# Suppressed electric quadrupole collectivity in $^{32}Si$

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University of Liverpool
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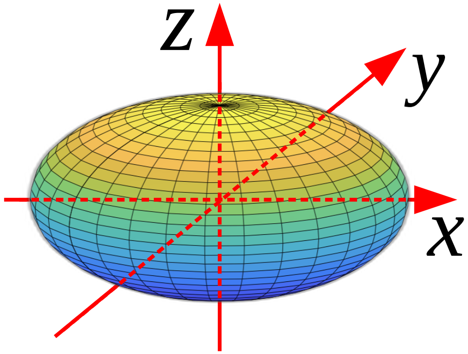
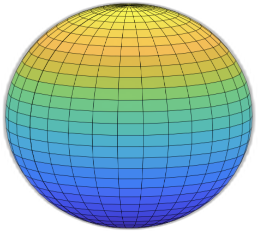
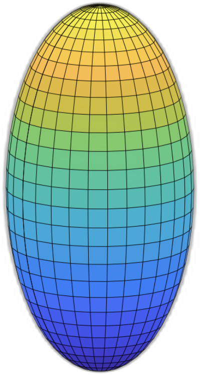
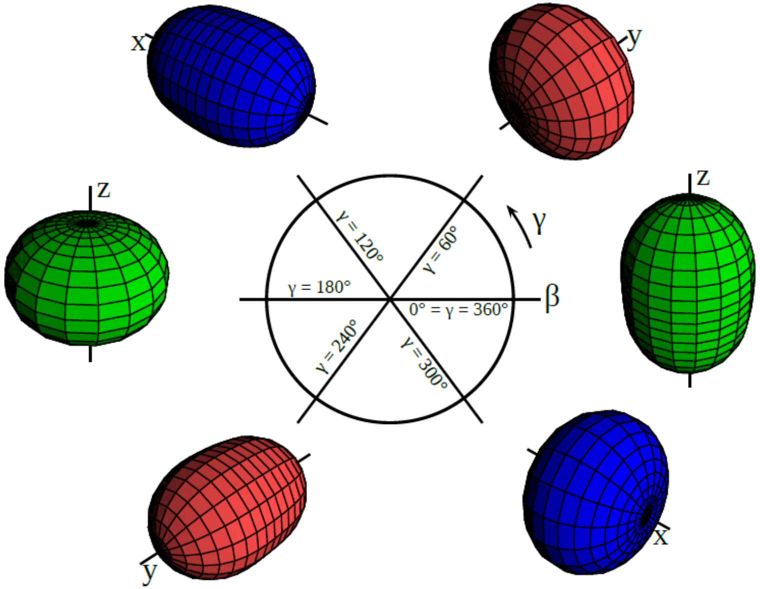
# Nuclear deformation

UNIVERSITY OF SURREY

| Oblate | Spherical | Prolate |
|---|---|---|
|  |  |  |
| $dy = dx > dz$ | $dx = dy = dz$ | $dx = dy < dz$ |
|  |  |  |

Triaxial shapes – $dx \neq dy \neq dz$

Shape defined by two parameters:
- β – Magnitude
- γ – Form (prolate/oblate)



# Nuclear deformation

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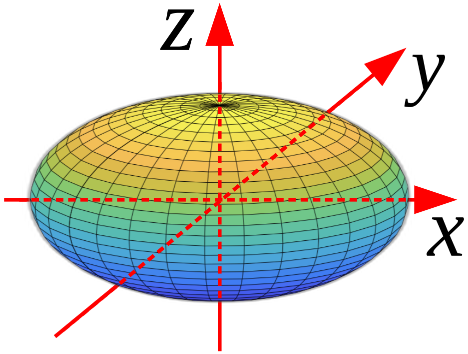
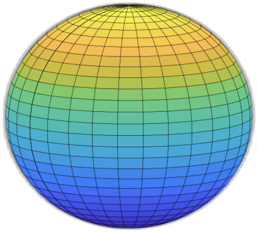
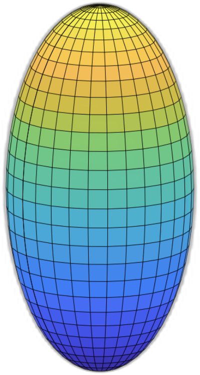
|  |  |  |

Triaxial shapes – $dx \neq dy \neq dz$

Shape defined by two parameters:
- β – Magnitude
- γ – Form (prolate/oblate)

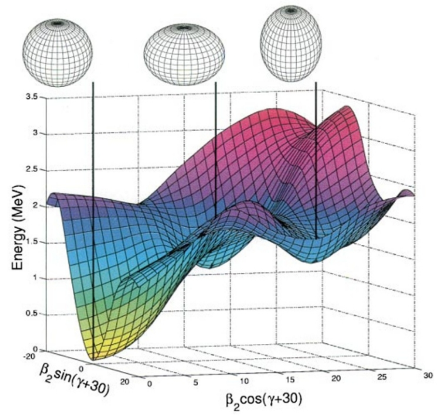
Two experimental observables that allow us to calculate β and γ:

- Reduced transition probability, B(E2)
- Spectroscopic quadrupole moment, $Q_s$

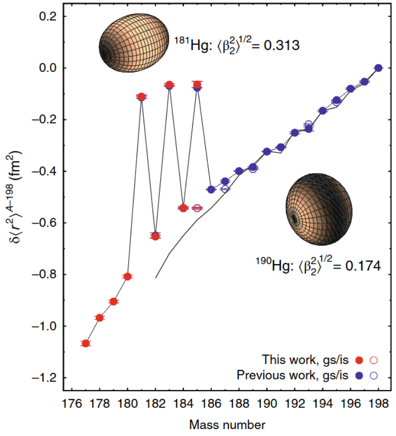
(Usually) measure these observables for the first $2^+$ state (which can be constructed using the quadrupole operator)

