Coulomb Excitation with Stable and Radioactive Beams

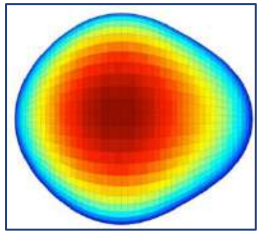
Jack Henderson

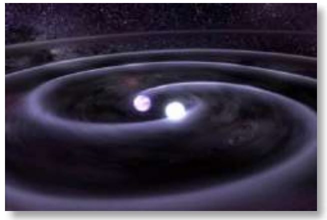
University of Warsaw Nuclear Physics Seminar, 10/04/2025

Introduction

Why is nuclear physics interesting?

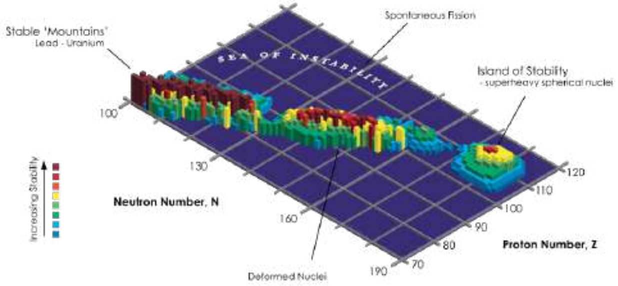
Emergent phenomena in a strongly-interacting many-body system: Halo-nuclei, bubble nuclei, collective motion.

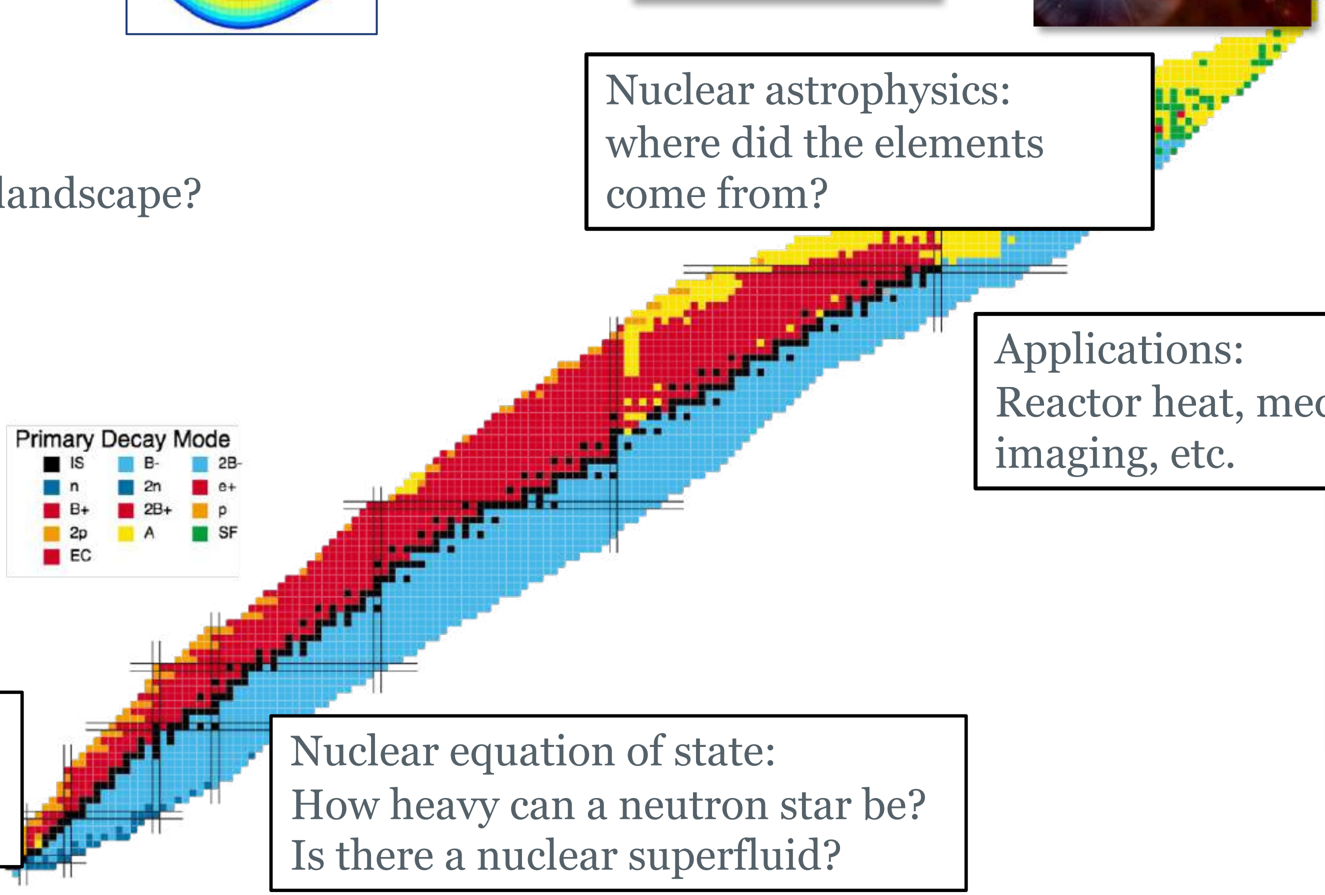




Nuclear astrophysics: where did the elements come from?

Where are the limits of the nuclear landscape?





Applications: Reactor heat, medical imaging, etc.

Tests of fundamental physics: CKM unitarity, neutrinoless double-beta decay, EDM measurements

Nuclear equation of state: How heavy can a neutron star be? Is there a nuclear superfluid?

Why is nuclear physics ~~interesting~~ difficult?

The nucleus is a **finite strongly-interacting**, **many-body** system

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The **finite nature** of the nucleus means we can't make trivial use of high-N methods from e.g., material science

Surface terms matter!

