Shape and collectivity in ^{80}Ge studied via Coulomb excitation

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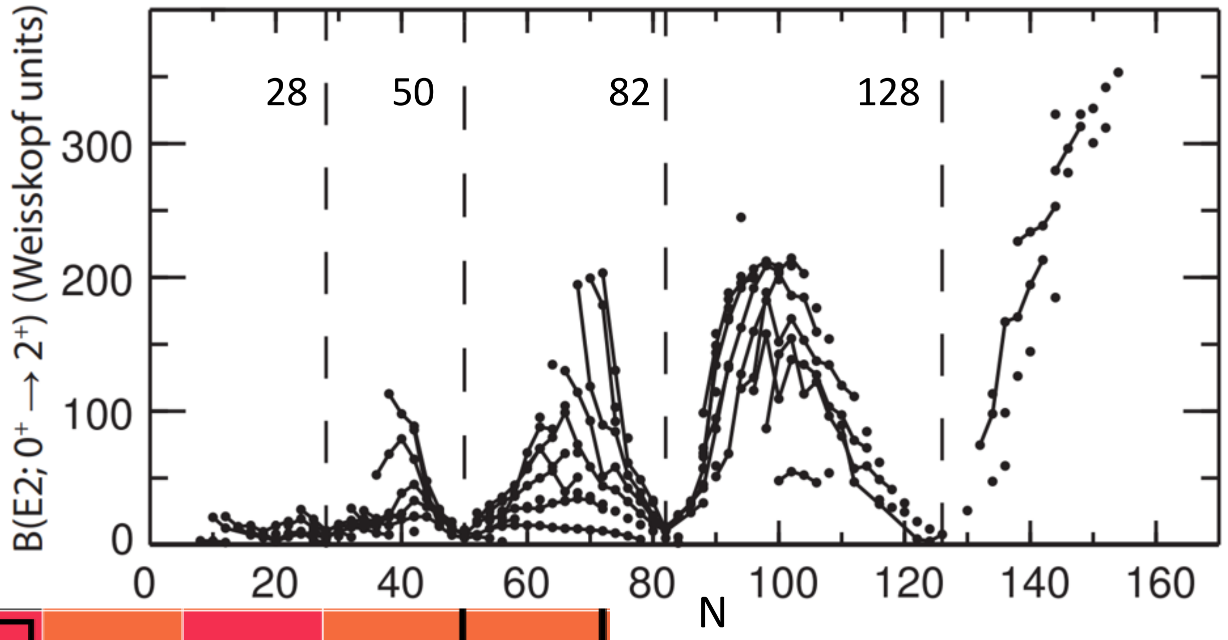
Collectivity in Nuclei

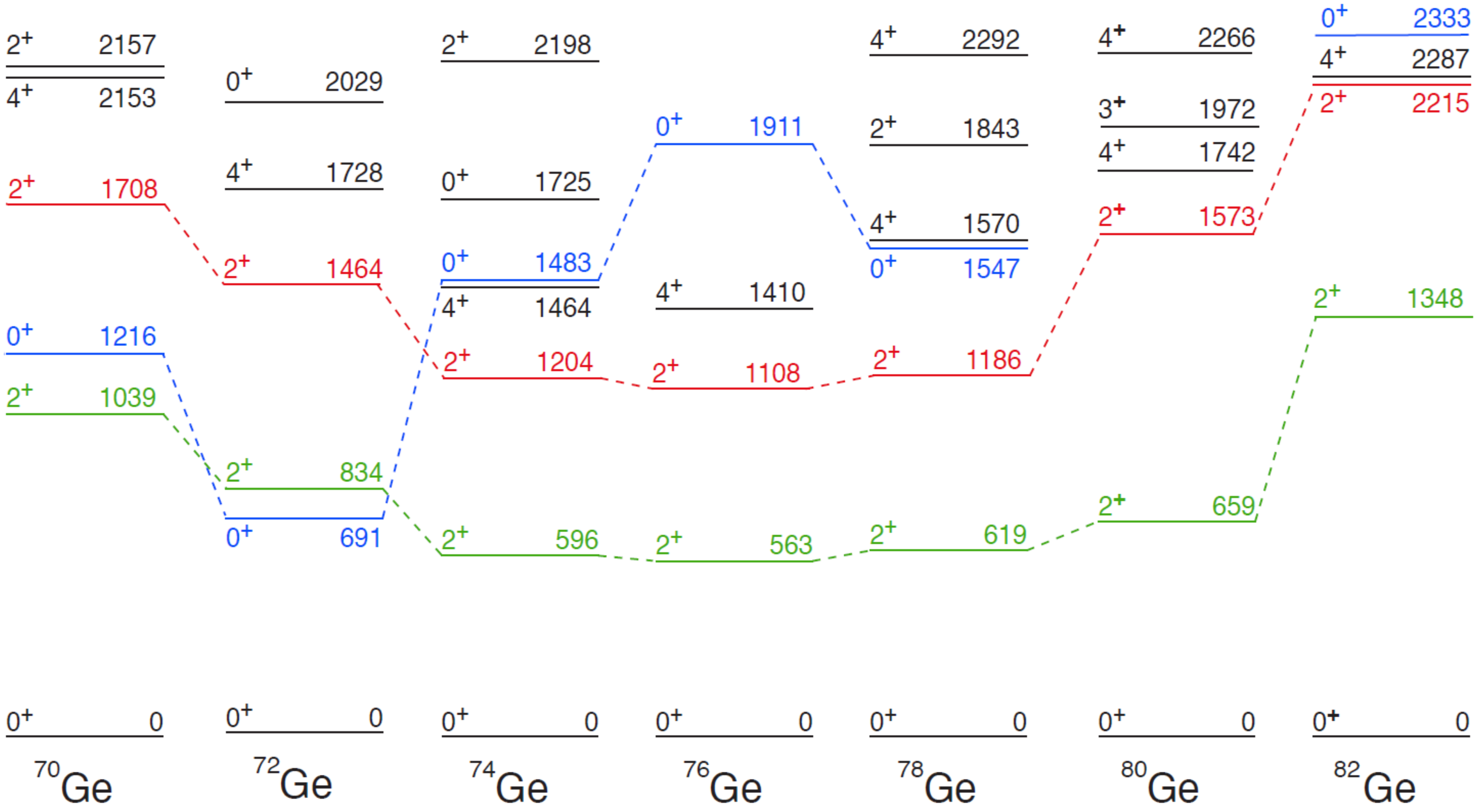
- Track evolution of collectivity and shape along isotopic chains
  - Particularly interesting in unstable nuclei
- Germanium isotopes



72 Se e- capture	73 Se β+	74 Se 2β+	75 Se e- capture	76 Se Stable	77 Se Stable	78 Se Stable	79 Se β-	80 Se 2β-	81 Se β-	82 Se 2β-	83 Se β-	84 Se β-
71 As β+	72 As β+	73 As e- capture	74 As β+	75 As Stable	76 As β-	77 As β-	78 As β-	79 As β-	80 As β-	81 As β-	82 As β-	83 As β-
70 Ge Stable	71 Ge e- capture	72 Ge Stable	73 Ge Stable	74 Ge Stable	75 Ge β-	76 Ge 2β-	77 Ge β-	78 Ge β-	79 Ge β-	80 Ge β- ★	81 Ge β-	82 Ge β-
69 Ga Stable	70 Ga β-	71 Ga Stable	72 Ga β-	73 Ga β-	74 Ga β-	75 Ga β-	76 Ga β-	77 Ga β-	78 Ga β-	79 Ga β-	80 Ga β-	81 Ga β-
68 Zn Stable	69 Zn β-	70 Zn 2β-	71 Zn β-	72 Zn β-	73 Zn β-	74 Zn β-	75 Zn β-	76 Zn β-	77 Zn β-	78 Zn β-	79 Zn β-	80 Zn β-

Nuclear Structure in the Germanium Isotopes

- Shape transition in ^{70}Ge [1]
  - Based on quadrupole moments
- Shape coexistence in ^{72}Ge [2]
  - Based on quadrupole shape invariants
- Triaxiality in $^{72-78}$Ge



[1] R. Lecomte *et al.*, Phys. Rev. C **22**, 1530 (1980)   [2] D. Ayangeakaa *et al.*, Phys. Lett. B **754**, 254 (2016)

Nuclear Structure in the Germanium Isotopes

- Triaxiality Suggested for $^{84-88}$Ge [3]
  - Based on low-lying level schemes