# Nuclear deformation

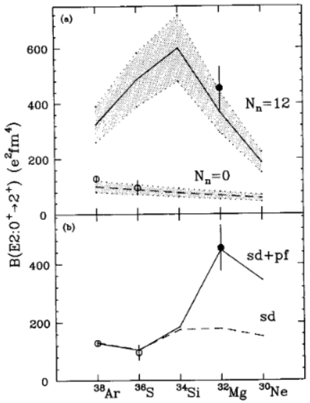
## Shape coexistence



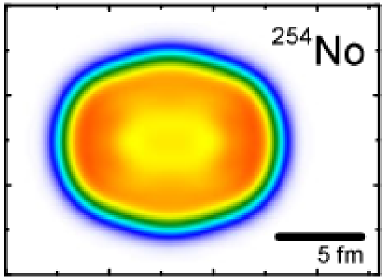

## Phase transitions




## Shell evolution

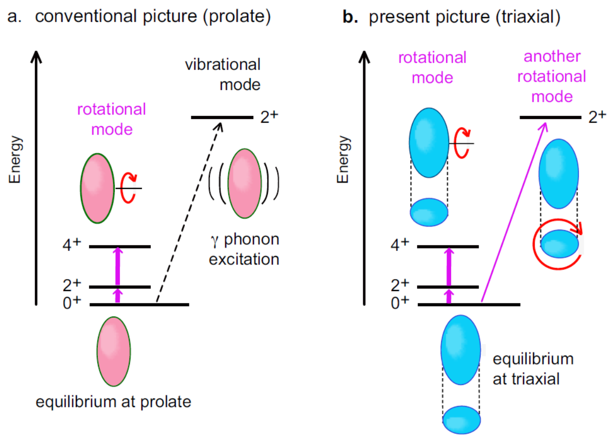



## Deformation in superheavy nuclei



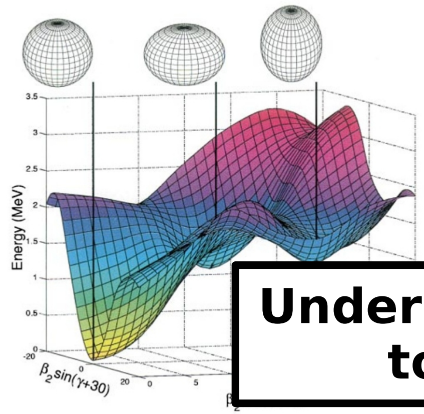

## Exotic nuclear shapes – e.g. octupole deformation


## Different modes of excitation

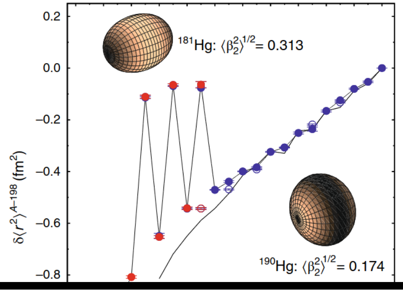


# Nuclear deformation

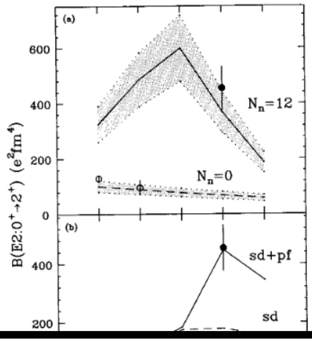
Shape coexistence



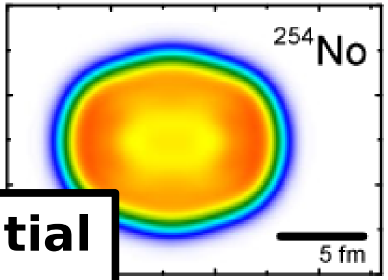

Phase transitions




Shell evolution

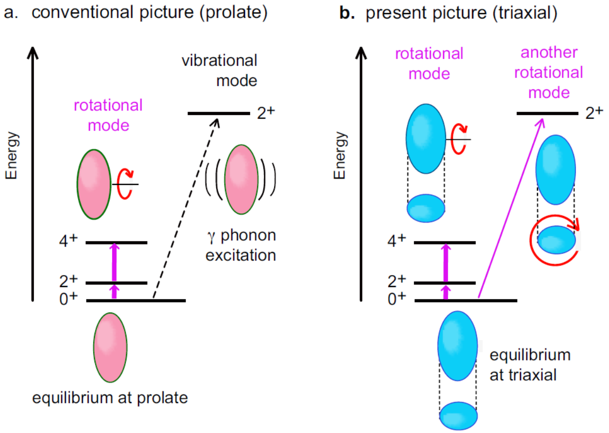



Deformation in superheavy nuclei



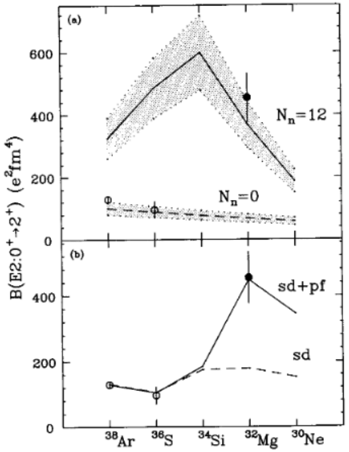

**Understanding self-organisation of nuclei is essential to solving the quantum many-body problem**

Exotic nuclear shapes – e.g. octupole deformation

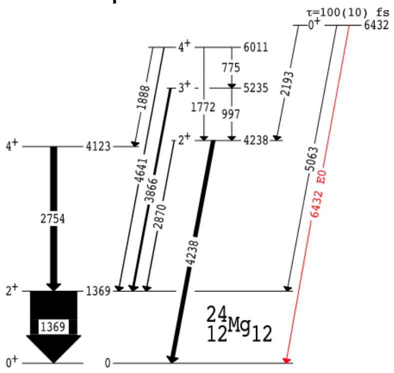
# The *sd*-shell

## Shell evolution



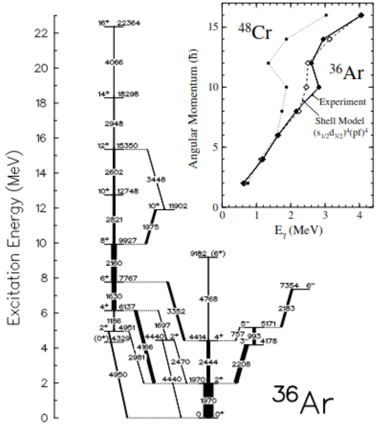

T. Motobayashi, *et al.*, PLB **346** (1995)

## Shape coexistence



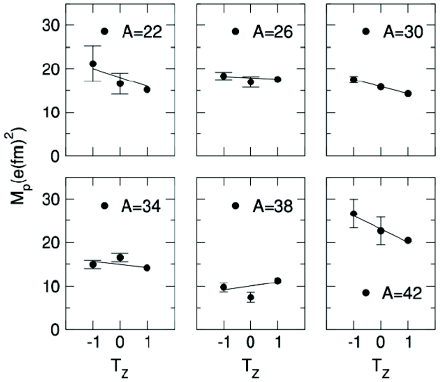

J.T.H. Dowie, *et al.*, PLB, **811** 135855 (2020)