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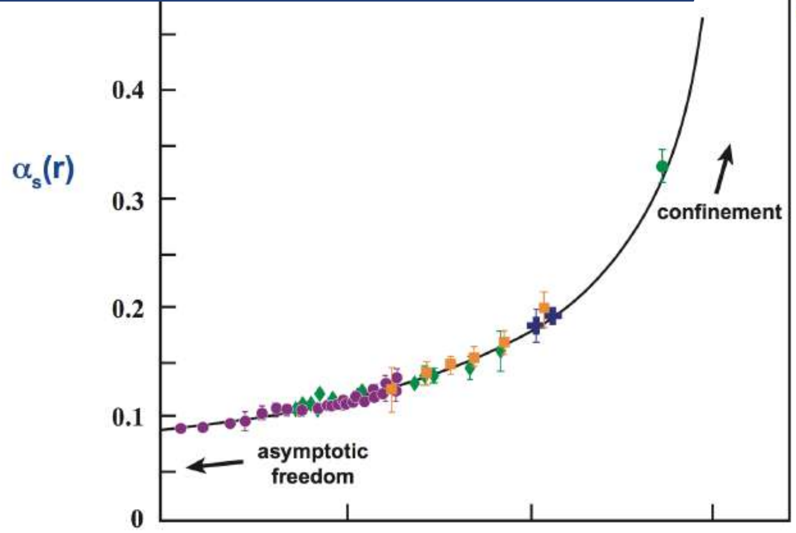
M. R. Pennington, J. Phys G **43** 054001



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Surface terms matter!

Strongly interaction is non-perturbative at low energy (high separation) – cannot trivially neglect low energy (high separation) terms.

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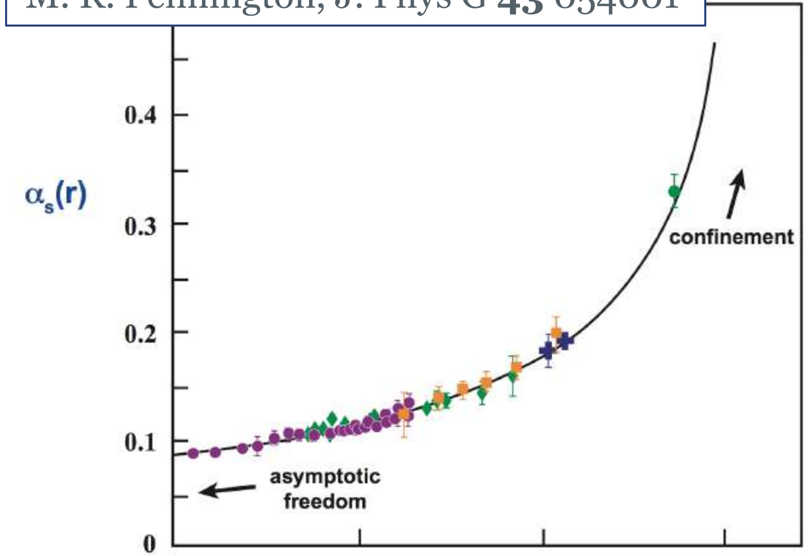
M. R. Pennington, J. Phys G **43** 054001



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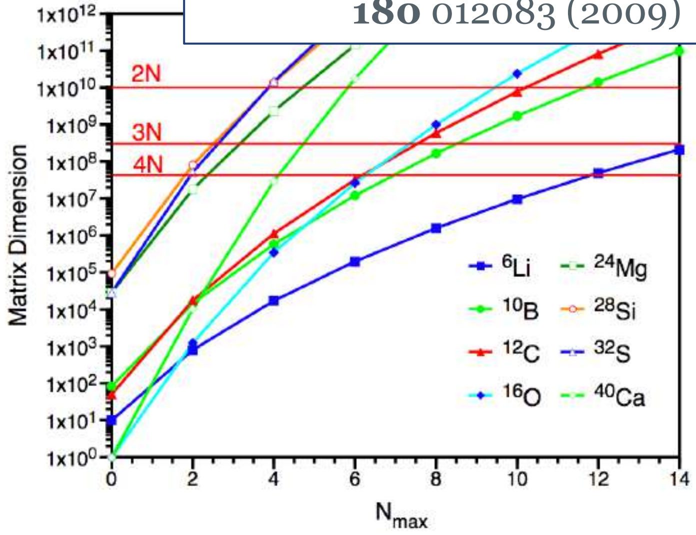
Surface terms matter!

J. P. Vary et al., J. Phys. Conf. Series **180** 012083 (2009)



Even with a well understood interaction, solving the **many-body** problem is complicated

Nominally requires diagonalizing the complete highly multi-dimensional Hamiltonian

Rapidly becomes intractable

Why collectivity?

The nucleus is a **finite strongly-interacting**, **many-body** system

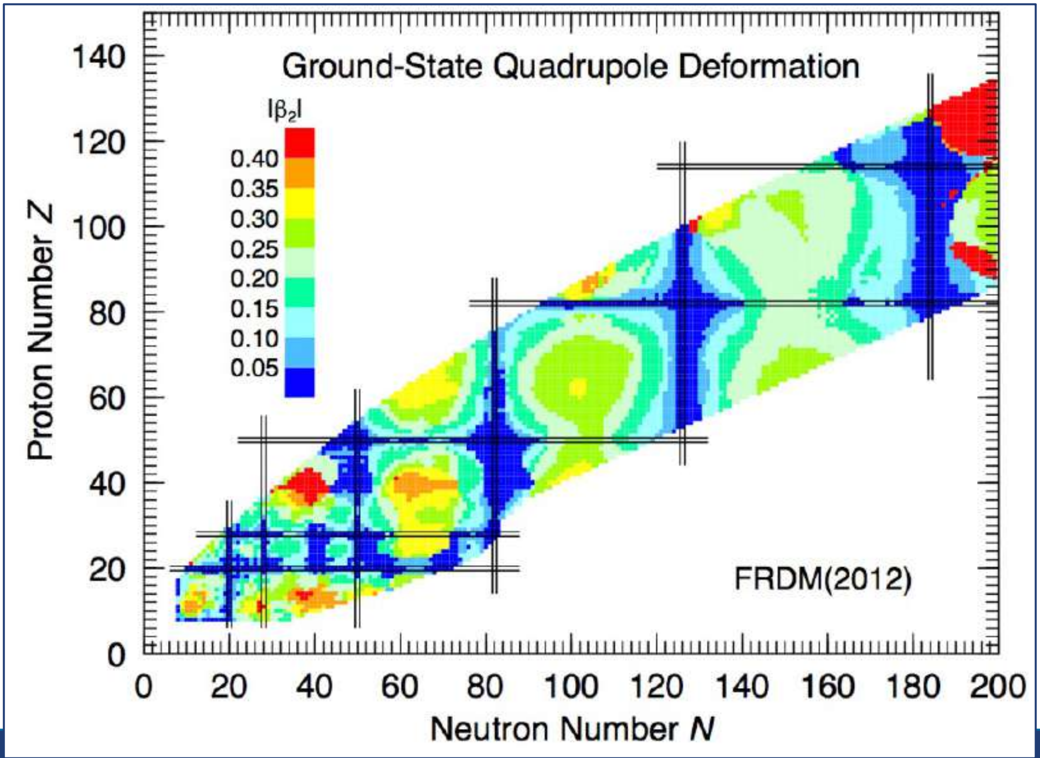
Collective nuclear properties are emergent properties of the nuclear system arising because of the strongly-interacting, many-body nature of the problem

Collectivity (and deformation) is an extreme test of nuclear models

Experimental signature for collectivity is corresponding electric-multipole strength (e.g. E2, E3, E4, etc..)