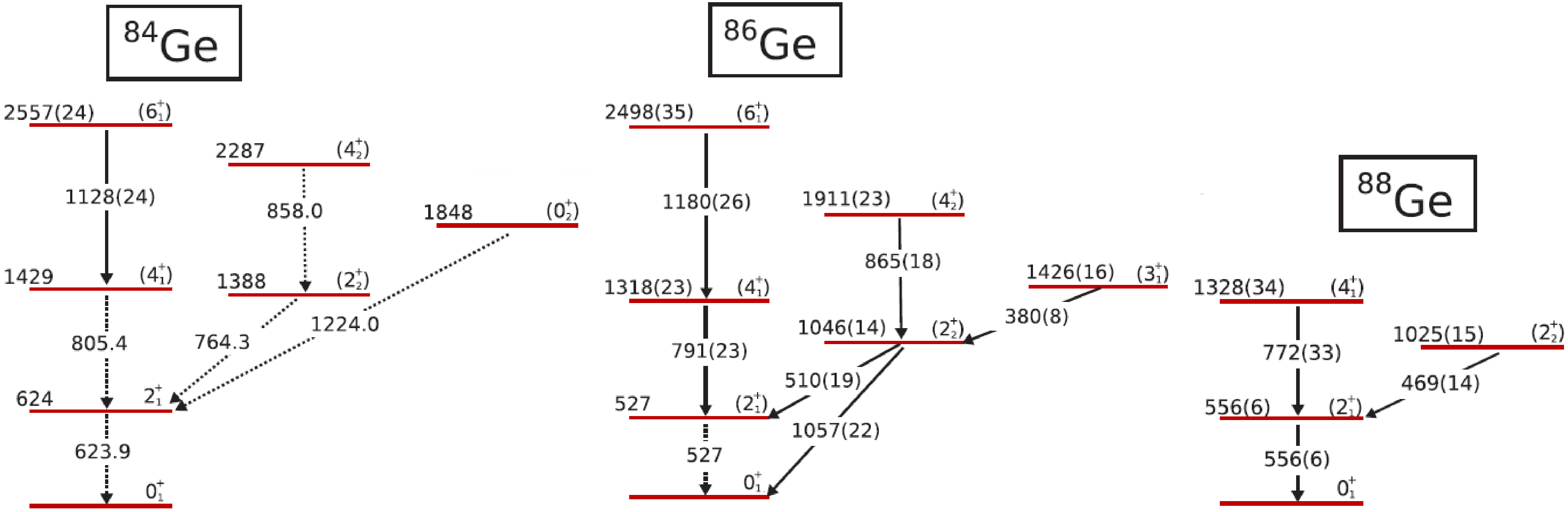


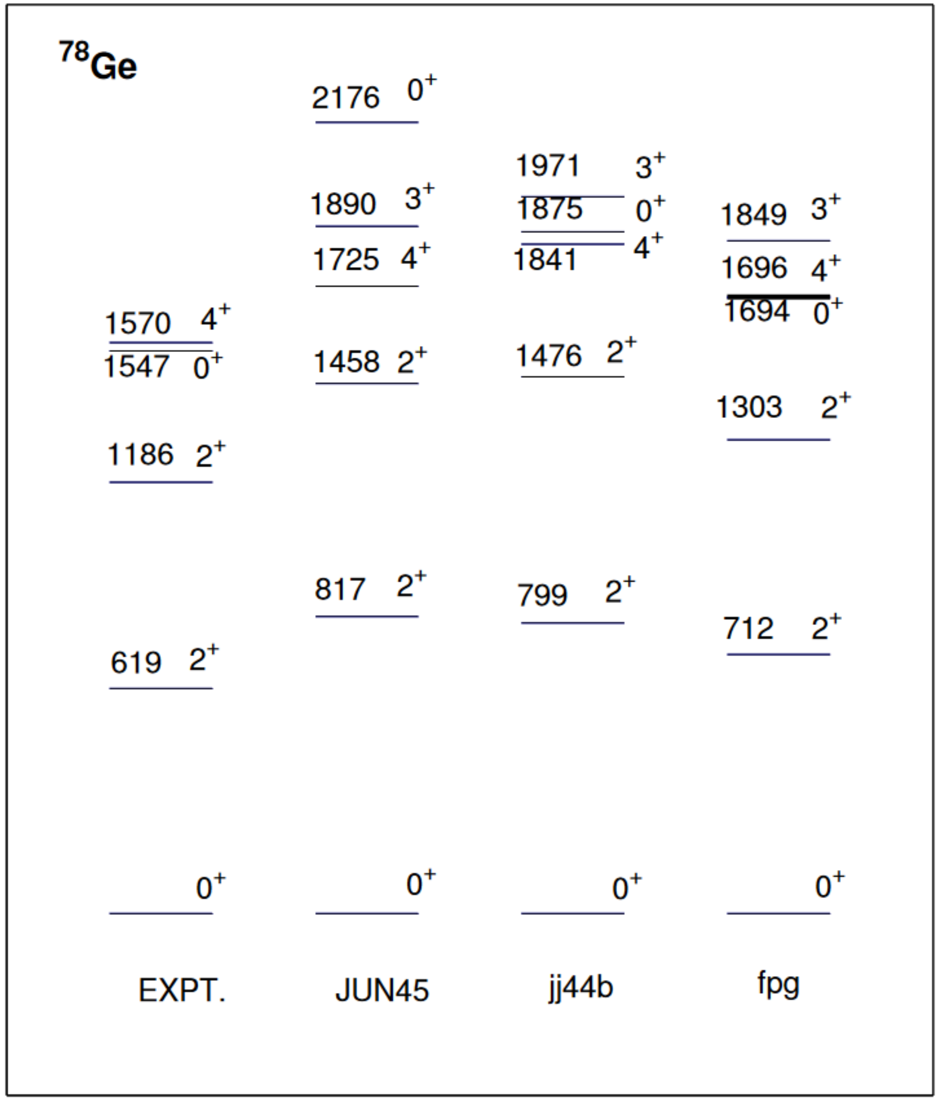
Fig. from [3]

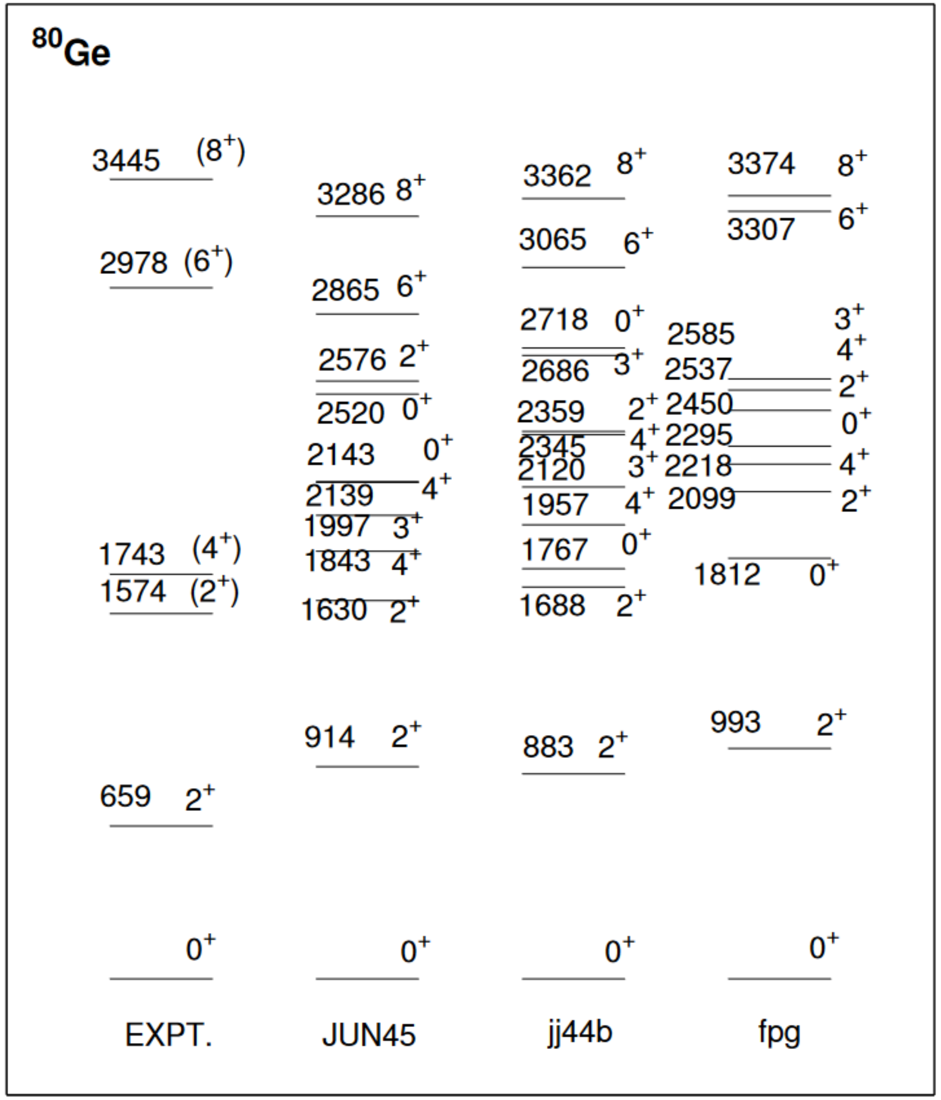
[3] M. Lettmann *et al.*, Phys. Rev. C **96**, 011301(R) (2017)

Interest in the Germanium Isotopes

Fig. from [4]

- Rich testing ground for nuclear models
- Shell model [4] and beyond-mean-field [5] methodologies used





[4] J. G. Hirsch and P. C. Srivastava, J. Phys.: Conf. Ser. **387**, 012020 (2012)

[5] K. Nomura *et al.*, Phys. Rev. C **95**, 064310 (2017)

Interest in the Germanium Isotopes

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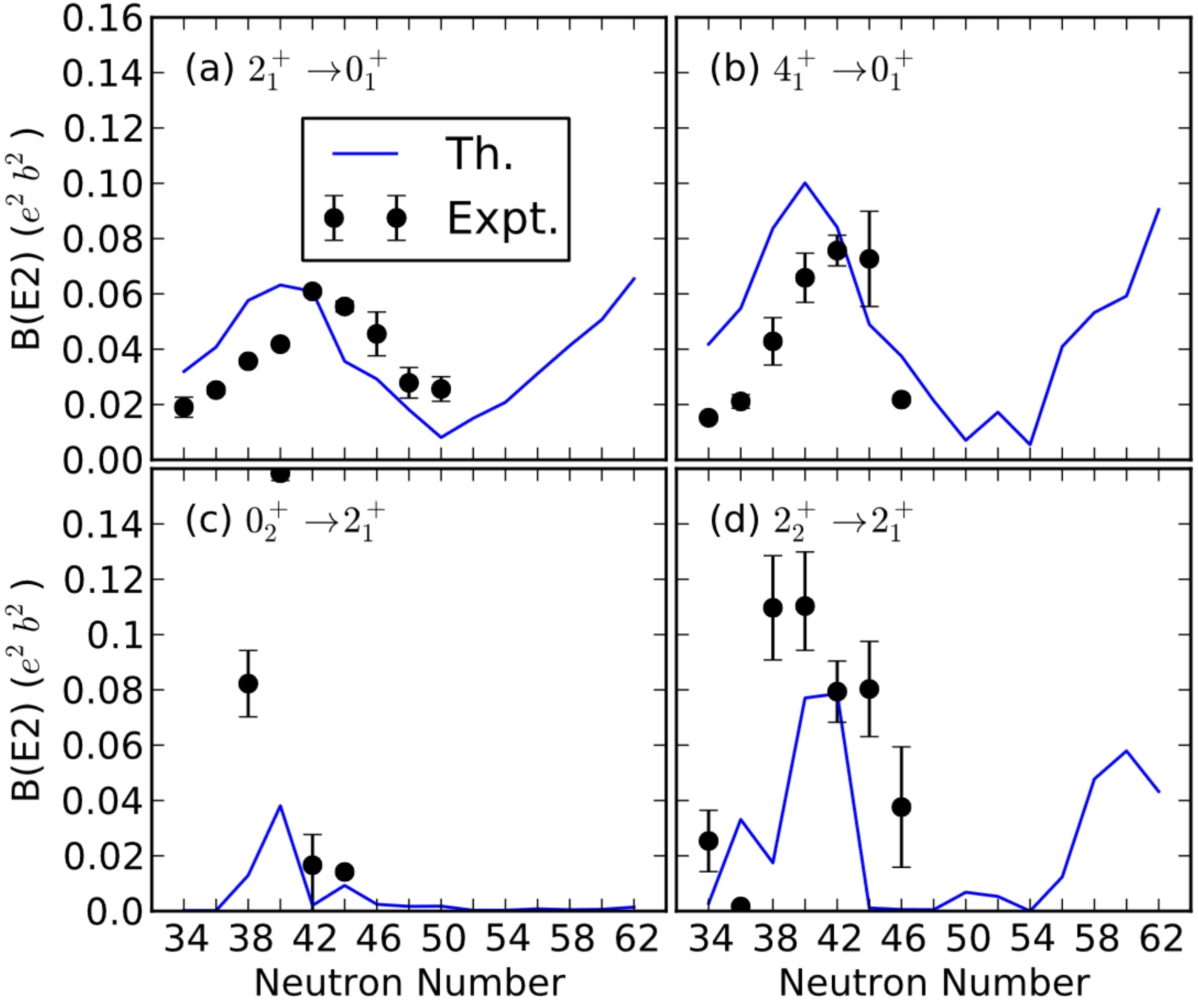
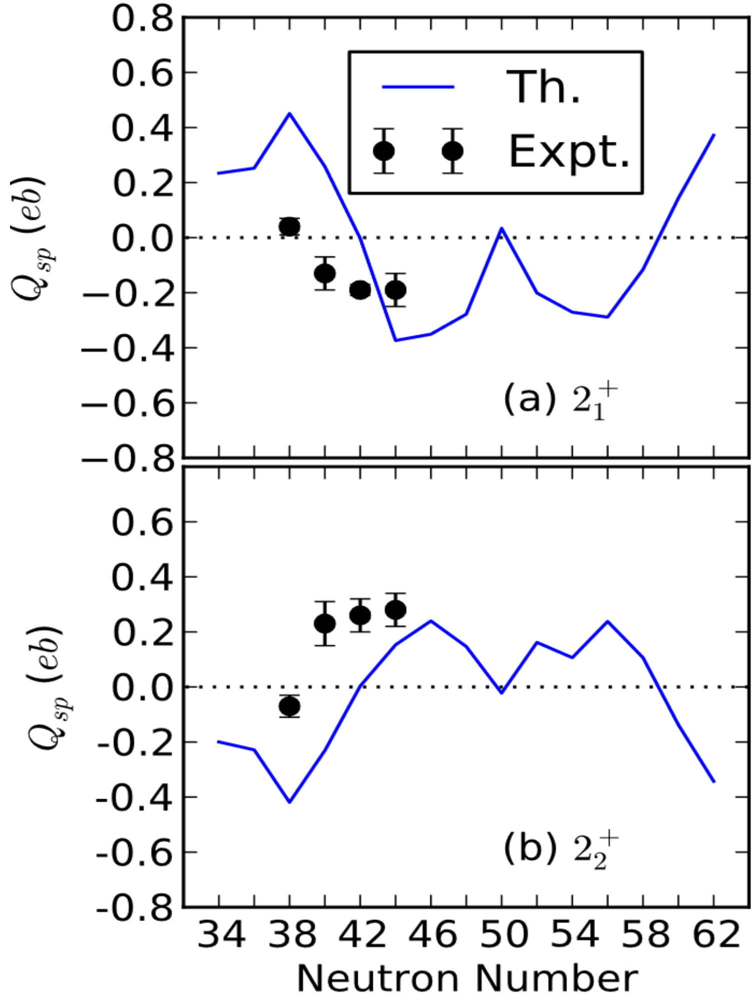


Fig. from [5]



[4] J. G. Hirsch and P. C. Srivastava, J. Phys.: Conf. Ser. **387**, 012020 (2012)

[5] K. Nomura *et al.*, Phys. Rev. C **95**, 064310 (2017)

Interest in ^{80}Ge

- Recent interest in ^{80}Ge due to reported 0_2^+ state below the 2_1^+ [6]
- More recent measurement found no evidence for a first-excited 0^+ state [7,8]
  - The 0_2^+ state in ^{80}Ge has not been located experimentally