## Superdeformation

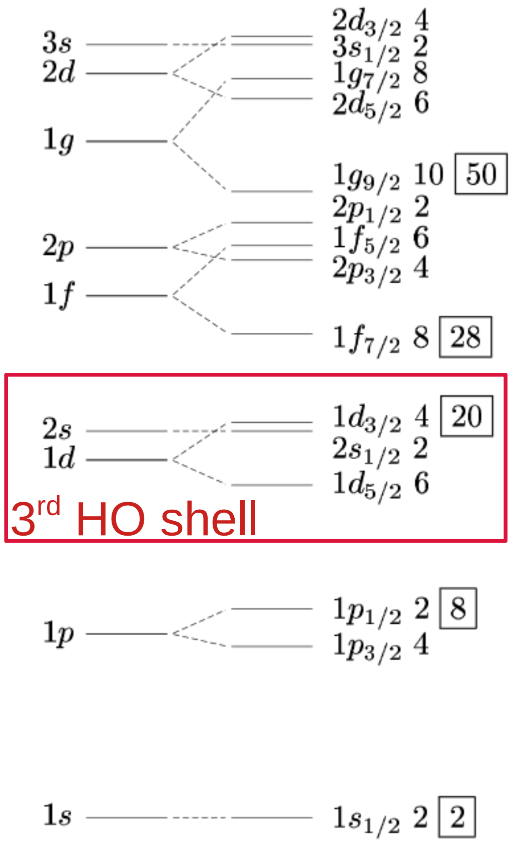



C. E. Svensson, *et al.*, PRL **85** 13 (2000)

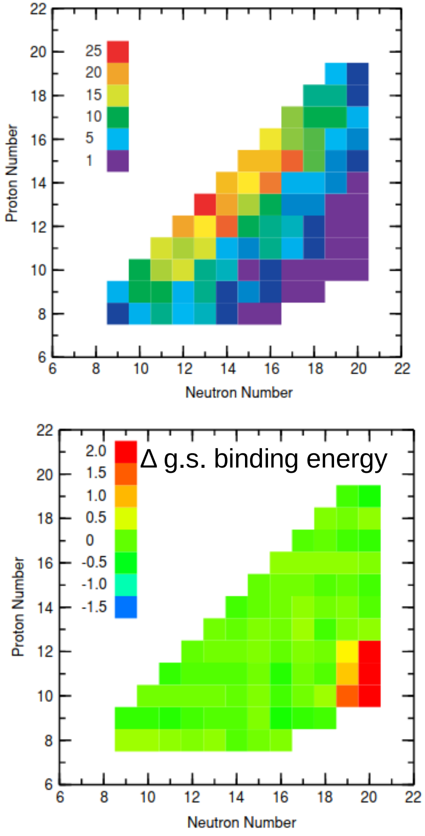
## Isospin breaking (N=Z)




