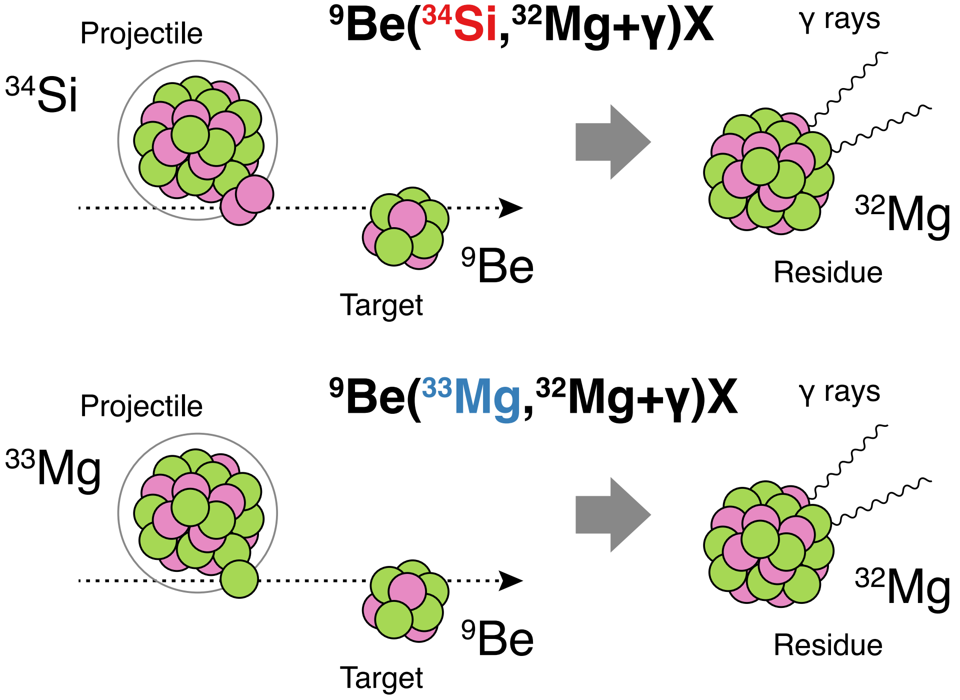


^{32}Mg spectroscopy

States in ^{32}Mg populated using two different direct reactions:
two-proton knockout from ^{34}Si and one-neutron knockout from ^{33}Mg

- ^{34}Si is normal while ^{33}Mg is intruder-dominated—very different population of final states in ^{32}Mg
- Spin-parity assignments through momentum distribution analysis
- Experimental cross sections can be compared with theory predictions