Fig. from [4]

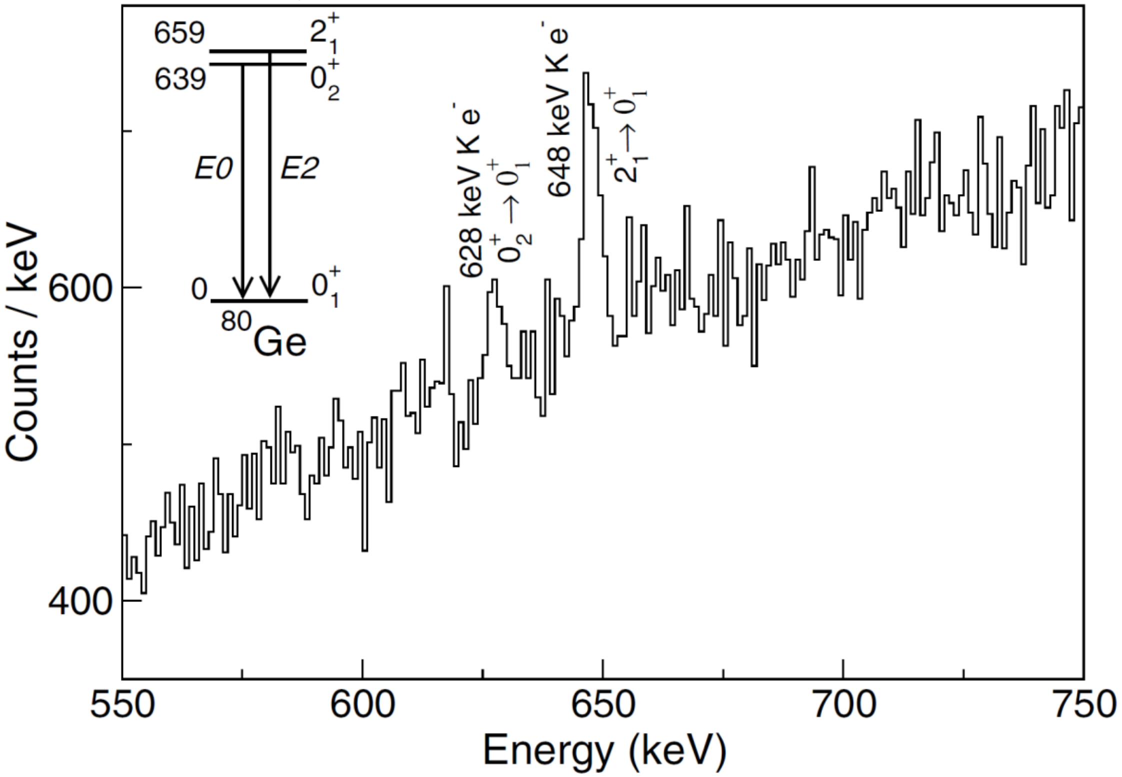
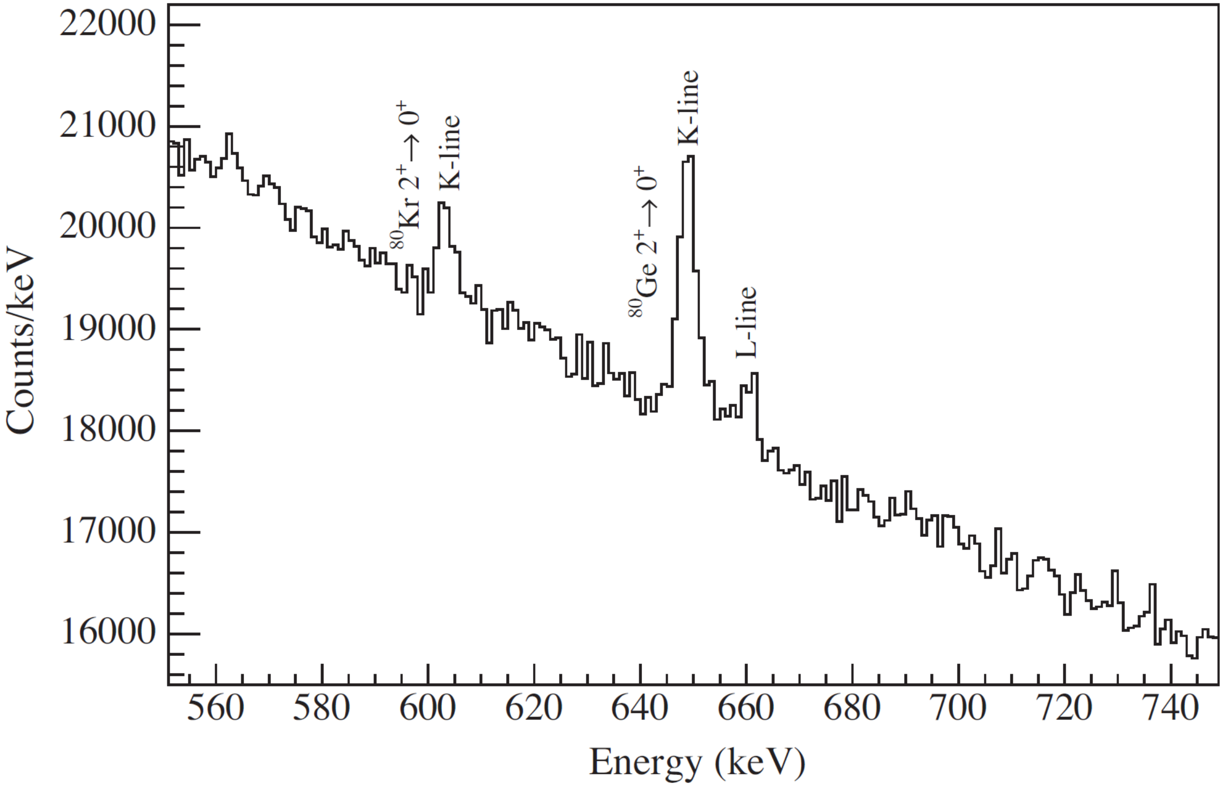
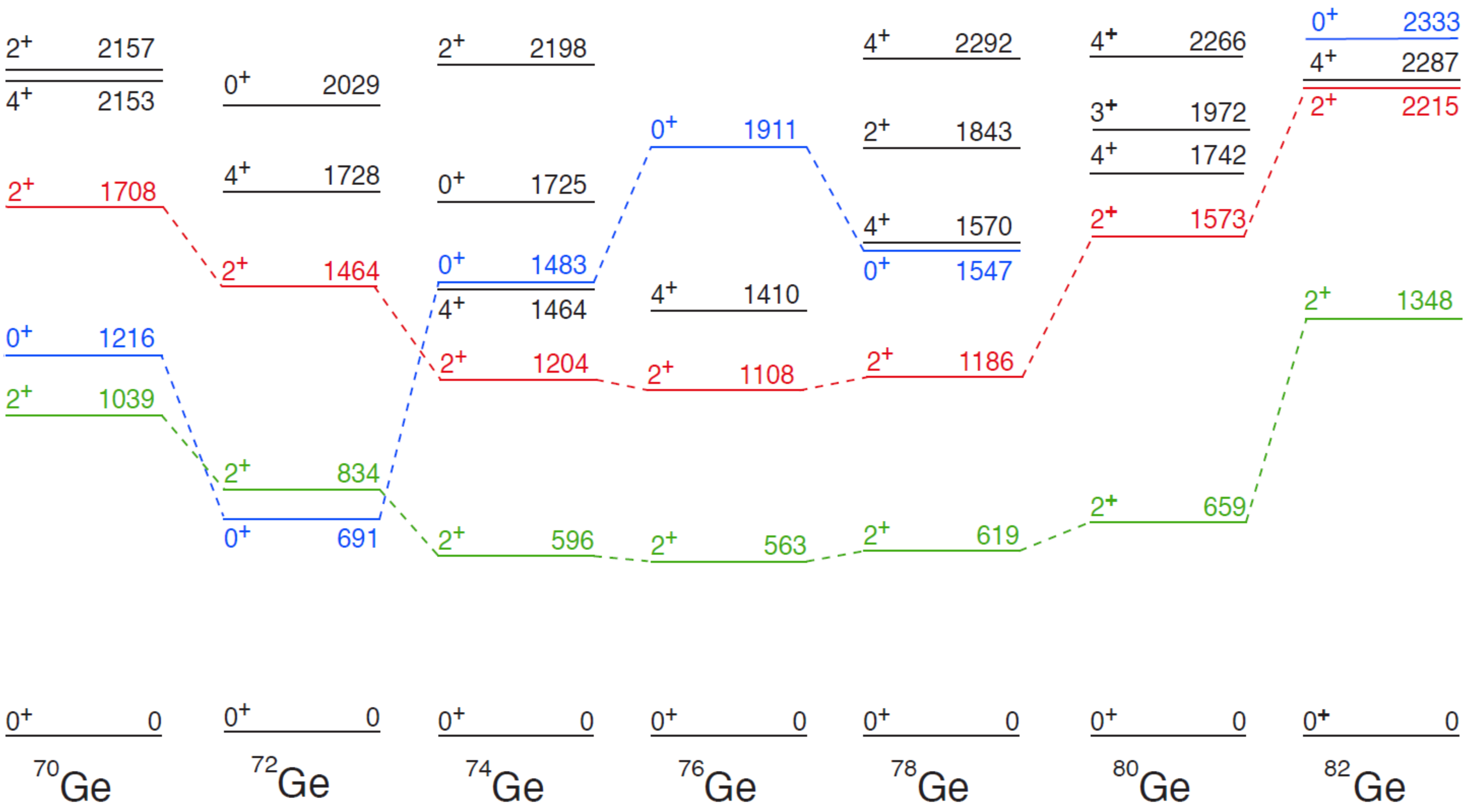


Fig. from [5]



[6] A. Gottardo *et al.*, Phys. Rev. Lett. **116**, 182501 (2016)
[7] F. H. Garcia *et al.*, Phys. Rev. Lett. **125**, 172501 (2020)
[8] S. Sekal *et al.*, Phys. Rev. C **104**, 024317 (2021)

Interest in ^{80}Ge



Interest in ^{80}Ge

- Recent interest in ^{80}Ge due to reported 0_2^+ state below the 2_1^+ [6]
- More recent measurement found no evidence for a first-excited 0^+ state [7,8]
  - The 0_2^+ state in ^{80}Ge has not been located experimentally

- Investigate ^{80}Ge with Coulomb Excitation
- Goal: Measure $B(E2; 0_1^+ \rightarrow 2_1^+)$ and $Q(2_1^+)$
  - Direct measure of nuclear shapes in neutron-rich Ge isotopes

[6] A. Gottardo *et al.*, Phys. Rev. Lett. **116**, 182501 (2016)
[7] F. H. Garcia *et al.*, Phys. Rev. Lett. **125**, 172501 (2020)
[8] S. Sekal *et al.*, Phys. Rev. C **104**, 024317 (2021)

Coulomb Excitation

- Electromagnetic interaction
  - Restrict bombarding energy [9]
- Observables: Gamma-ray yields vs scattering angle
- Sensitivity to B(E2) values and quadrupole moments
  - Reorientation effect