Inhibited near nuclear magic numbers – but … everywhere

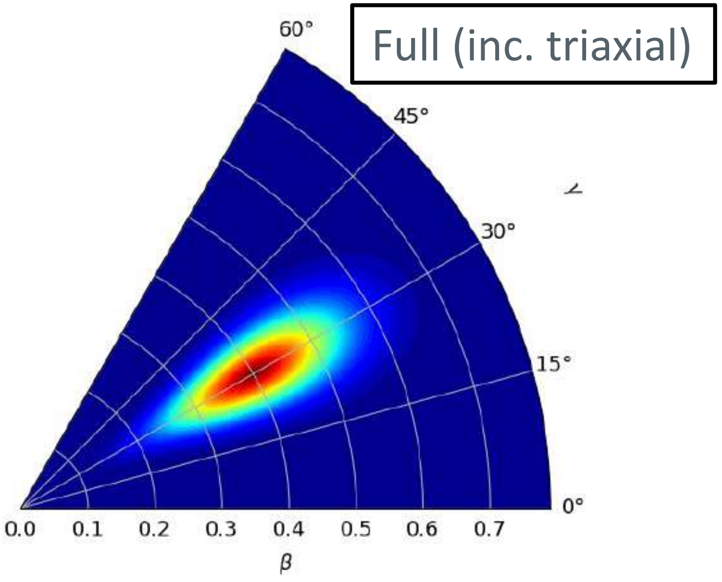
P. Möller et al., At. Nucl. Data Tables **109** 1 (2016)

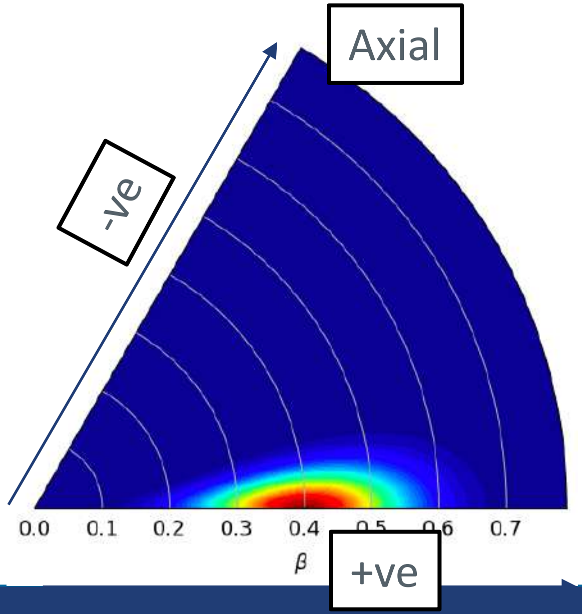


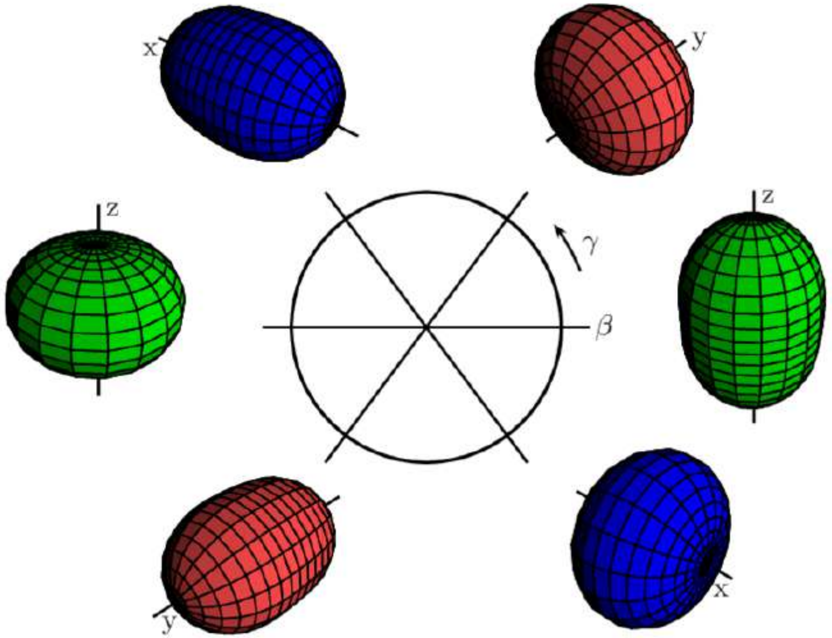
Language

The language of deformation is rooted in the Bohr Hamiltonian, which uses Hill-Wheeler coordinates to relate cartesian axis lengths to β and γ deformation parameters