F. M. Prados Estévez, *et al.*, PRC **75** 014309 (2007)



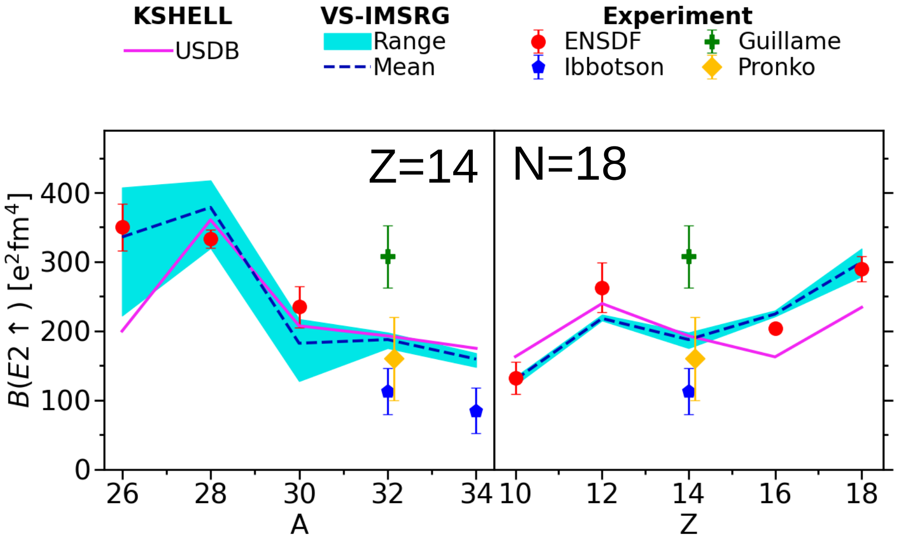

## USDB




B. A. Brown and W. A. Richter, PRC **74** 034315 (2006)

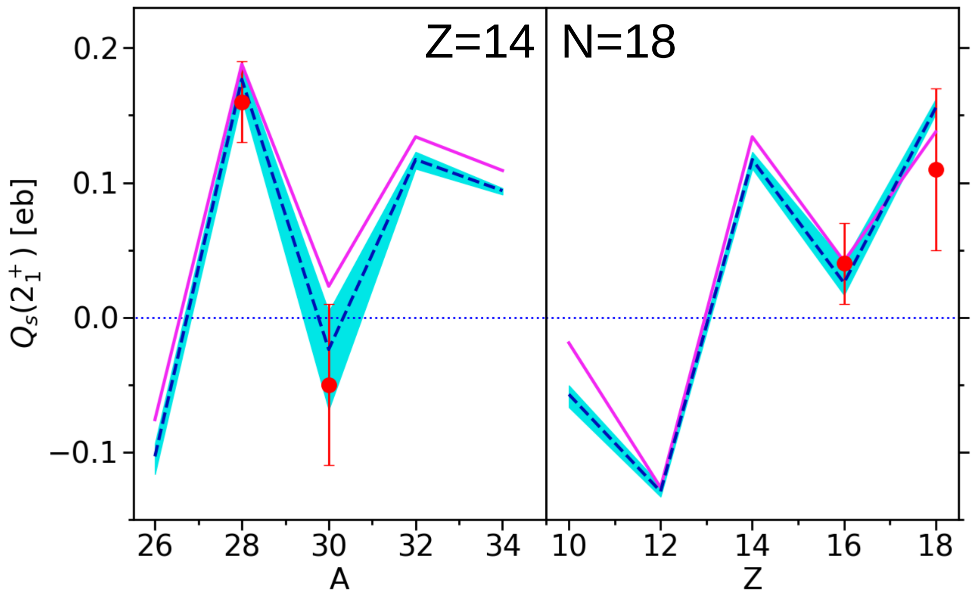
# $^{32}$Si at a glance

Disagreement between previous B(E2) values



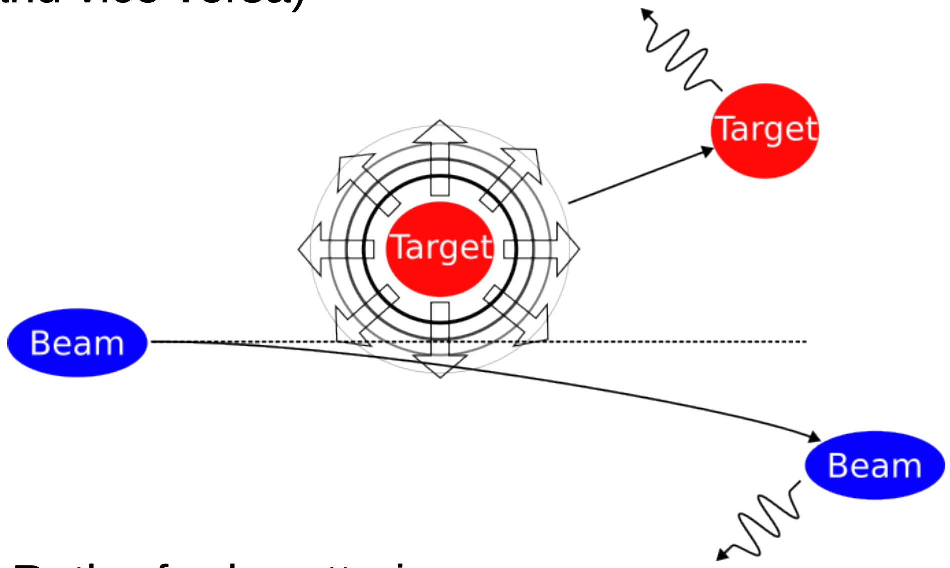

USDB shell model calculations do relatively good job in the region

No previous measurement of spectroscopic quadrupole moment, $Q_s$



# Coulomb excitation

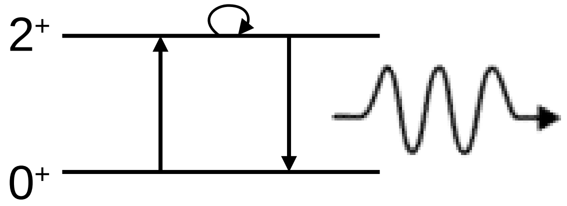
Beam nucleus is present in the electric field of target (and vice versa)




Rutherford scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{zZe^2}{4\pi\epsilon_0}\right)^2 \left(\frac{1}{4T_a}\right)^2 \frac{1}{\sin^4\frac{\theta}{2}}$$

Both nuclei are inelastically excited through the Coulomb potential




We carefully choose the energy and scattering angle to suppress nuclear excitation

Cline criterion – 5 fm between nuclear surfaces

To first order: $P \propto |\langle 0^+ \| E2 \| 2^+ \rangle|^2$

Or…
The B(E2) value

# Coulomb excitation

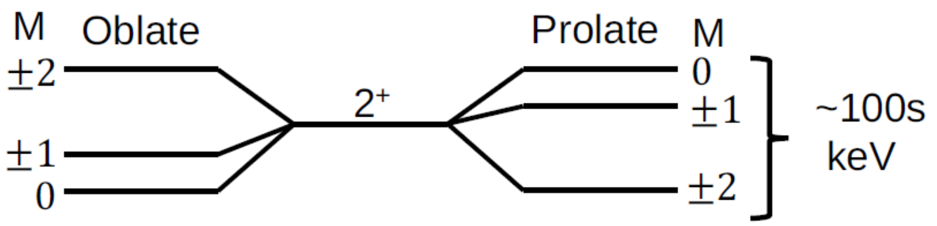
We can also access $Q_s$ from angular distribution for state population

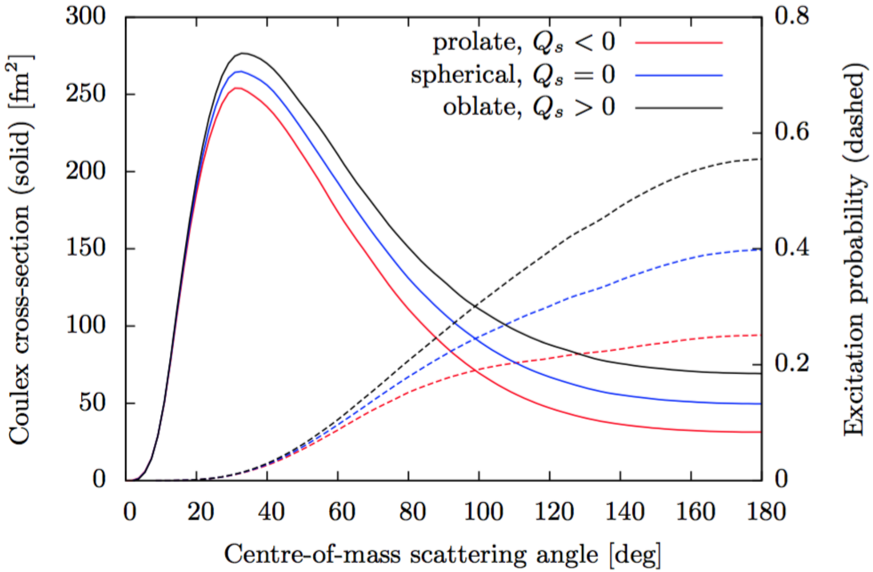
**The reorientation effect:**
Nuclei reorient in electric field gradient to minimise their energy

Typical Coulomb excitation reaction: dV/dr = $10^{30}$ V/cm

$$E(t) \propto eQ_s Z/r^3(t)$$

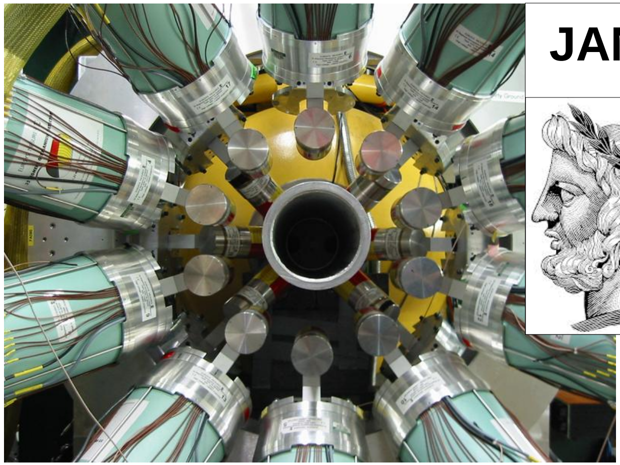
Breaking of m-state degeneracy depends on $Q_s$