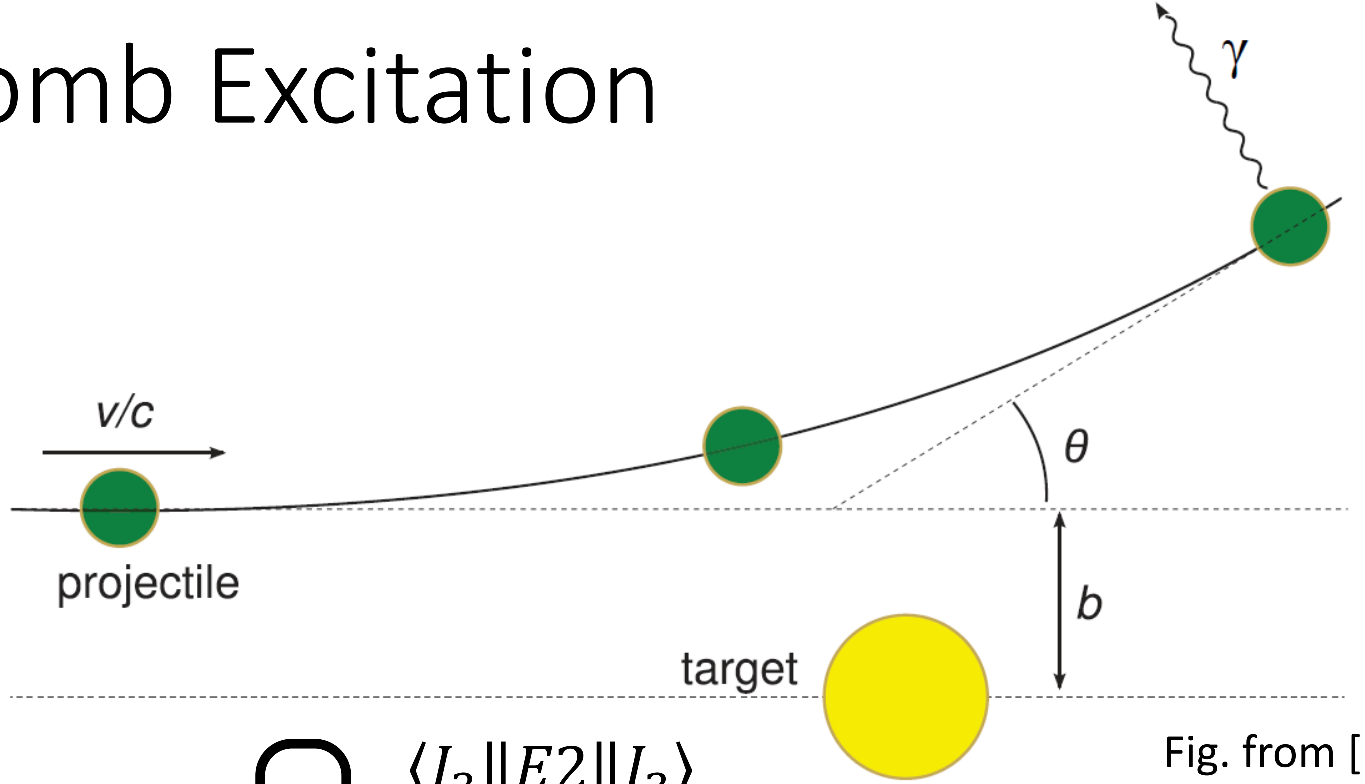
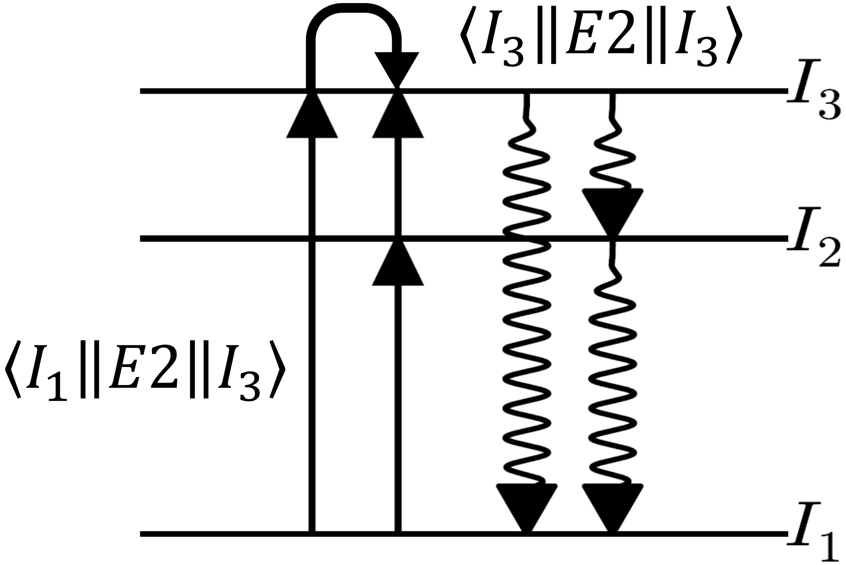


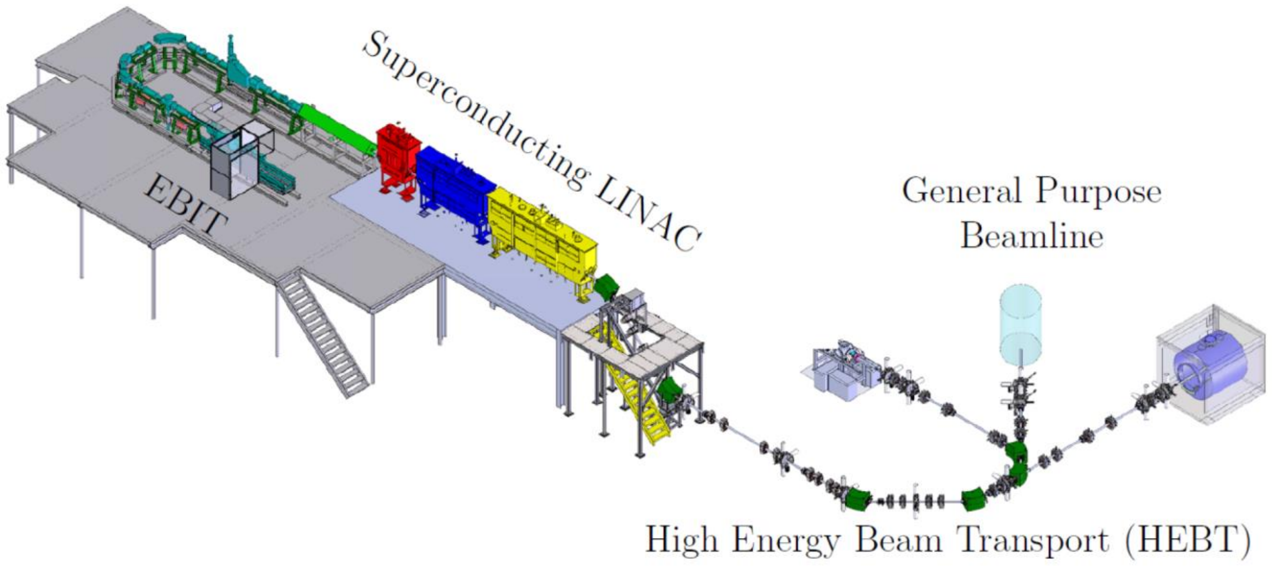
Fig. from [10]



[9] D. Cline, Annu. Rev. of Nucl. Part. Sci. **36**, 683 (1986)

[10] B. Longfellow. Ph.D. Dissertation, Michigan State University (2020)

Experimental Details



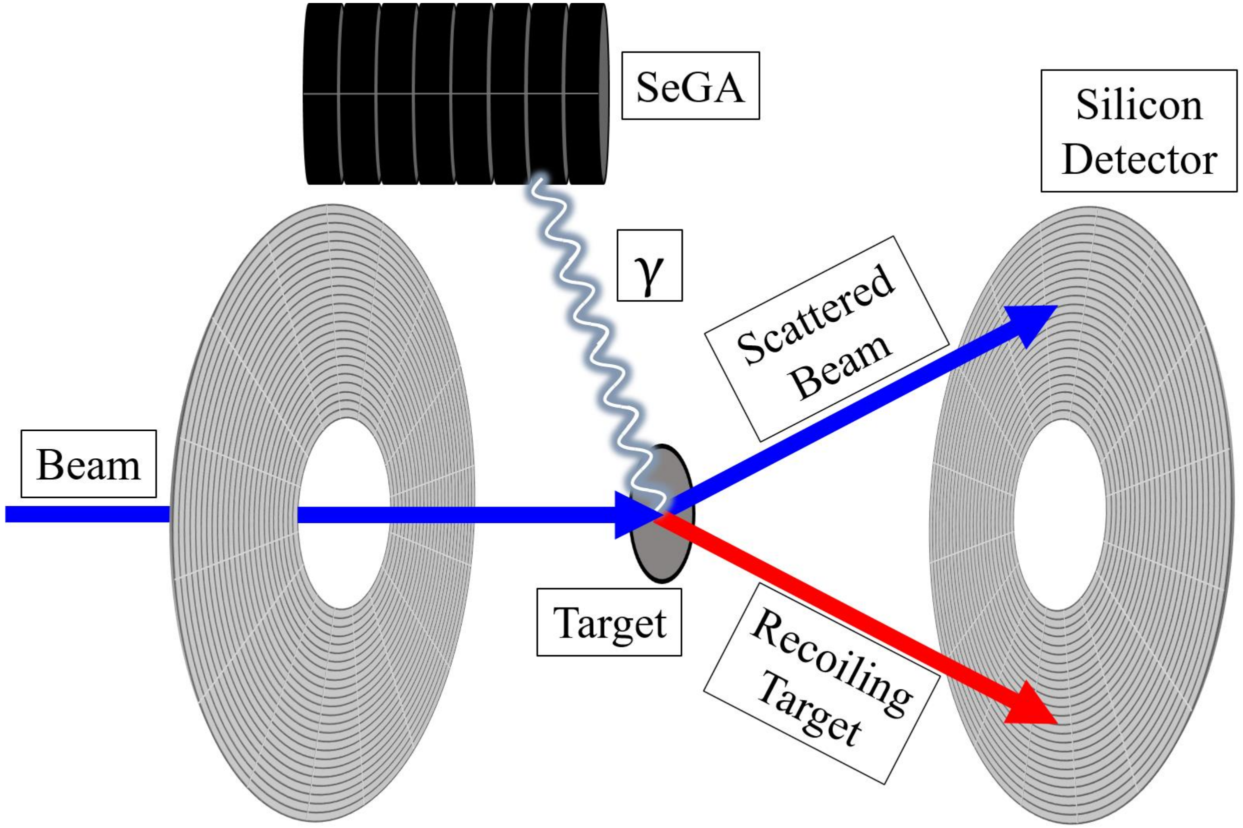
- Performed at the NSCL [11] ReA3 [12] facility
  - RIB produced by CCF
- ^{80}Ge selected by A1900 [13]
  - Beam thermalized in a gas cell [14]
- Injected into ReA3 linear accelerator
- Delivered to the experimental setup

- 2.52 MeV/u ^{80}Ge impinged on ^{196}Pt
  - 1.59 mg/cm^2 target
  - Target excitations used for normalization

[11] A. Gade and B. M. Sherill, Phys. Scr. **91**, 053003 (2016)
[12] A. C. C. Villari *et al.*, IPAC'16 1287
[13] D. J. Morrissey *et al.*, Nucl. Instrum. Meth. Phys. Res. B **204**, 90 (2003)
[14] C. S. Sumithrarachchi et al., Nucl. Instrum. Meth. Phys. Res. B **463**, 305 (2020)

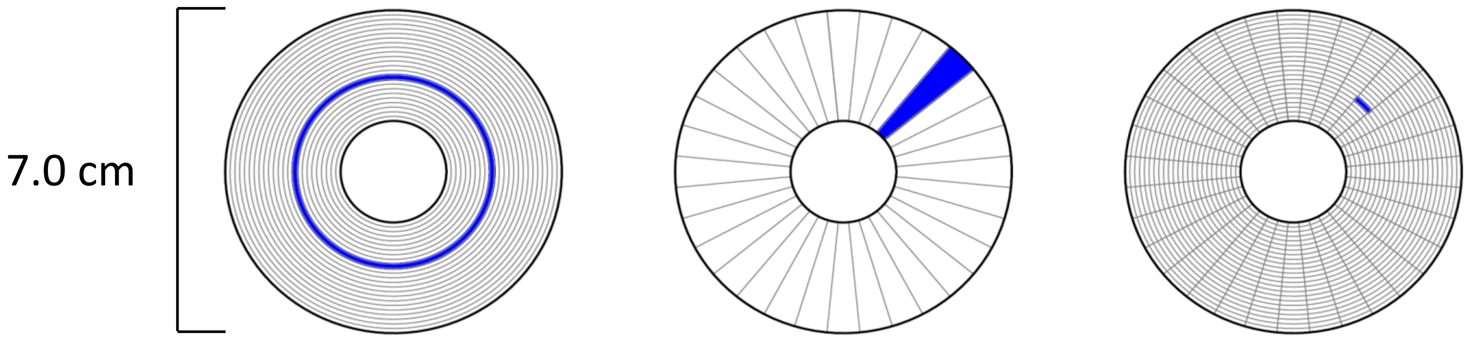
The JANUS Setup

- Joint Array for Nuclear Structure (JANUS) [15]
  - Low energy Coulomb Excitation
  - Commissioned 2017
  - Particle-γ coincidences
- Segmented Germanium Array (SeGA) for γ-ray detection
- Two silicon detectors for particle detection
  - Reaction target placed between silicon detectors