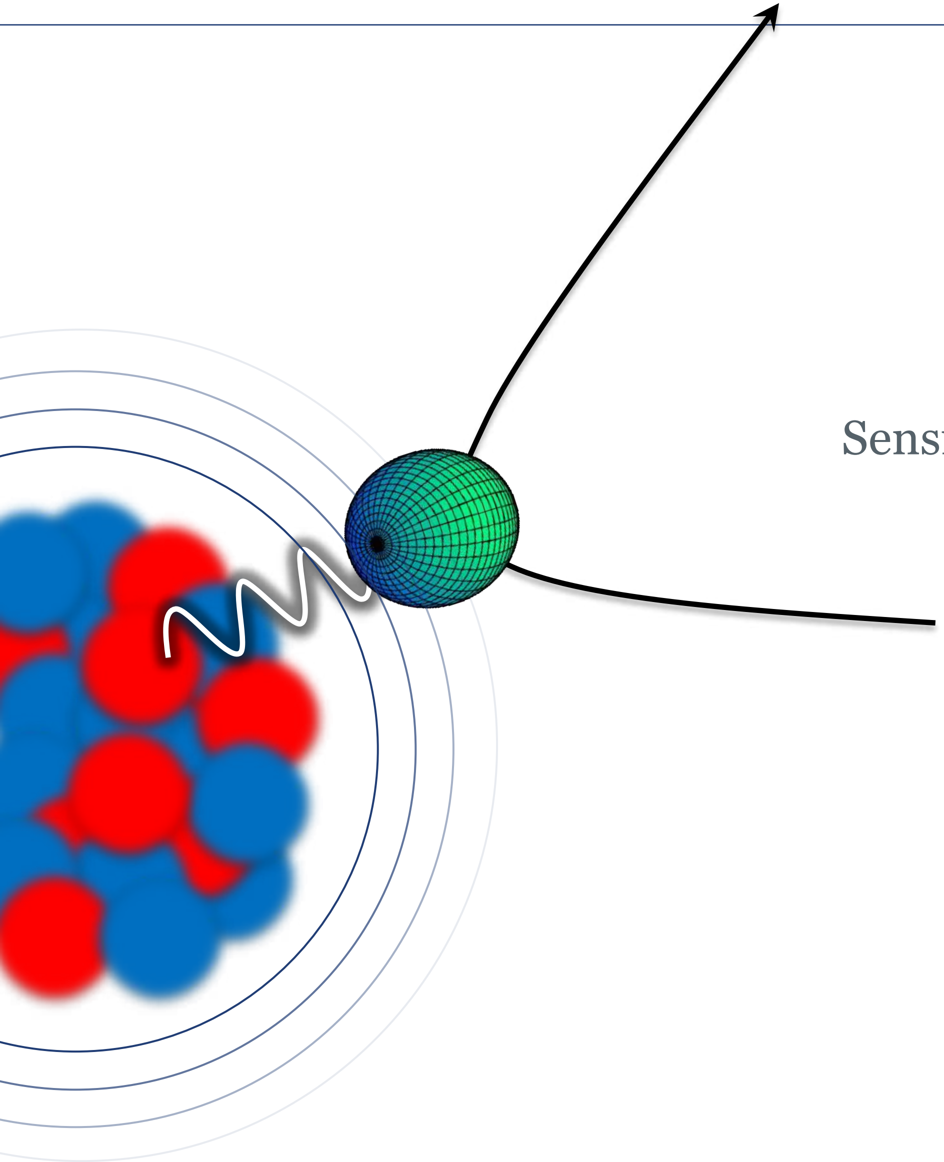
$$R_k = R_0(1 + \frac{5}{4\pi}\beta_2 \cos(\gamma - \frac{2}{3}\pi k))$$







The Method: Coulomb excitation



Why Coulomb excitation?

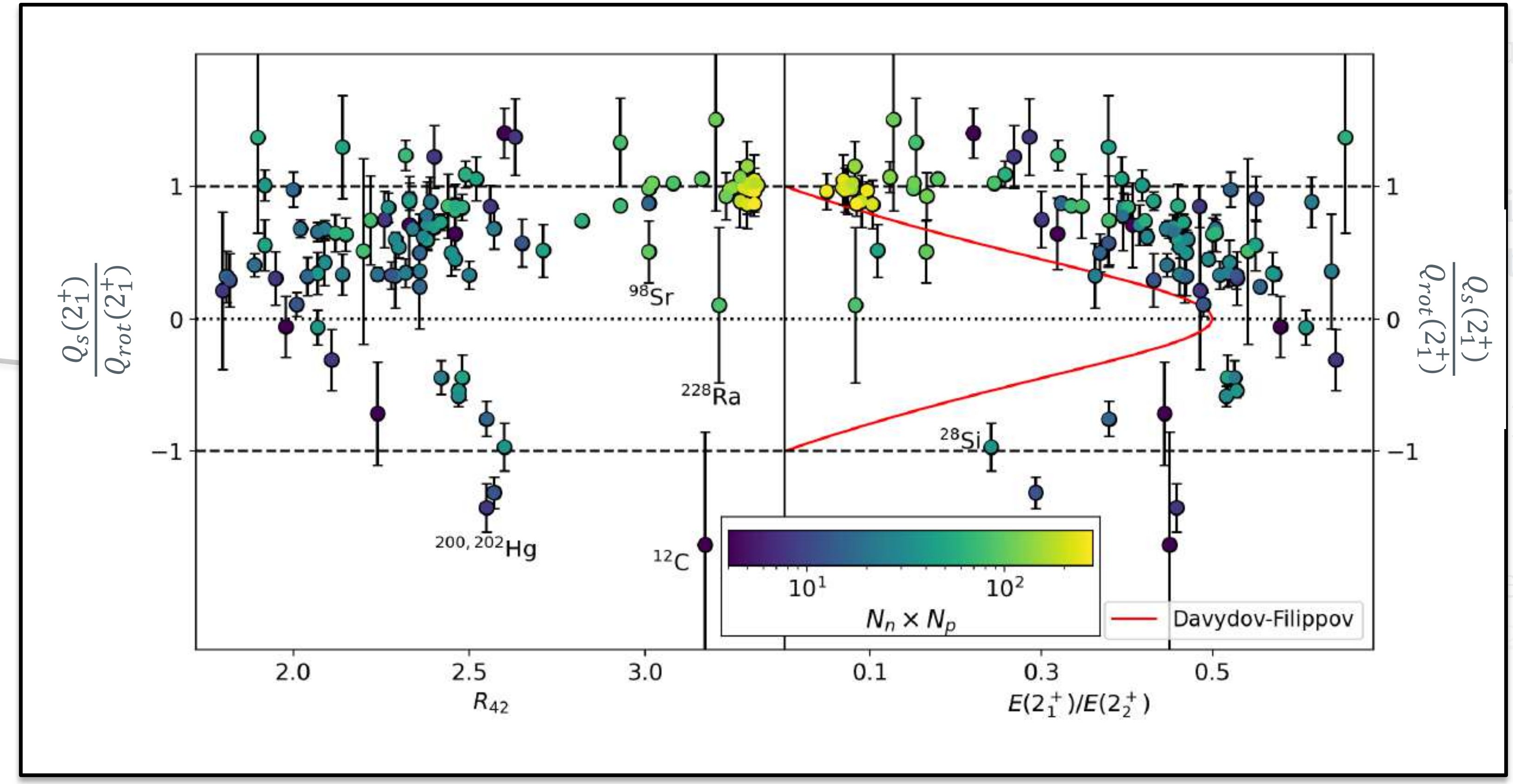
Electromagnetic ("model independent") probe of the nucleus