M. Zielinska et al. Eur. J. Phys. A **52** 99 (2016)

# Experiment at NSCL



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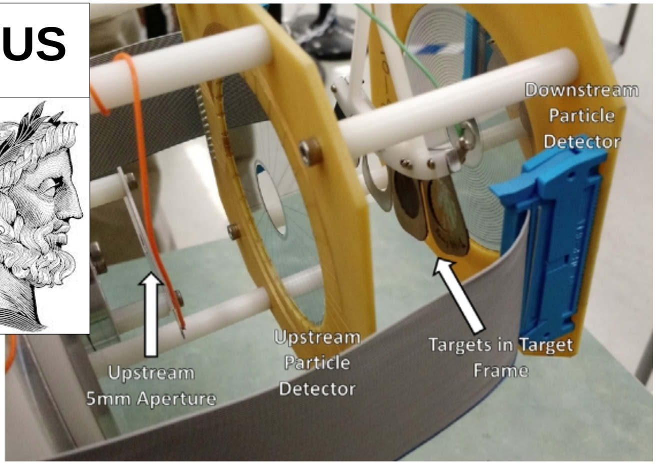
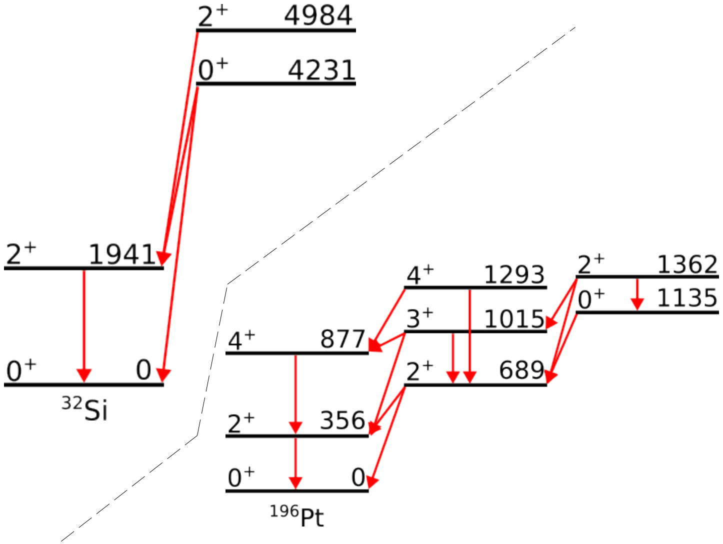



- "Safe" Coulomb excitation of $^{32}$Si beam on a $^{196}$Pt target.
- Beam energies: 3.57 and 3.48 MeV/u
- Beam intensity: $10^6$ pps
- Target thickness: 1 mg/cm$^2$




<u>SeGA</u>

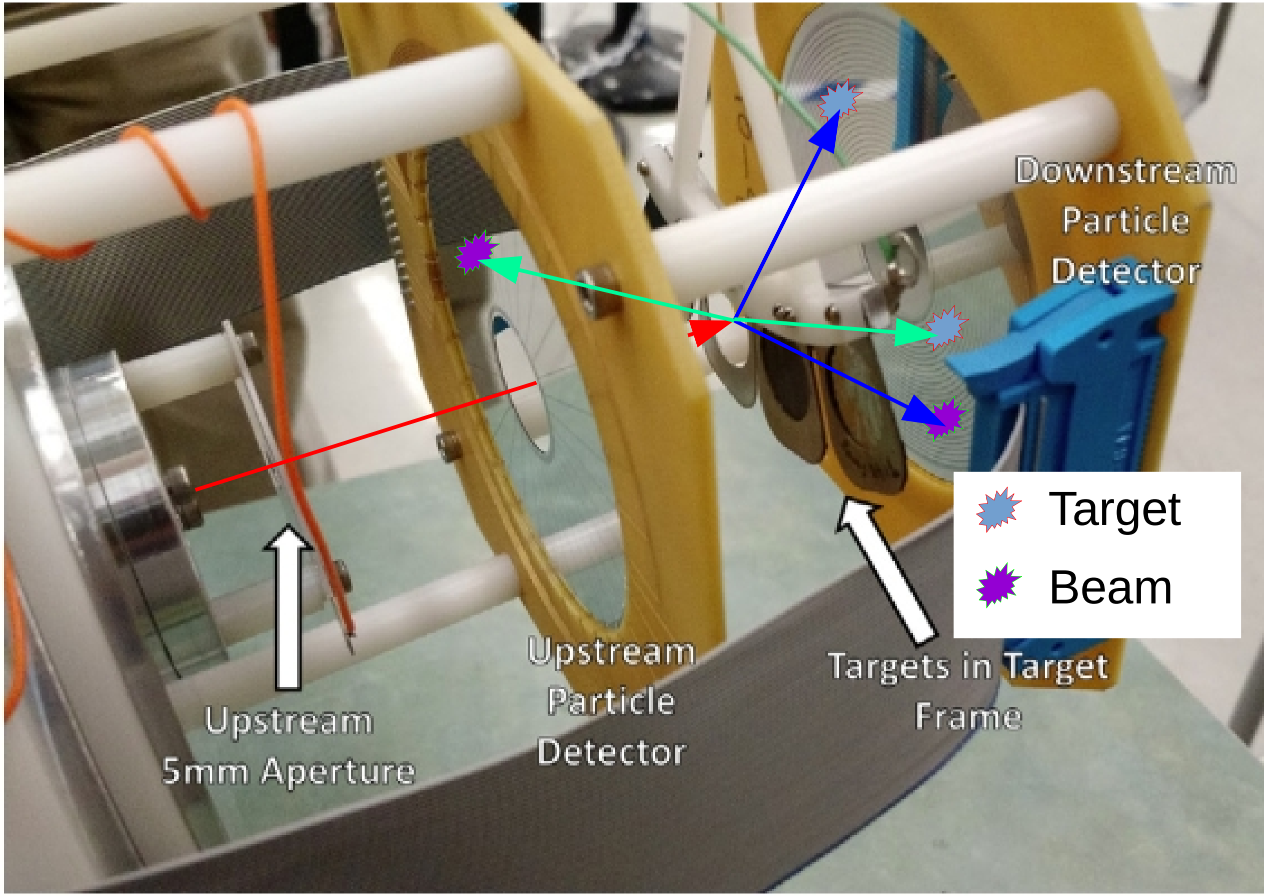
- Array of 16 32-fold segmented germanium crystals.
- Energy resolution of ~2.5 keV FWHM at 1332 keV.
- Efficiency of ~6% at 1 MeV.