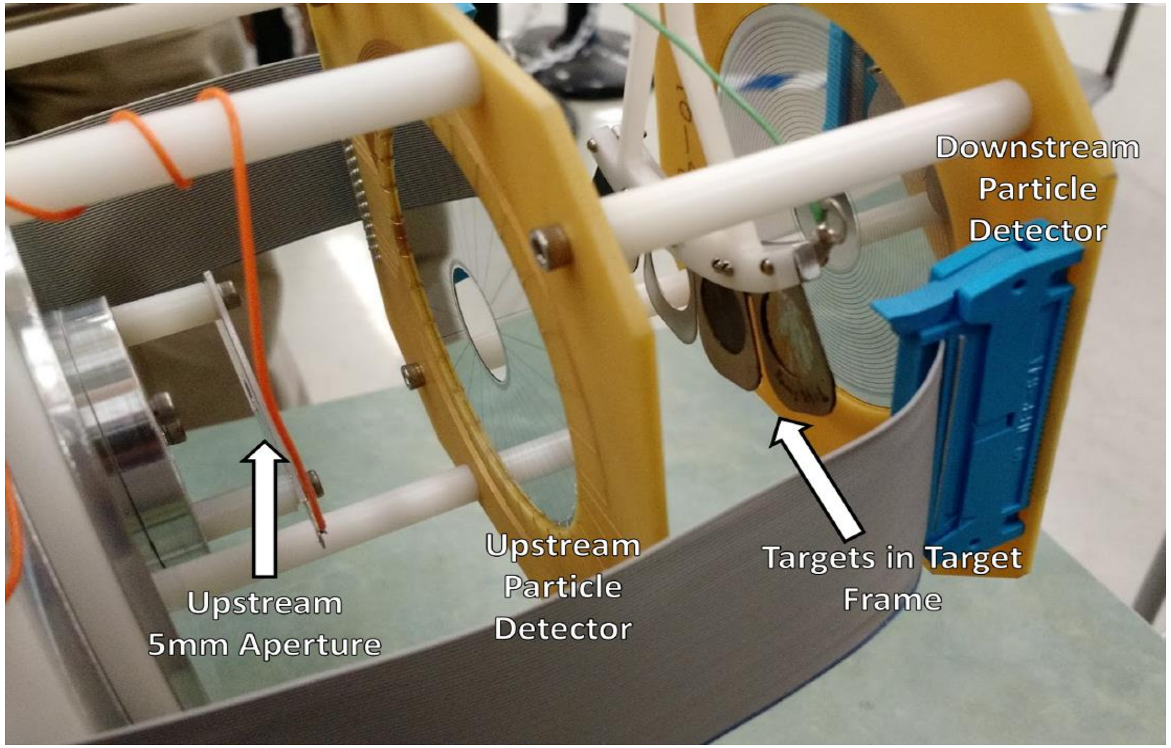


[15] E. Lunderberg *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A 885 (2017)

The Silicon Detectors

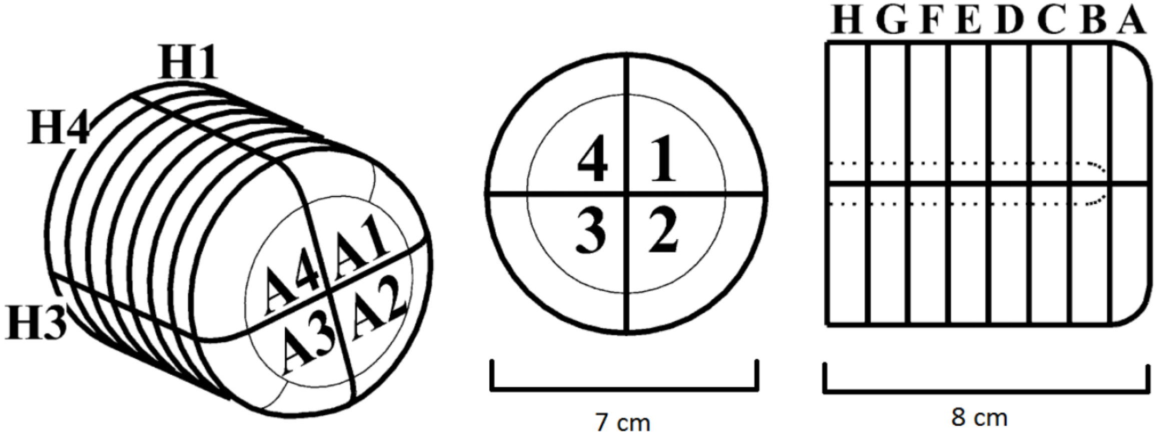


- Two annular Si detectors
  - 300 μm thick
  - 1.1 cm and 3.5 cm radii
- 56 segments, 768 pixels
  - 24-fold radial segmentation
  - 32-fold azimuthal segmentation
  - 1 mm x 5 mm pixels
    - » 1.5° in θ, 11.3° in φ

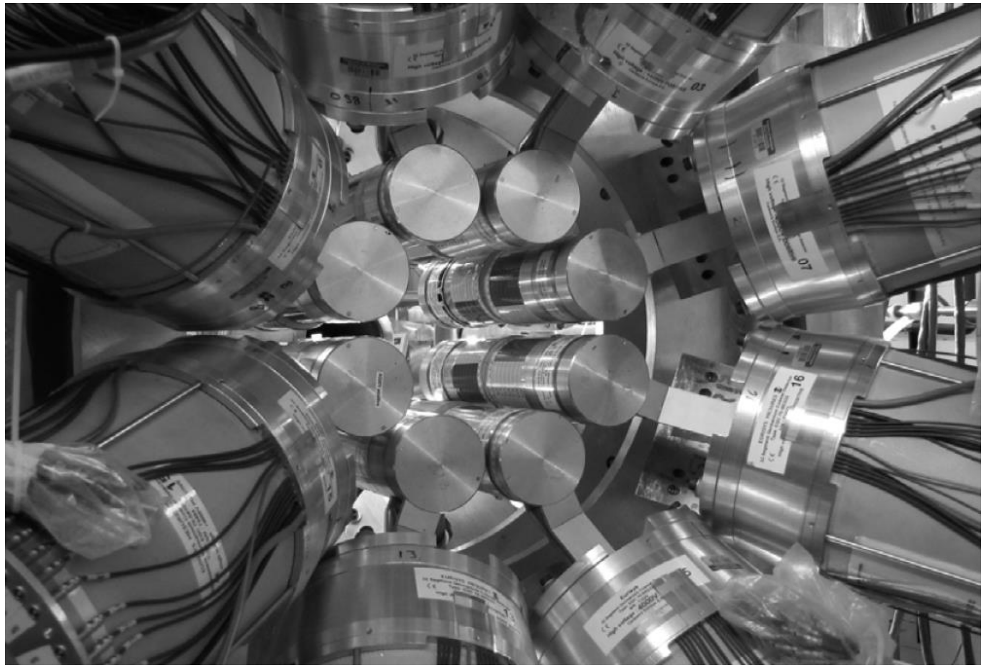


[15] E. Lunderberg *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A 885 (2017)

The Segmented Germanium Array



- 16 cylindrical HPGe detector crystals
  - 8 slices
  - 4 quadrants per slice
  - 1 central contact
- Concentrically surround target position

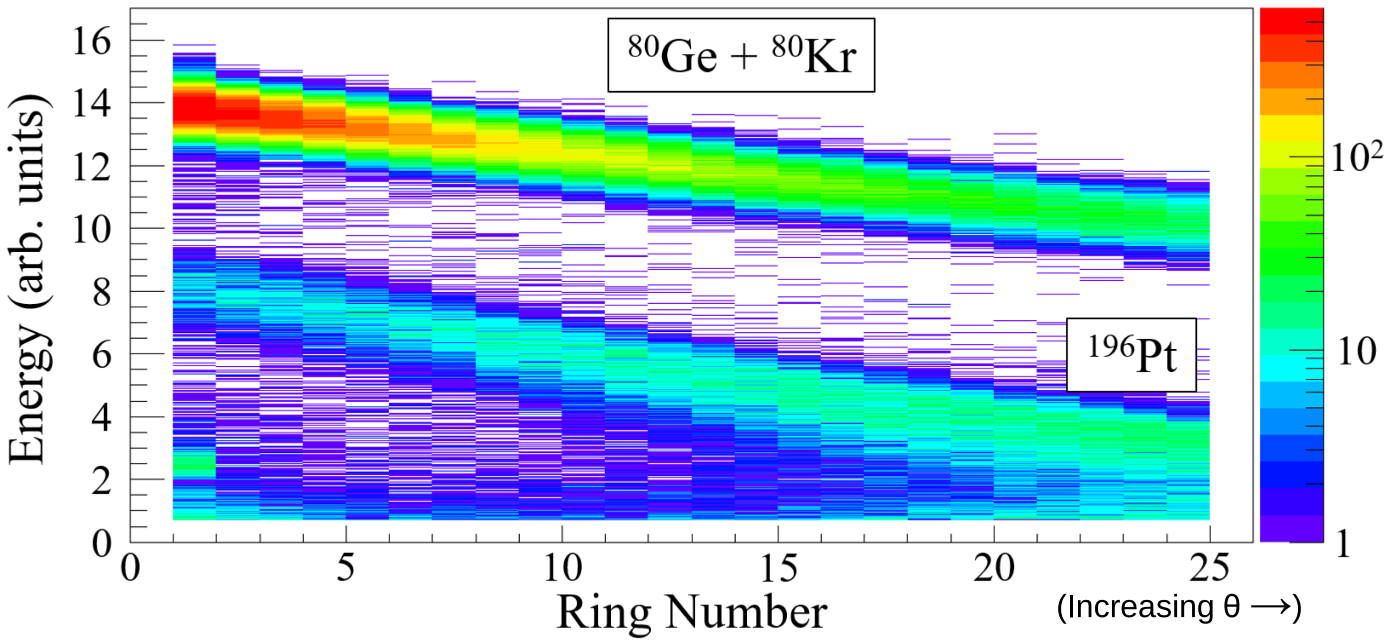


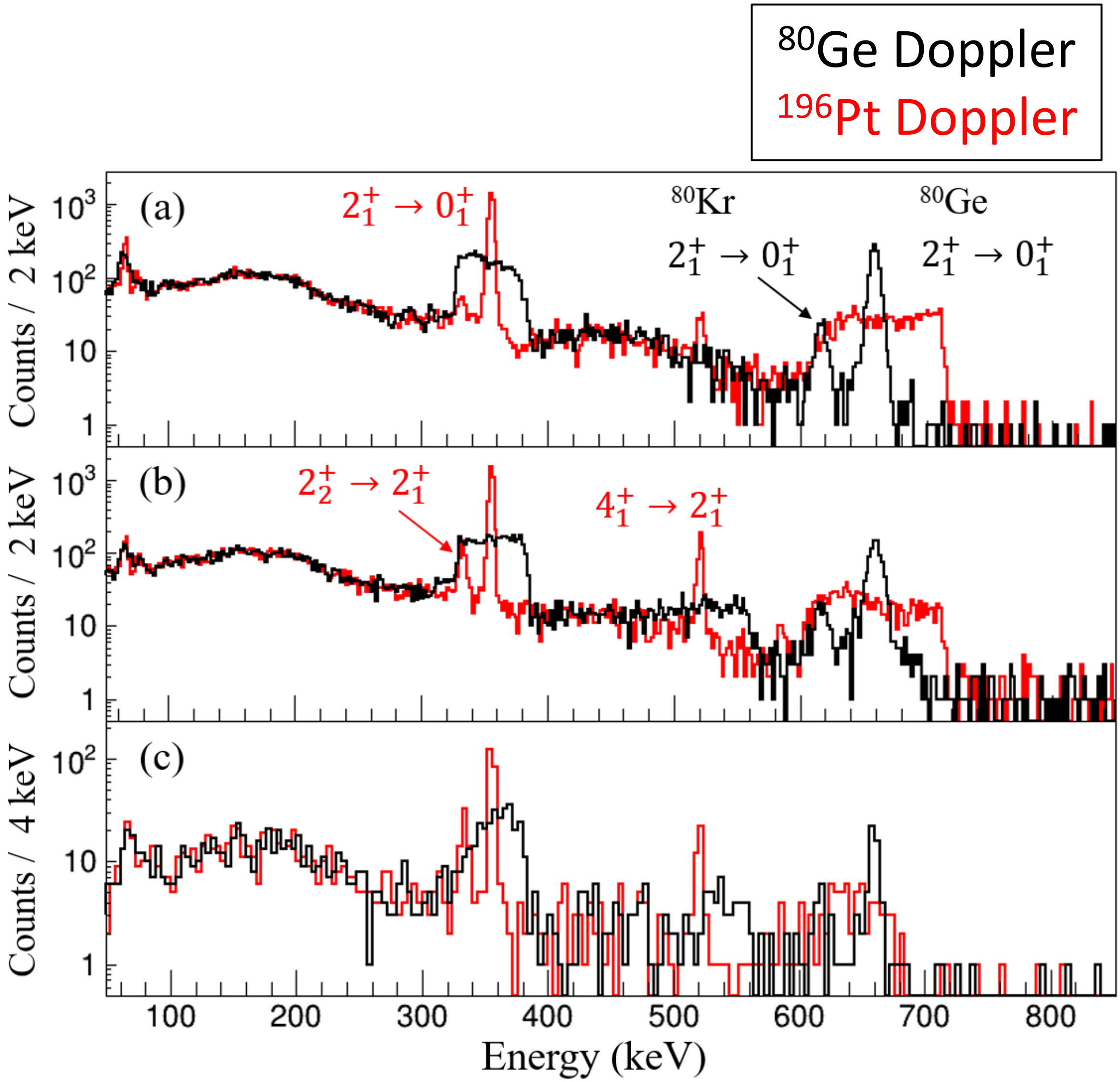
[16] W.F. Mueller *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A 466 (2001)