Sensitive to magnitudes and (relative) signs of electric multipole matrix elements including spectroscopic quadrupole moments

Large cross sections – well-suited to RIB

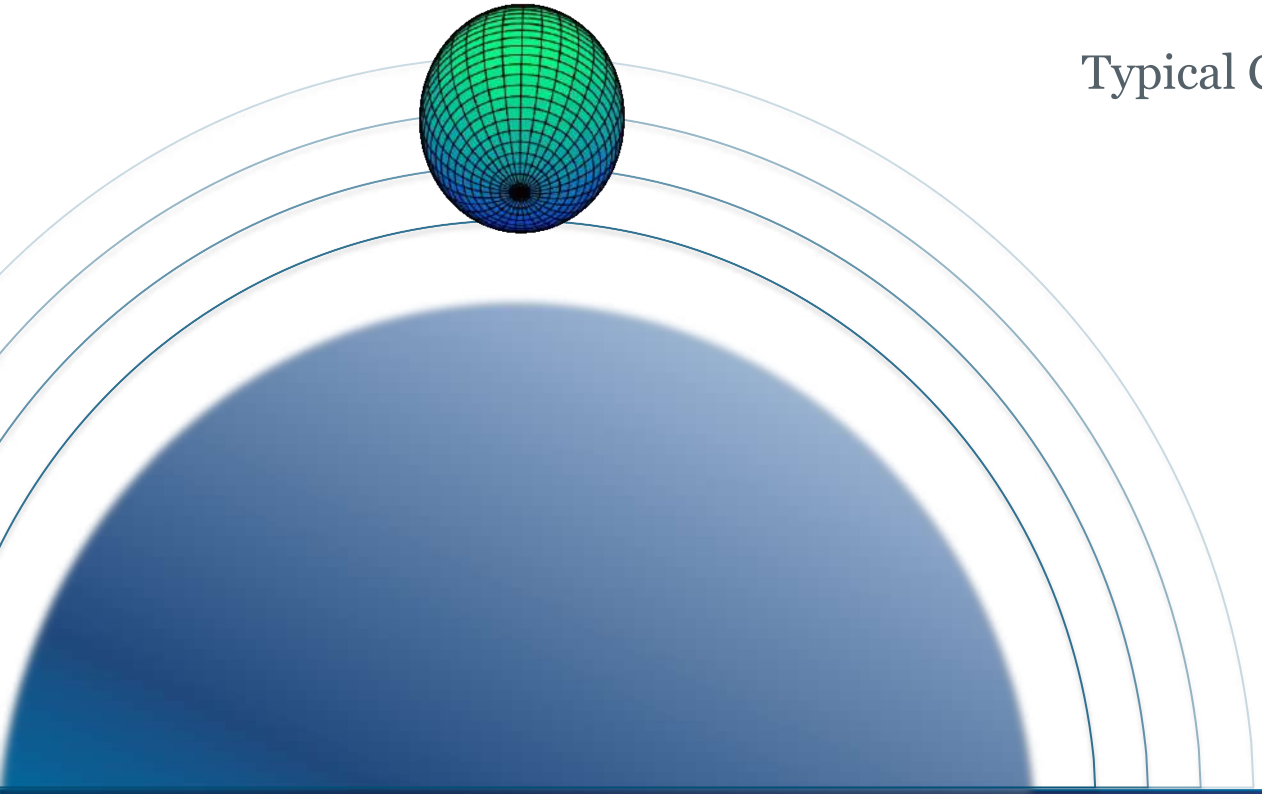
Exceptional probe of nuclear deformation through sum rules
Kumar PRL **28** 249 (1972)

The Method: Coulomb excitation



How do we access quadrupole moments?

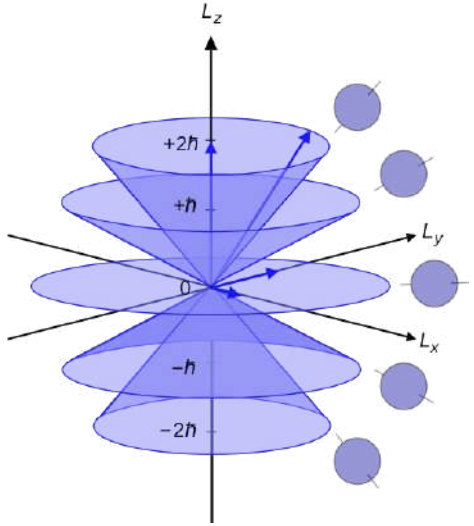
Qualitative picture: Nuclei reorient in electric field gradient to minimize their energy