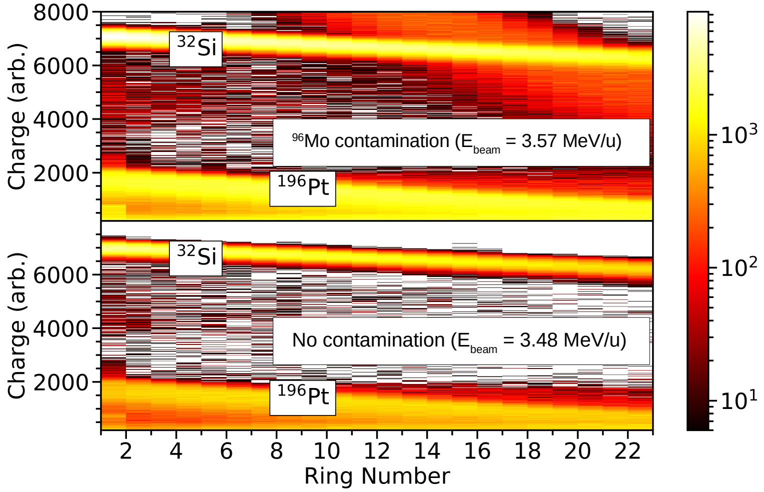
<u>Bambino 2</u>

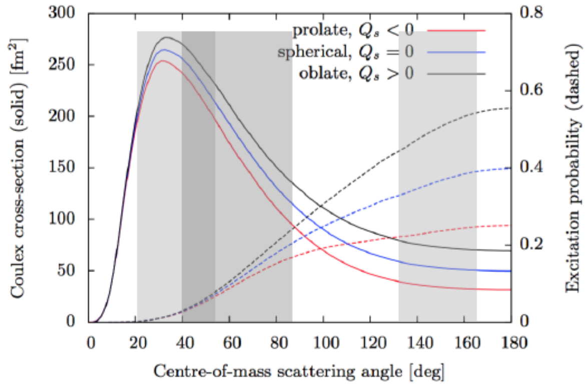
- 2 annular double-sided silicon detectors (S3).
- **Upstream** angular range,
- $\theta$: **130.6° – 159.9°**
- **Downstream** angular range,
- $\theta$: **20.1° – 49.4°**
- Angular resolution: **1.5°** in $\theta$ and **3°** in $\phi$

E. Lunderberg, *et al.*, Nucl. Instrum. Meth. A **885**, 37 (2018)

# Experiment at NSCL

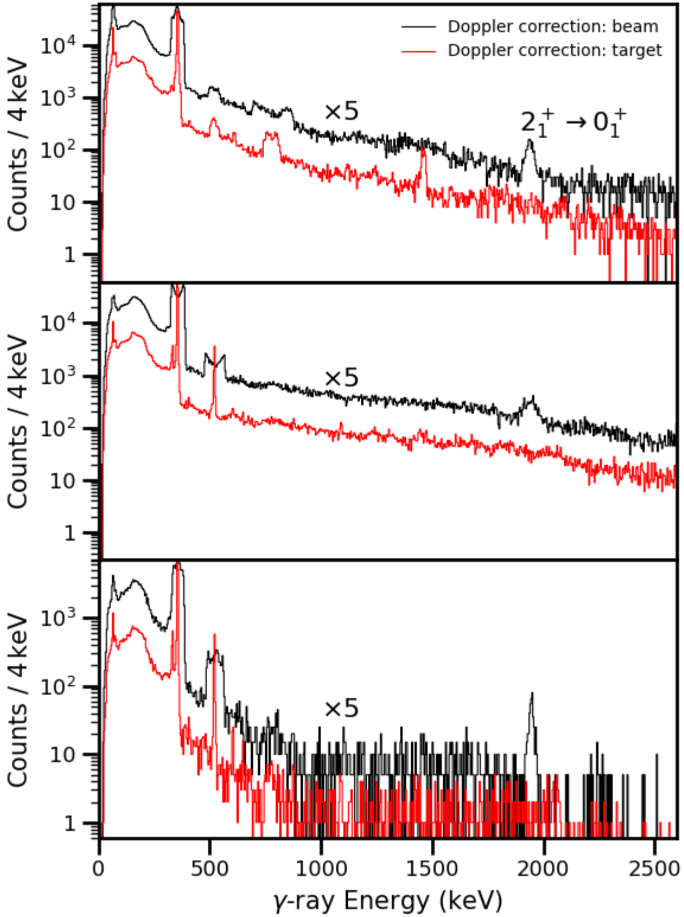



M. Zielinska et al. Eur. J. Phys. A **52** 99 (2016)

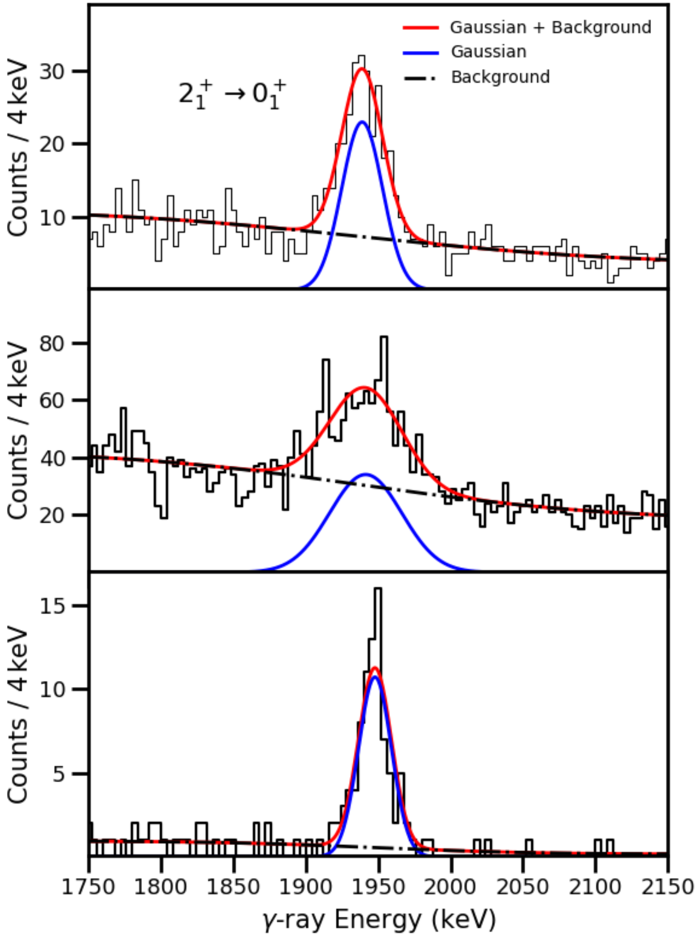
# Experiment at NSCL




$^{32}$Si detected downstream

$^{196}$Pt detected downstream

$^{32}$Si detected upstream

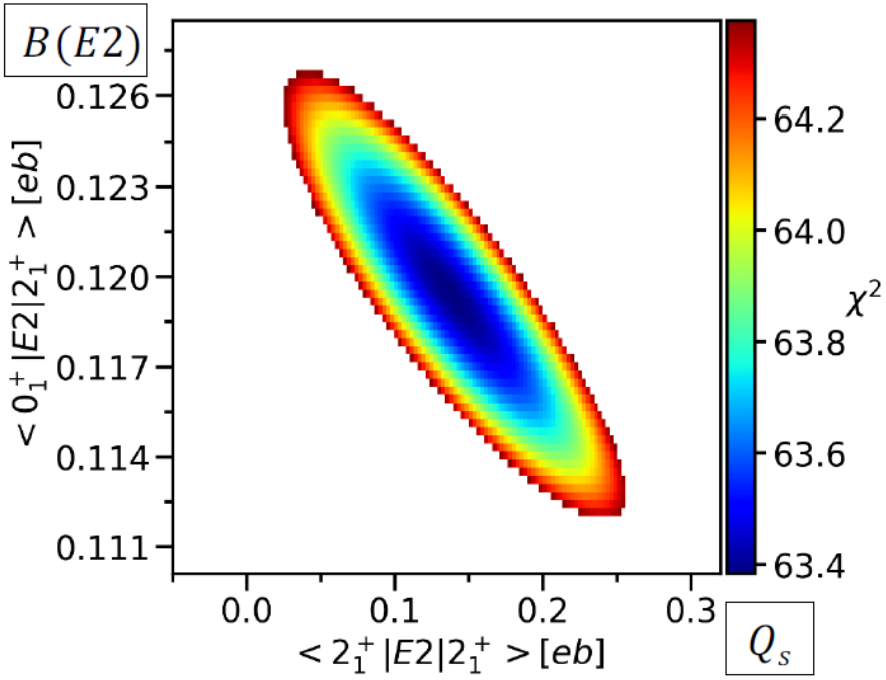


# GOSIA analysis

Yields evaluated using GOSIA.