^{9}Be(^{34}Si,^{32}Mg+γ)X

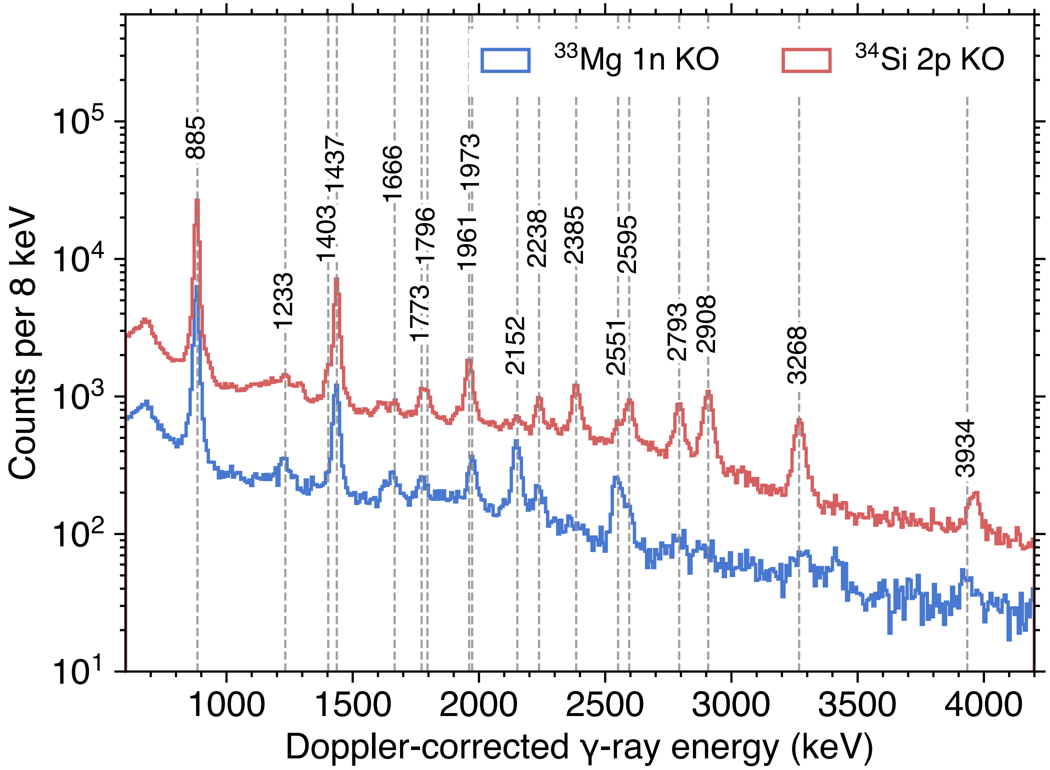
^{9}Be(^{33}Mg,^{32}Mg+γ)X

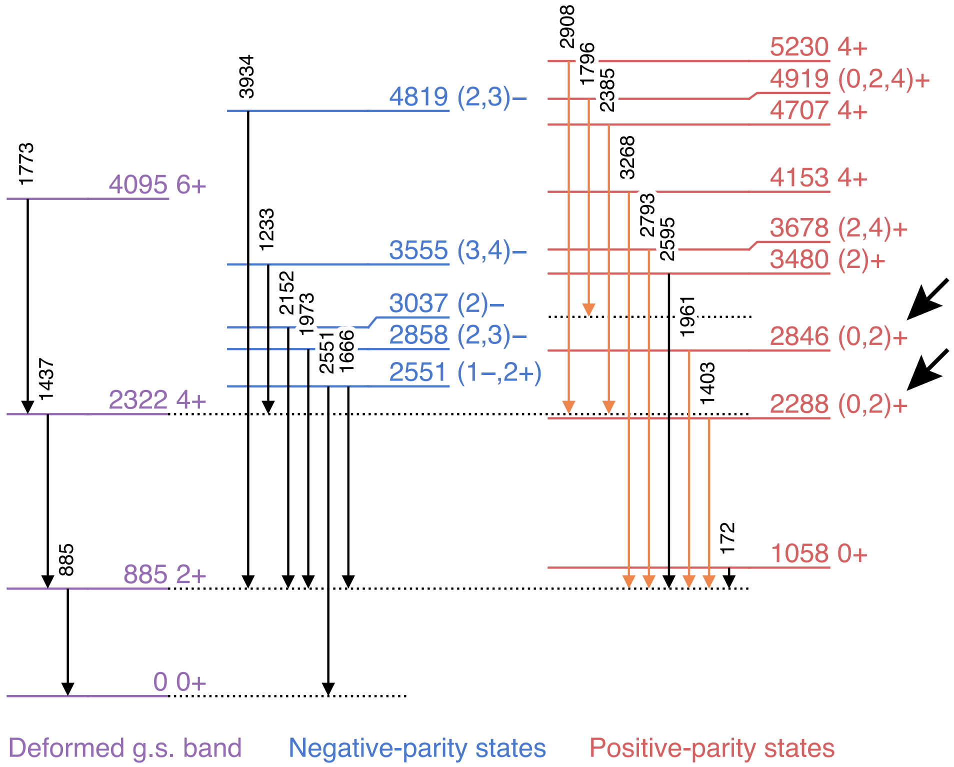
^{32}Mg main results

Normal positive-parity states and intruder negative-parity states

Coexistence of a variety of structures in ^{32}Mg

N. Kitamura et al., PLB **822**, 136682 (2021)



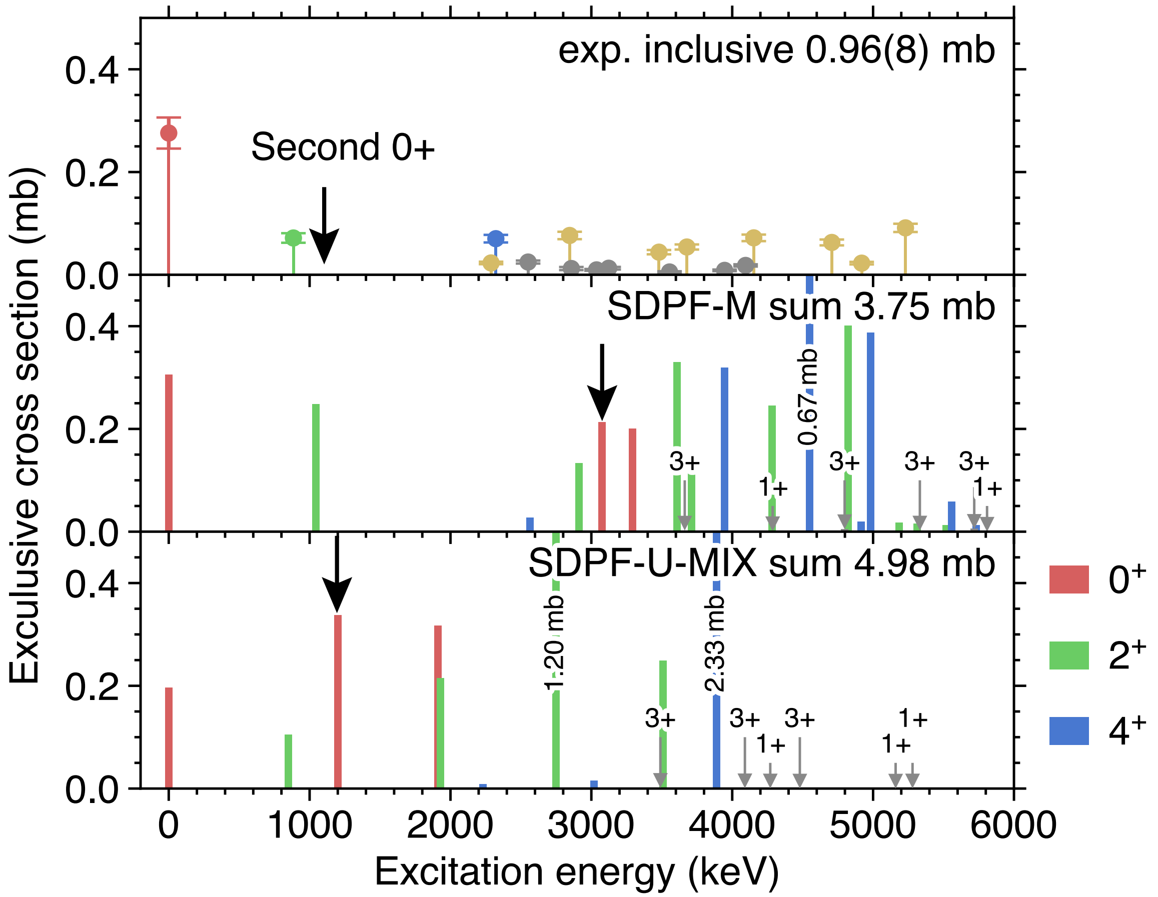


1n knockout is also sensitive to ^{33}Mg(g.s.) spin-parity—determined to be $3/2^-$

Comparison with theory: ^{34}Si two-proton knockout

Experimental results and theory predictions differ greatly

- Reproduction of the second 0^+ energy is a challenging task
- SDPF-U-MIX correctly reproduces the second 0^+ energy, but the cross sections are incompatible with experiment



Summary

The island of inversion

- A rich test ground for nuclear theories and our understanding

Experiment

- Detailed in-beam γ-ray spectroscopy of ^{30}Mg and ^{32}Mg using direct nucleon knockout reactions
- Level schemes and spin-parity assignments have been updated

Findings

- Establishment of negative-parity states in ^{30}Mg
- Coexistence of a variety of structures in ^{32}Mg
- Consistent description of all observables is yet to be achieved
- The picture of the transition into the island and shape coexistence is much more complex