Typical CoulEx reaction: $dV/dr \approx 10^{30}$ V/cm^2

Nucleus aligns relative to symmetry axis

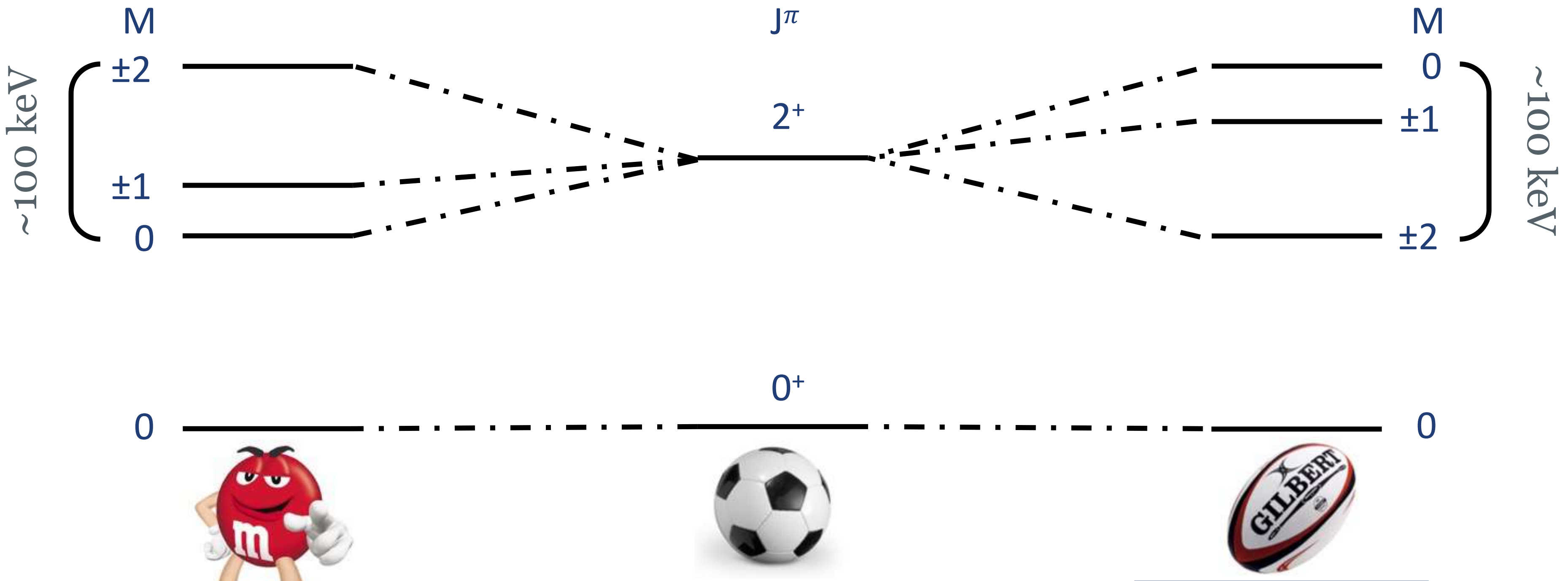
Breaks m-state degeneracy



The Method: Coulomb excitation

Splitting ∝ dV/dr ~ 10^{30} V/cm

$$E(t) \propto eQ_sZ/r^3(t)$$



Oblate splitting

Spherical

Prolate splitting

The Method: Coulomb excitation

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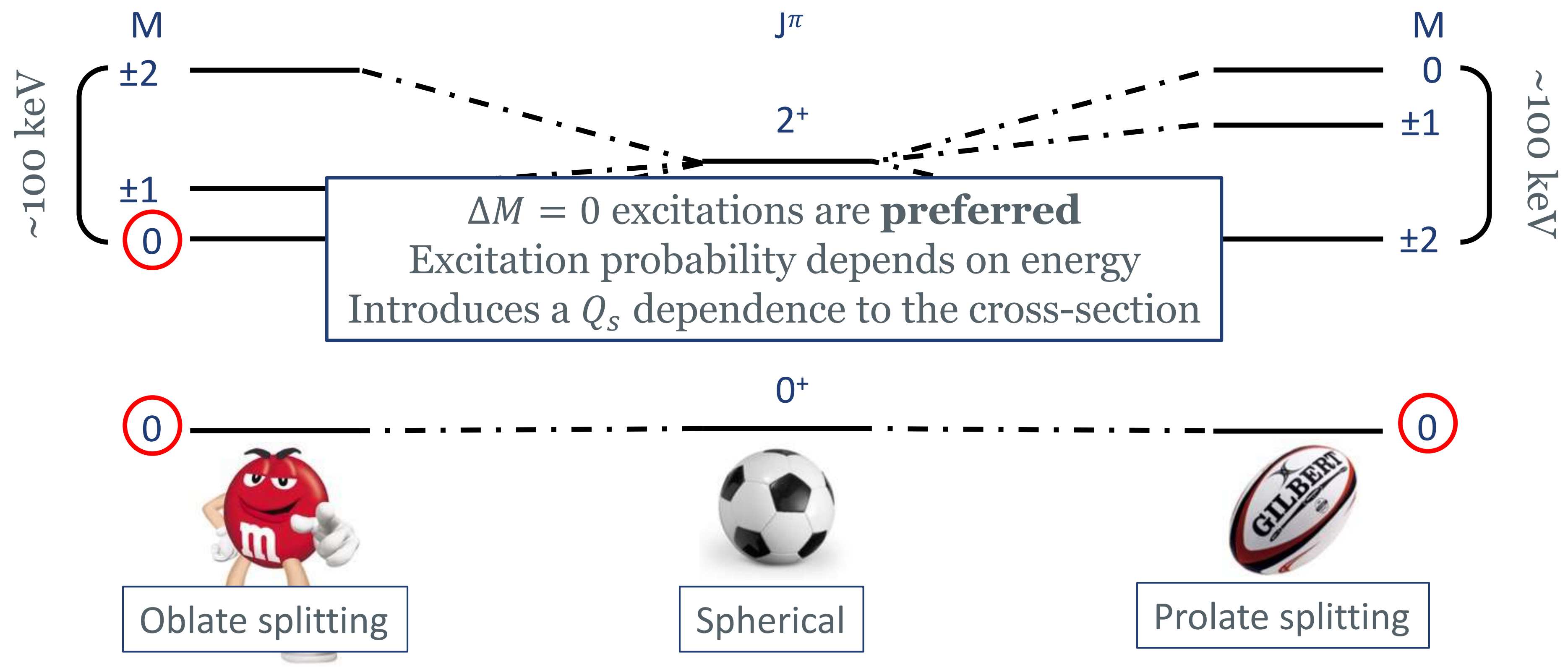


$\Delta M = 0$ excitations are **preferred**
Excitation probability depends on energy
Introduces a Q_s dependence to the cross-section