$\chi^2$ minimization of matrix elements performed using the MIGRAD algorithm in the ROOT MINUIT library.

Simultaneous fitting of $^{196}$Pt matrix elements accounts for systematic errors.

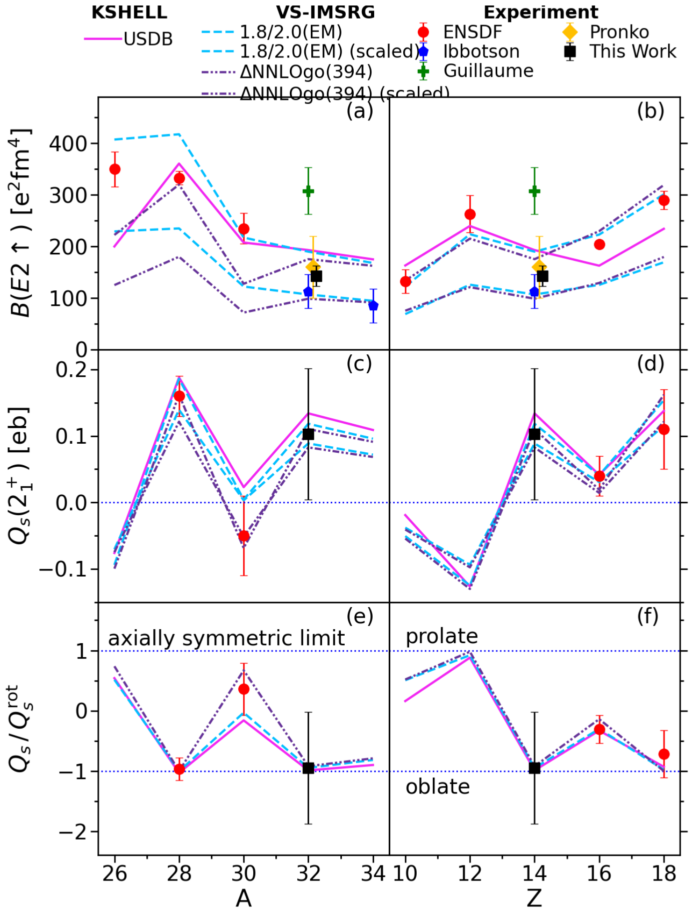



<u>Final Result</u>

$B(E2;0_1^+ \rightarrow 2_1^+)$ = 135(19) $e^2fm^4$ = 22(3) W.u.

$Q_s(2_1^+)$ = 0.14(8) eb

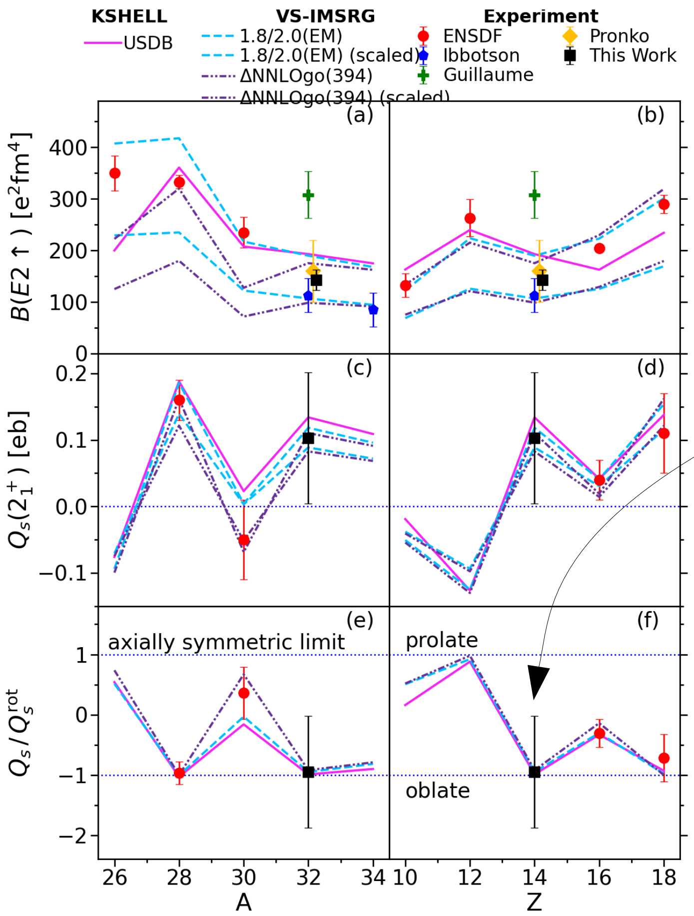
# How do the results compare...




J. Heery, *et al.*, Phys. Rev. C **109**, 014327 (2024)

- Result for $Q_s(2_1^+)$ compares well to USDB (although note large errors)
- B(E2) value is significantly overestimated by USDB for $^{32}$Si and $^{34}$Si
- USDB is reproducing shape well, but under predicts the magnitude of deformation
- Ab-initio VS-IMSRG compares well... but note there is a truncation to the evolution of the electromagnetic operators at the two-body level [IMSRG(2) approximation]
- Comparison of data for several sd-shell nuclei shows calculations underpredict E2 matrix elements by ≈25% [S. R. Stroberg *et al.*, PRC **105**, 034333 (2022)]
- Scaled results are similar to USDB

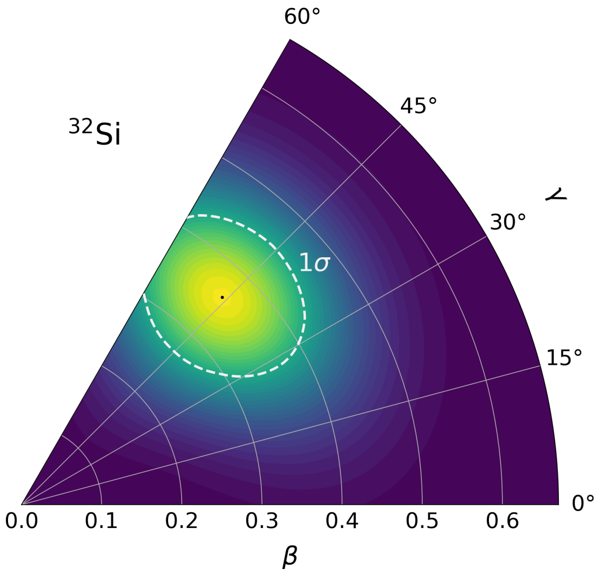
# How do the results compare...