Experimental Data

- Both scattered beam and recoiling target detected
  - Small ^{80}Kr contamination
- Gamma-rays from both nuclei detected in SeGA
- Doppler correction via high segmentation

Figs. from [17]



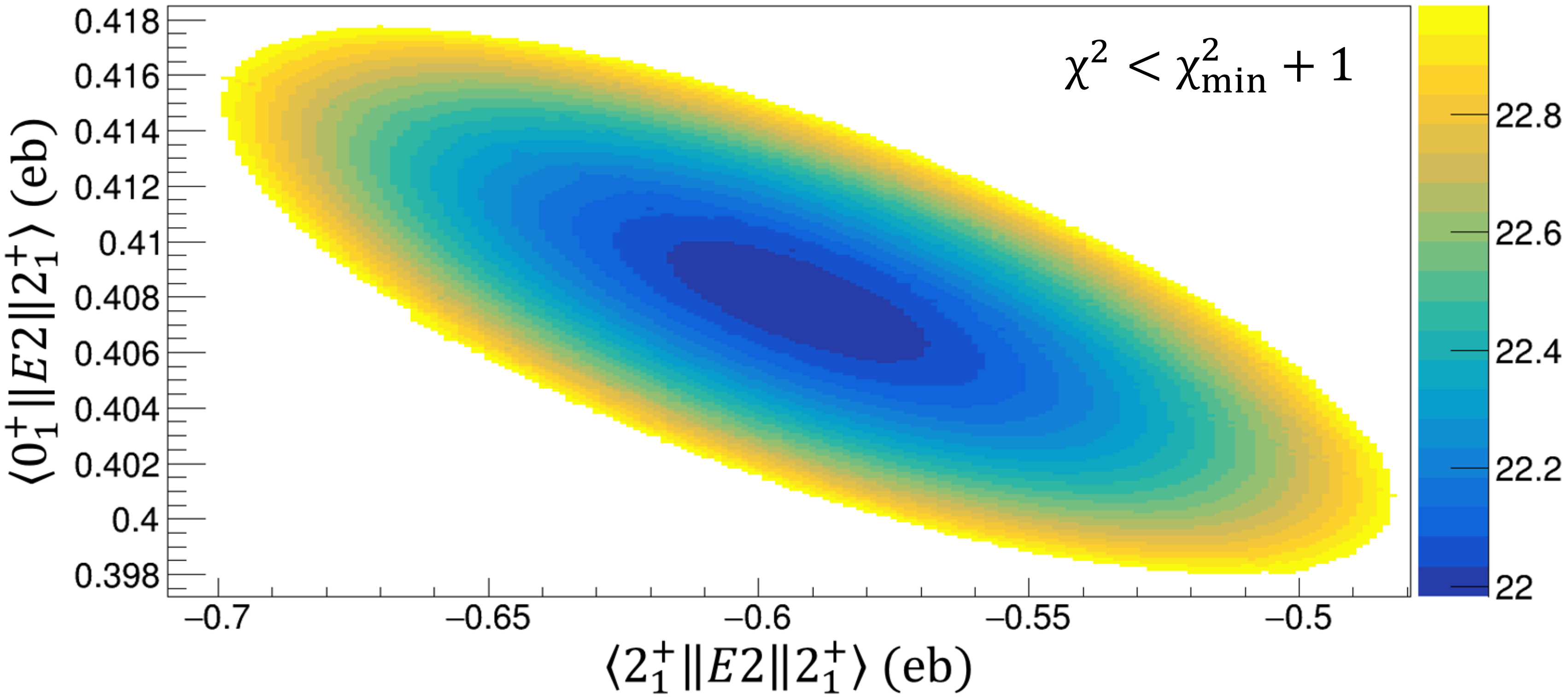


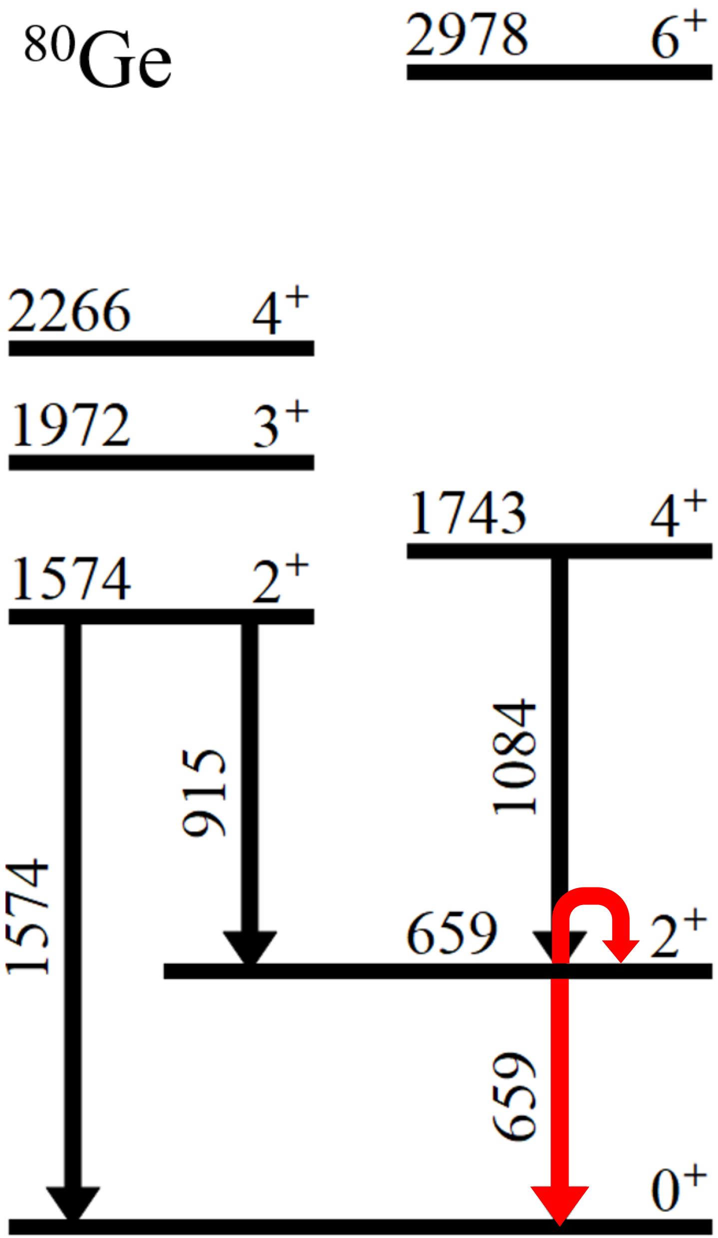
[17] D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)

GOSIA2 Analysis

- Coulomb excitation codes GOSIA and GOSIA2 [18]
  - Target excitations used for normalization
- Correlation with $\langle 2_1^+||\mathrm{E2}||2_1^+\rangle$ is largest uncertainty on $\langle 0_1^+||\mathrm{E2}||2_1^+\rangle$

Figs. from [17]