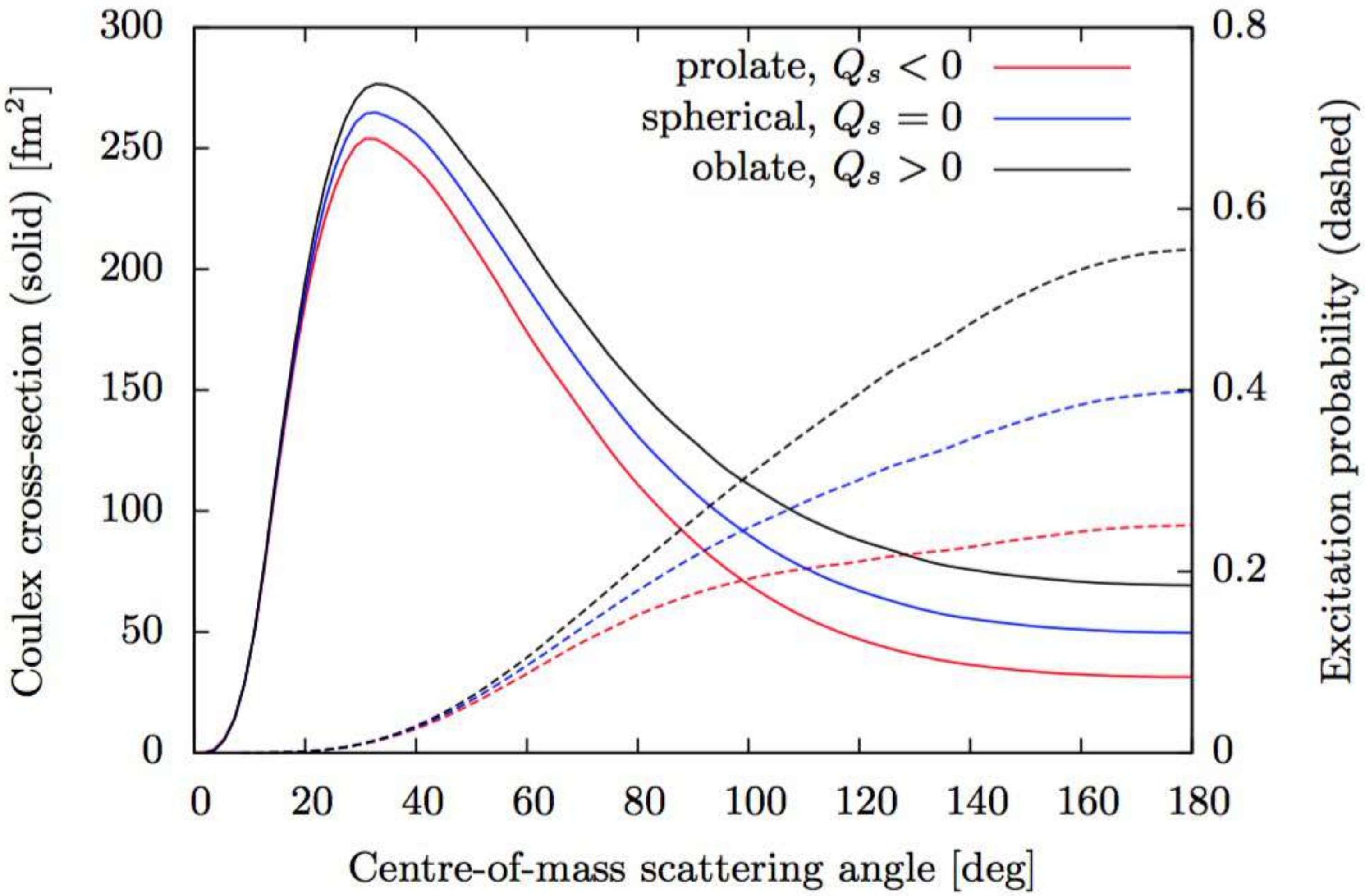
The Method: Coulomb excitation

Since angle and impact parameter are related, this introduces an additional angular dependence to the cross section

Also influences the angle-integrated cross-section

Measure the distribution and/or the integrated cross-section and access the quadrupole moment

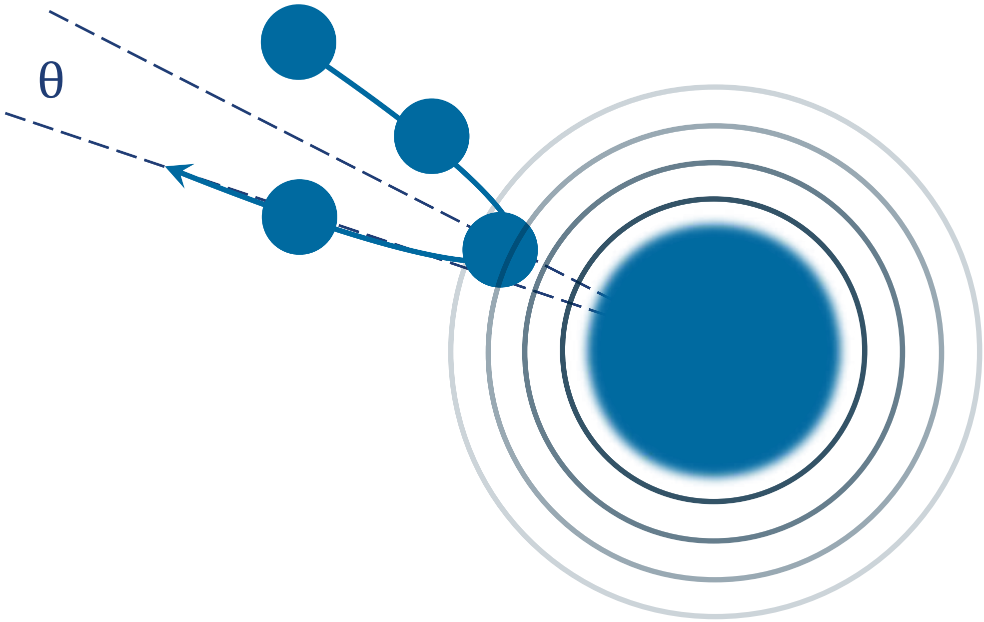
M. Zielinska et al. Eur. J. Phys. A **52** 99 (2016)



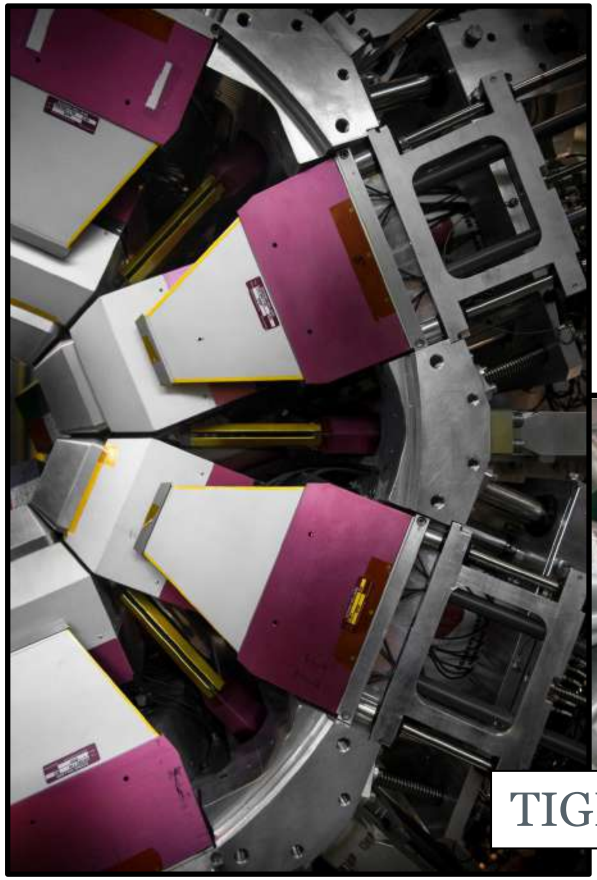
The Method: Coulomb excitation

$$\frac{da_k}{d\omega} = -i \sum_{\lambda\mu n} Q_{\lambda\mu}(\epsilon,\omega)\zeta_{kn}^{\lambda\mu} \langle I_k|M(\lambda)|I_n\rangle e^{(i\xi_{kn}(\epsilon \sinh \omega+\omega))} a_n(\omega)$$