J. Heery, *et al.*, Phys. Rev. C **109**, 014327 (2024)

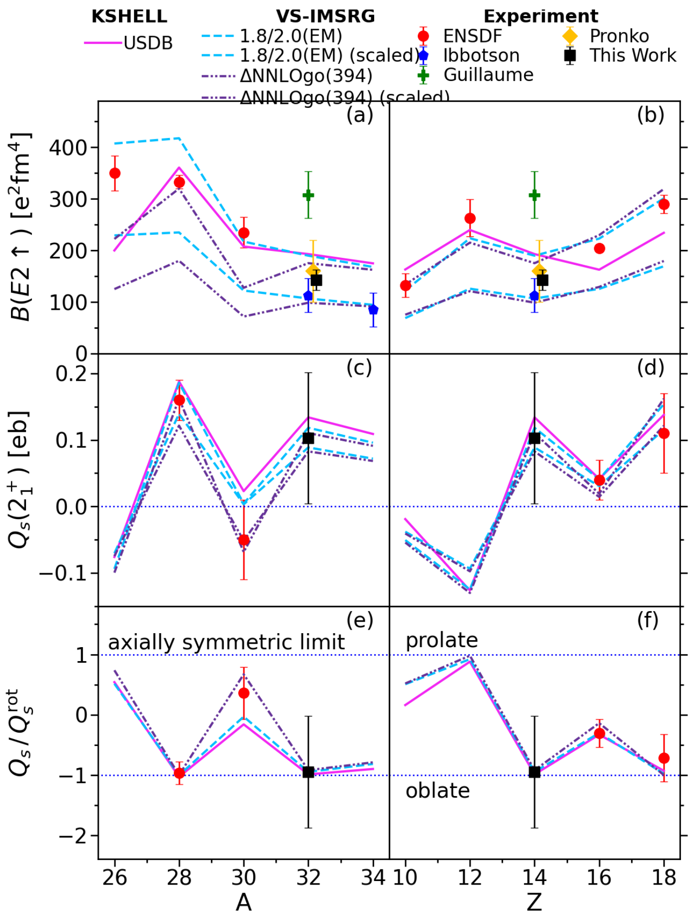
We can approximately calculate the γ parameter

$$\cos(3\gamma) \approx \cos(3\gamma)_{2_1^+} = -\frac{Q_s(2_1^+)}{\frac{2}{7}\sqrt{\frac{16\pi}{5}} \cdot B(E2; 0_1^+ \rightarrow 2_1^+)}$$



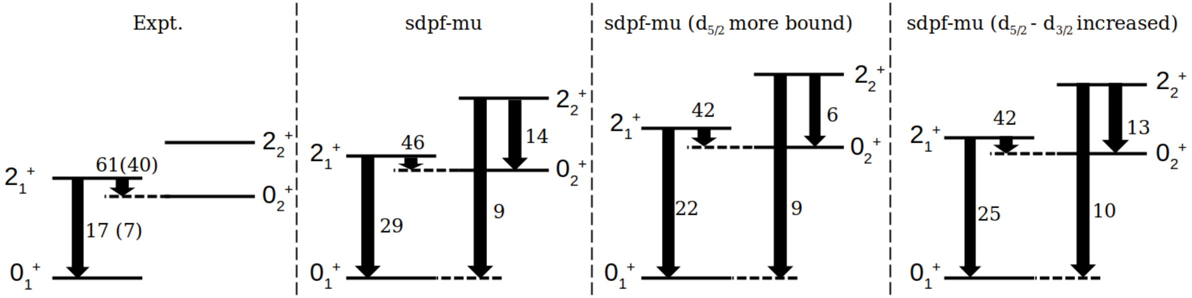

Full calculation using Kumar-Cline quadrupole invariants - exact within USDB model space

# Theoretical descriptions

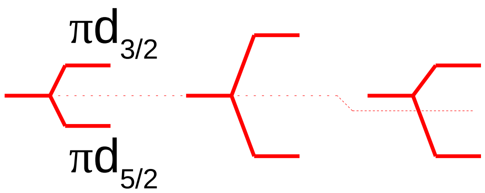



J. Heery, *et al.*, Phys. Rev. C **109**, 014327 (2024)

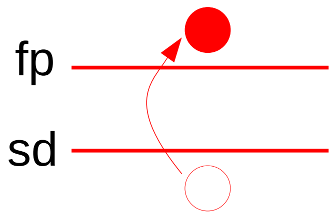
What do things look like in $^{34}$Si?



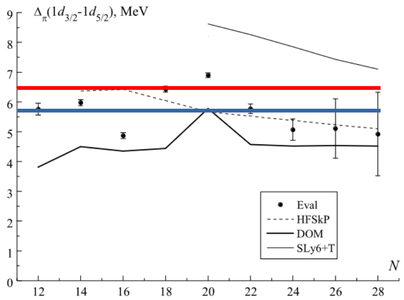

**Changes to $\pi d_{5/2}$, $\pi d_{3/2}$ shells**




**Out-of-shell excitations**




Some evidence for this at $^{32}$Si and $^{34}$Si
[O.V. Bespalova, *et al.*, Eur. Phys. J. A **54**, 2 (2018).]



# Summary

**$^{32}$Si – Inhibited quadrupole deformation**

- Nuclear deformation in $^{32}$Si has been investigated through “safe” Coulomb excitation at NSCL, MI, USA
- $B(E2; 0_1^+ \rightarrow 2_1^+) = 135(19)\ e^2fm^4$, $Q_s(2_1^+) = 0.14(8)$ eb
- Phenomenological and ab-initio calculations both reproduce oblate structure but overpredict the scale of deformation
- There is a reduced role of out-of-space excitations (core polarisation)

# [32]Si Thanks

**Collaborators:**
J. Henderson[1], C. R. Hoffman[2], A. M. Hill[3], B. Hu[4], J. D. Holt[4,5,6], T. Beck[3,6], C. Cousins[1], P. Farris[3,6], A. Gade[3,6], S. A. Gillespie[6], H. Iwasaki[3,6], S. Kisyov[7], A. Kuchera[8], B. Longfellow[7], C. Müller-Gatermann[2], E. Rubino[6], R. Russell[1], R. Salinas[3,6], A. Sanchez[3,6], D. Weisshaar[6], C. Y. Wu[7], J. Wu[6]

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