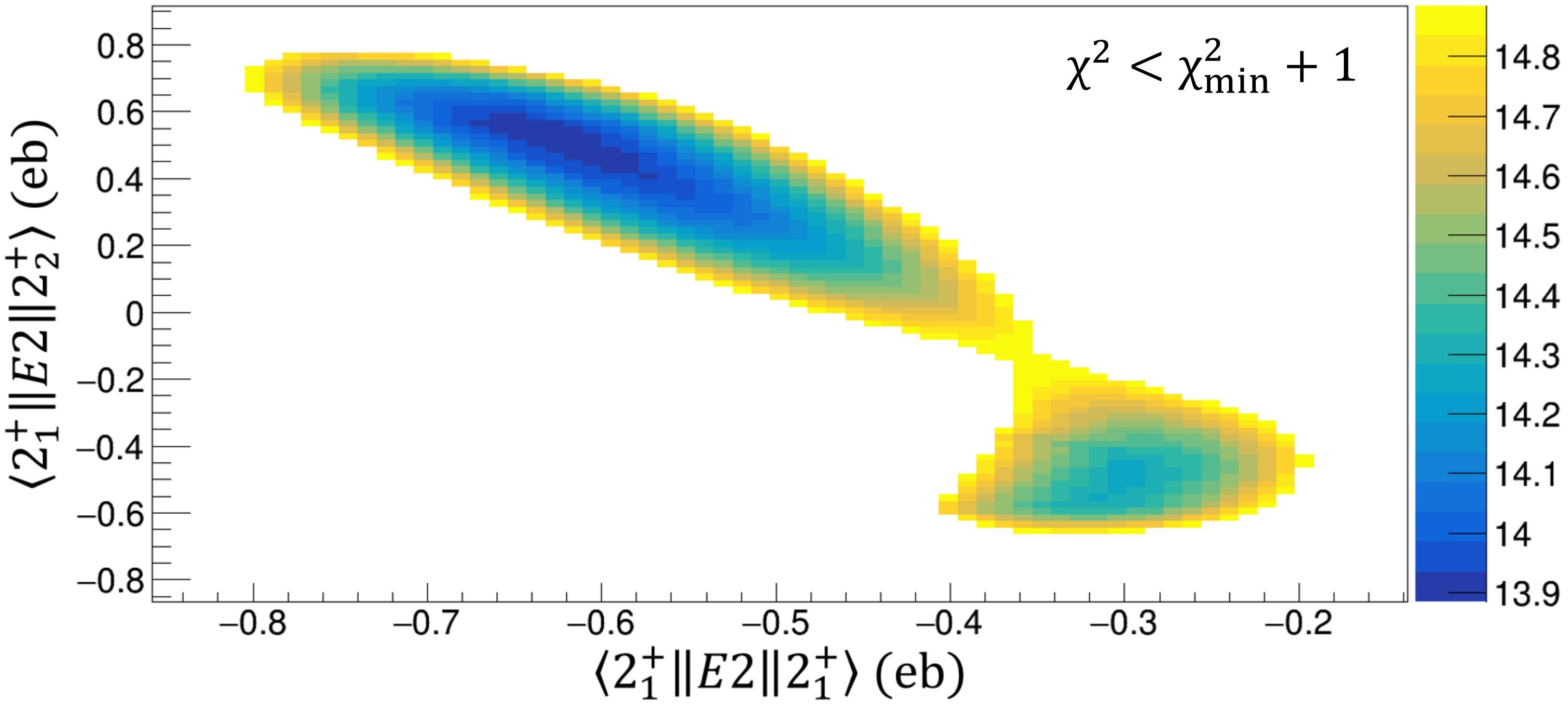


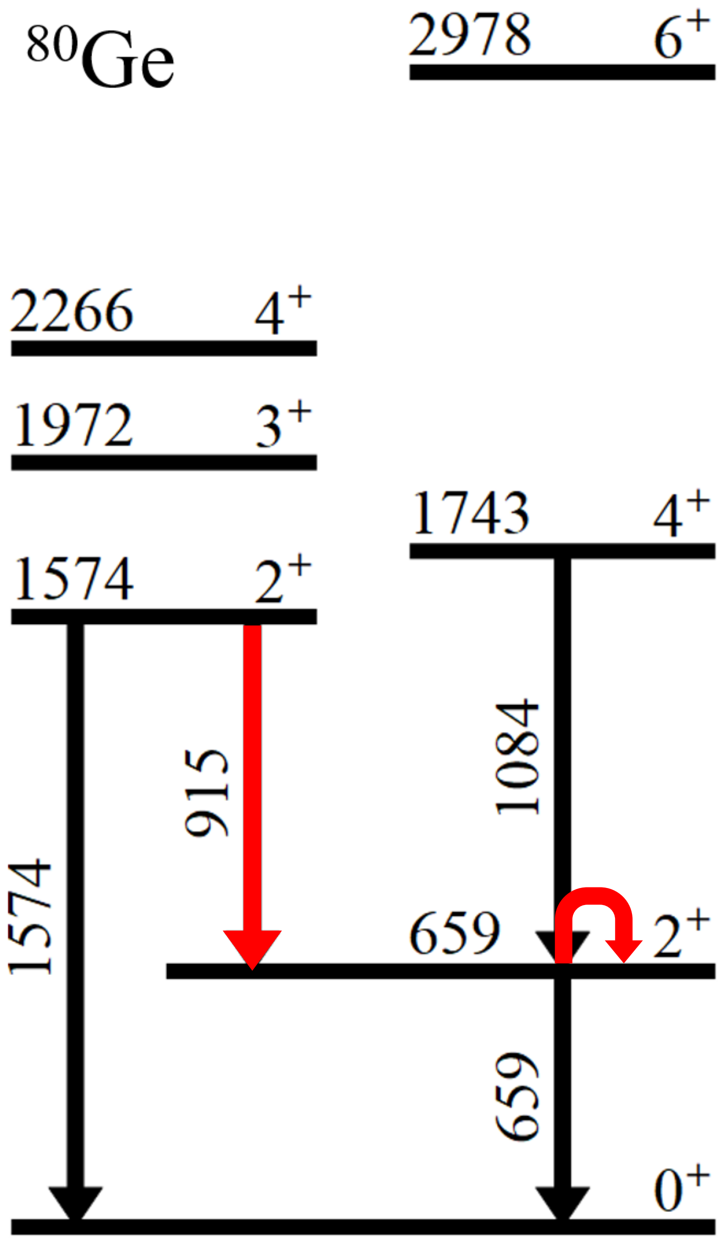
[17] D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)
[18] T. Czosnyka *et al.*, Bull. Am. Phys. Soc. 28, 745 (1983)

GOSIA Analysis

- Significant correlation observed between $\langle 2_1^+ || \mathrm{E2} || 2_1^+ \rangle$ matrix elements which couple to 2_2^+ state
  - Results in large, highly asymmetric uncertainty

Figs. from [17]

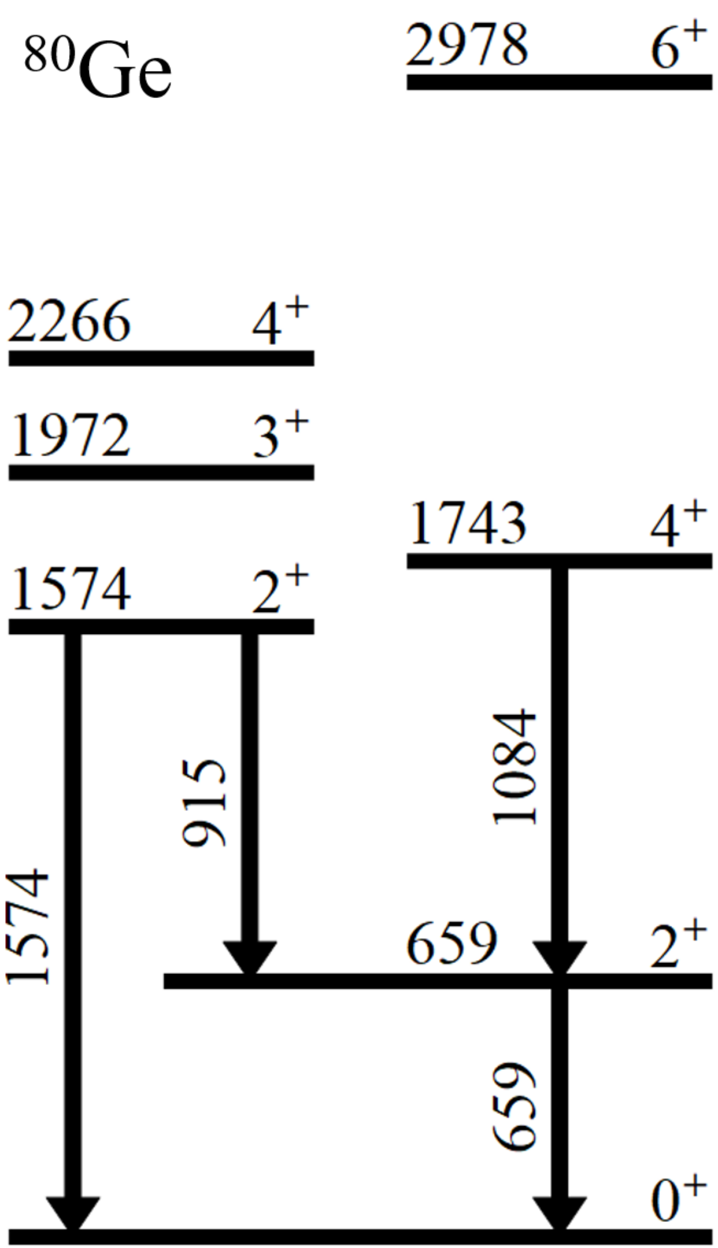




[17] D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)

Results

- Precision on $\langle 0_1^+||\mathrm{E2}||2_1^+\rangle$ improved
  - Previous measurements from [19,20]
- $\langle 2_1^+||\mathrm{E2}||2_1^+\rangle$ measured for the first time
- Matrix elements which couple to higher-lying states also measured or constrained



Figs. from [17]

Matrix element	This work	Ref. [19]	Ref. [20]
$\langle 0_1^+\|E2\|2_1^+\rangle$ (eb)	0.408(10)	0.373(36)	0.316(21)
$\langle 2_1^+\|E2\|2_1^+\rangle$ (eb)	-0.6^{+4}_{-2}		
$\langle 2_1^+\|E2\|4_1^+\rangle$ (eb)	0.76(20)		
$\langle 0_1^+\|E2\|2_2^+\rangle$ (eb)	$\|0.14(5)\|$		$\|0.11(2)\|$
$\langle 2_1^+\|E2\|2_2^+\rangle$ (eb)	$<\|0.8\|$		
$\langle 2_1^+\|M1\|2_2^+\rangle$ (μ_N)	$<\|0.5\|$		

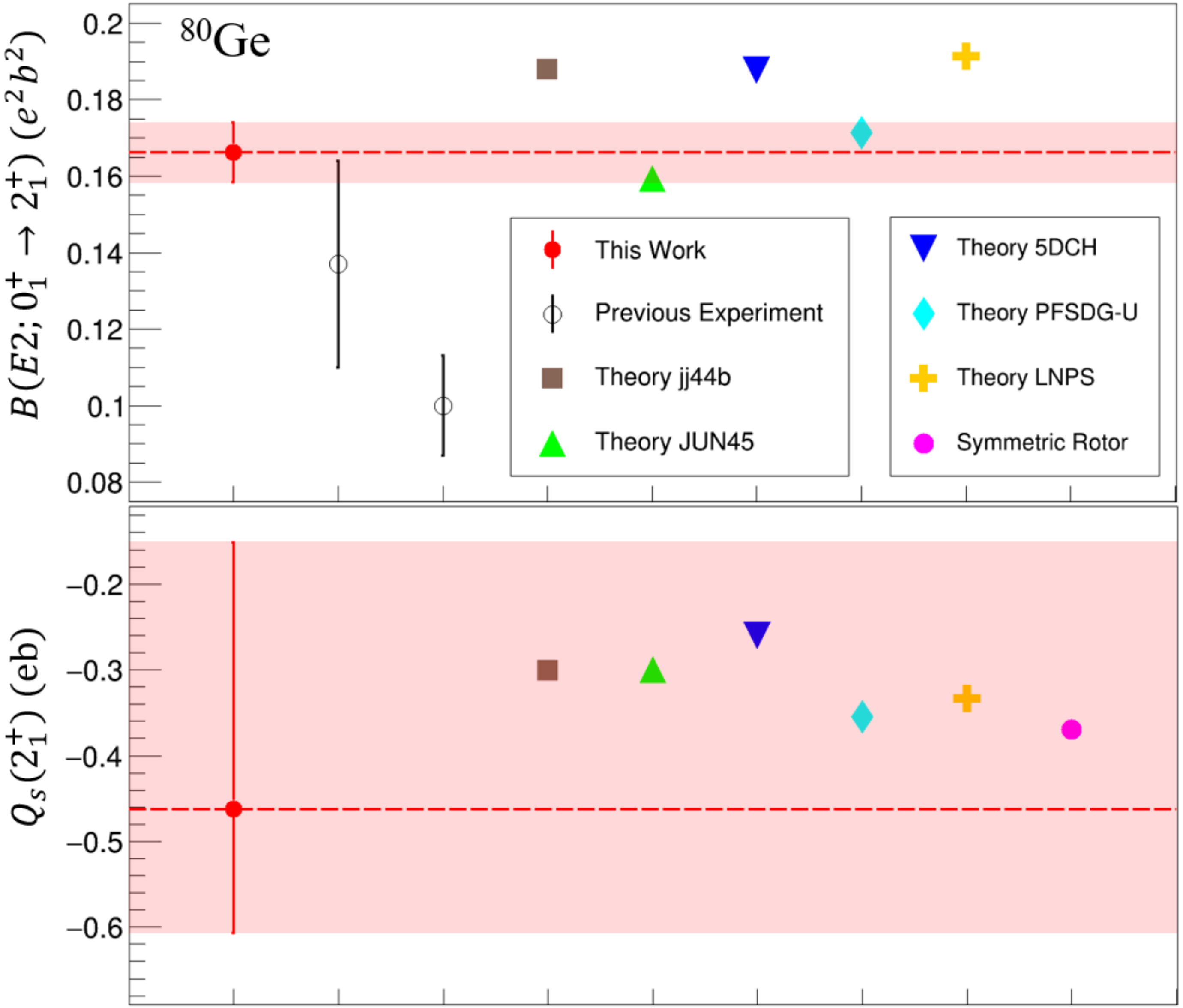
[17] D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)
[19] E. Padilla-Rodal *et al.*, Phys. Rev. Lett. **94**, 122501 (2005)
[20] H. Iwasaki *et al.*, Phys. Rev. C 78, 021304(R) (2008)

Shell Model Calculations

- Multiple different shell model calculations
  - Different model spaces and interactions

Figs. from [17]

^{80}Ge	$B(E2; 0_1^+ \rightarrow 2_1^+)$ (e^2b^2)	$Q_s(2_1^+)$ (eb)
Experiment		
This Work	0.166(8)	-0.46^{+31}_{-14}
Ref. [19]	0.139(27)	-
Ref. [20]	0.100(13)	-
Theory		
jj44b	0.188	-0.301
JUN45	0.159	-0.300
PFSDG-U	0.171	-0.355
LNPS	0.191	-0.334
5DCH	0.188	-0.260



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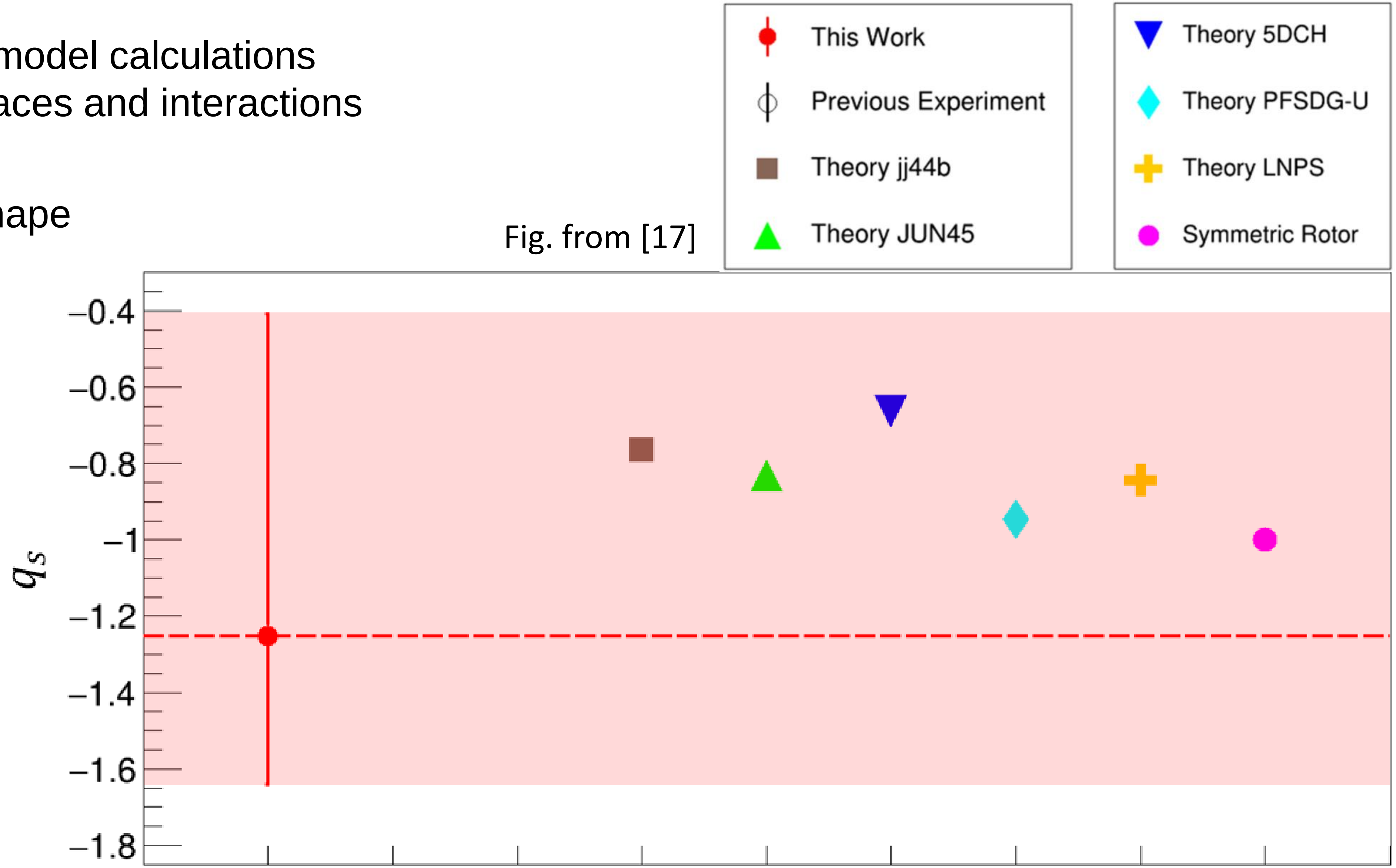
Shell Model Calculations

- Multiple different shell model calculations
  - Different model spaces and interactions

- $q_s \propto \frac{Q_s(2_1^+)}{\sqrt{B(E2)}}$ indicates shape

- $q_s = -1.3^{+8}_{-4}$

Fig. from [17]



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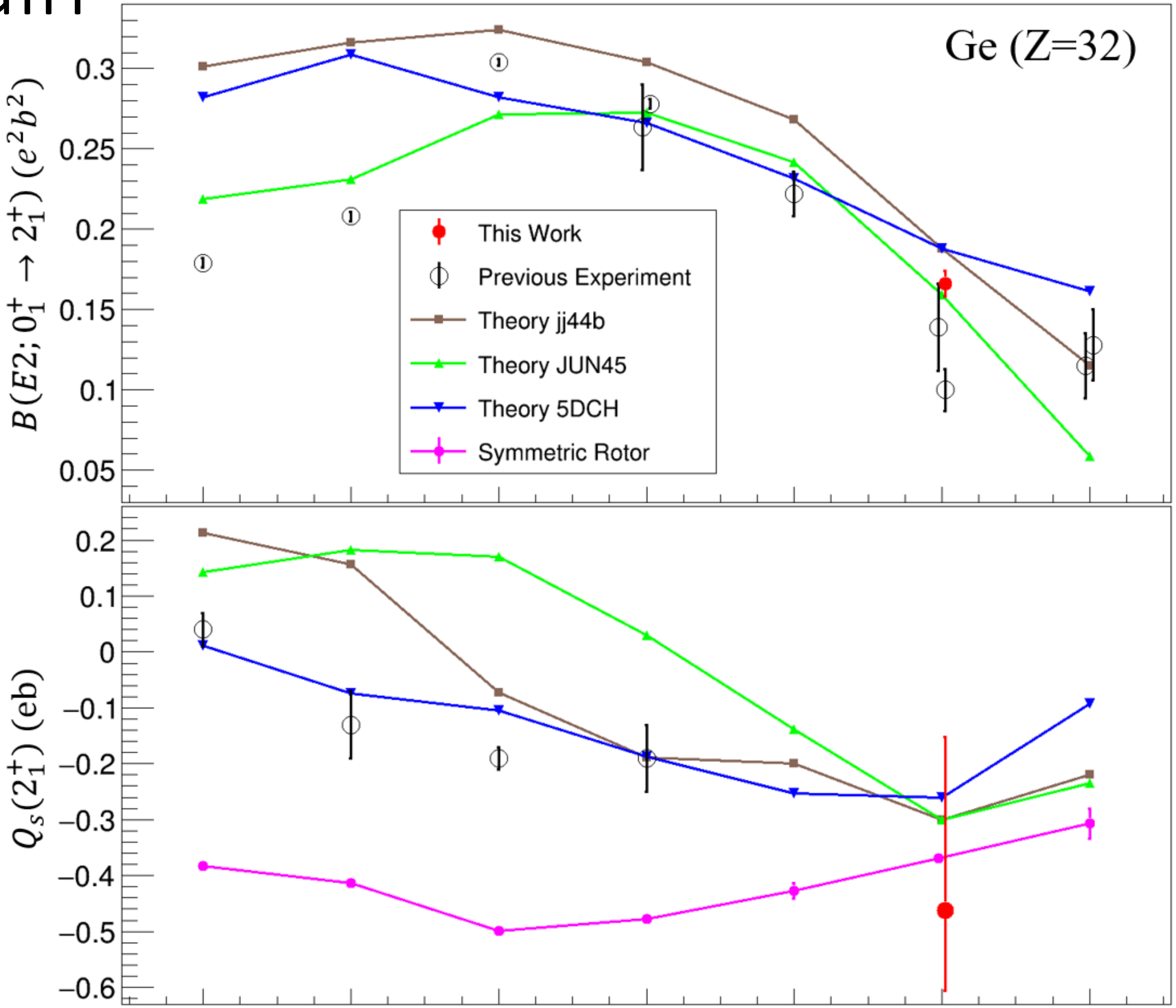
[19] E. Padilla-Rodal *et al.*, Phys. Rev. Lett. **94**, 122501 (2005)
[20] H. Iwasaki *et al.*, Phys. Rev. C 78, 021304(R) (2008)

The Ge Isotopic Chain

- Shell model calculations performed for the $^{70\text{-}82}$Ge isotopes
  - Trend of $B(E2; 0_1^+ \rightarrow 2_1^+)$ values reproduced
  - Evolution of collectivity well described

- $Q(2_1^+)$ values more challenging
  - Calculations predict minimum at ^{80}Ge
  - Consistent with current result

Fig. from [17]

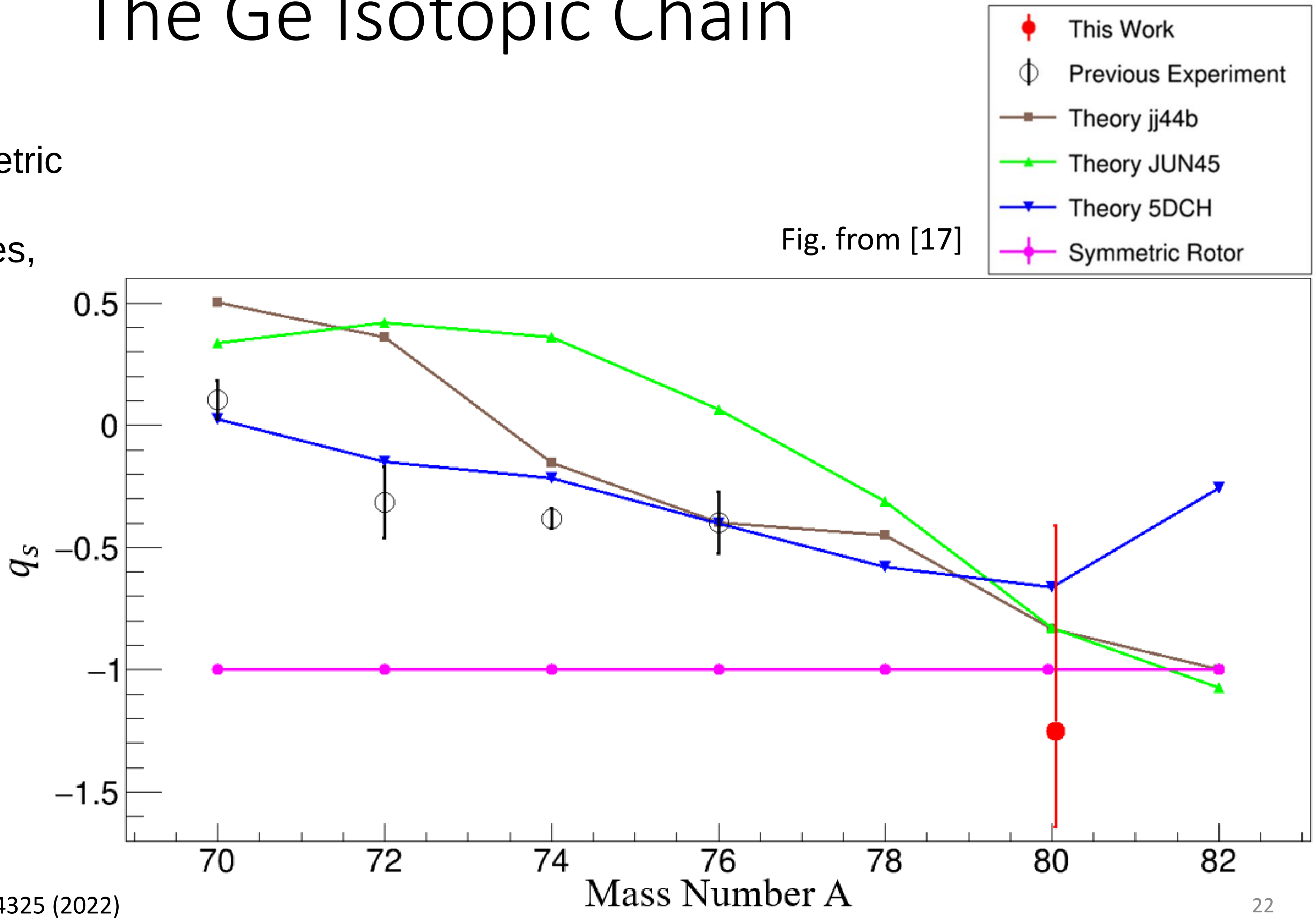


[17] D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)

The Ge Isotopic Chain

- Large q_s value in ^{80}Ge
- First indication of symmetric deformation
- Unlike lighter Ge isotopes, which display significant triaxiality

Fig. from [17]



[17] D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)

Summary

- The rare-isotope 80Ge was studied via Coulomb excitation at ReA3 facility using the JANUS setup
  - Measured $B(E2; 0_1^+ \rightarrow 2_1^+)$ and $Q(2_1^+)$
- Shell model calculations performed for comparison
  - $B(E2)$ values well described along isotopic chain
  - Both theory and experiment point to large $Q(2_1^+)$ in ^{80}Ge
  - Symmetric deformation, unlike lighter Ge isotopes
- Results recently published in Physical Review C
  - D. Rhodes *et al.*, Phys. Rev. C **105**, 024325 (2022)

Collaborators and Acknowledgements

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