a = (sub)state amplitude
μ = magnetic substate
k = (sub)state being populated
n = (sub)state connected to k
λ = multipole
$\langle I_k|M(\lambda)|I_n\rangle$ = electromagnetic matrix element connecting k and n
$Q_{\lambda\mu}(\epsilon,\omega)$ = collision function
$\zeta_{kn}^{\lambda\mu}$ = coupling parameter
ξ_{kn} = adiabaticity parameter



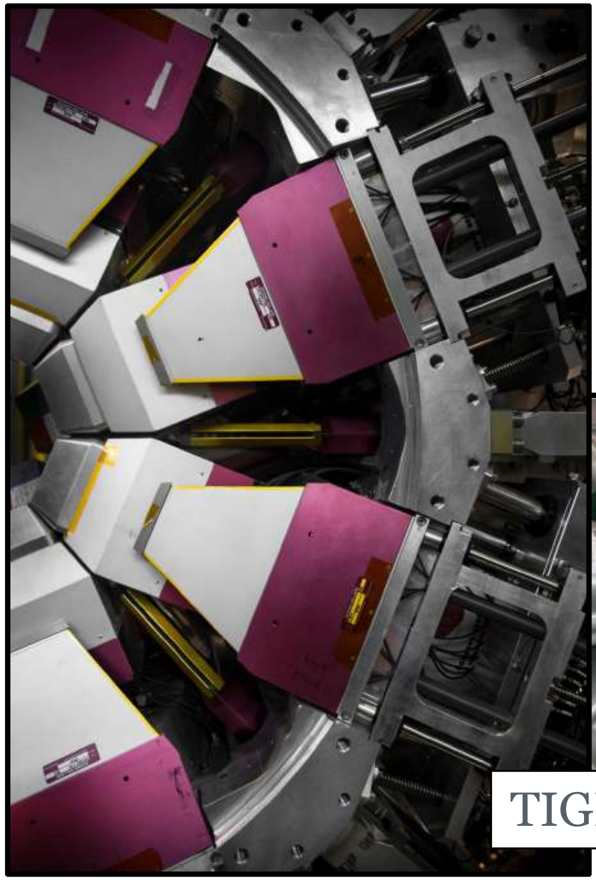
Results



TIGRESS + BAMBINO

GRETINA + CHICO2

Results



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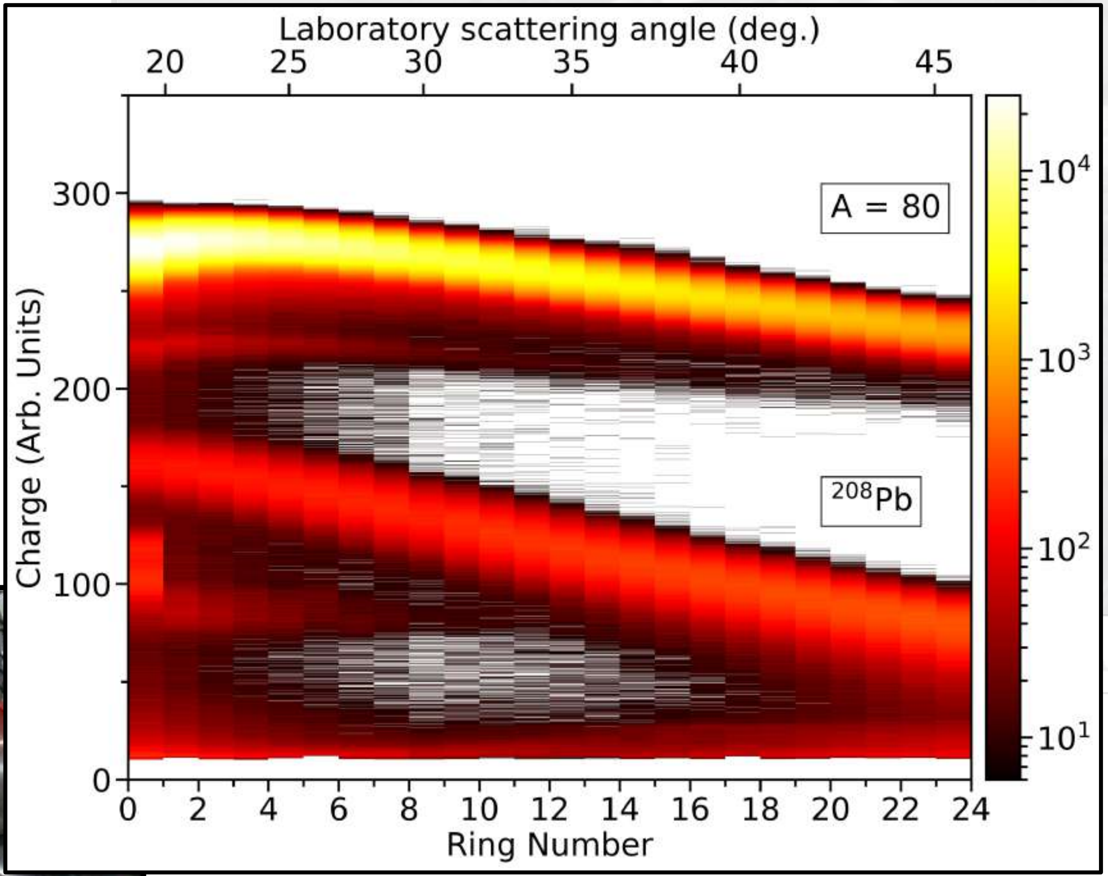
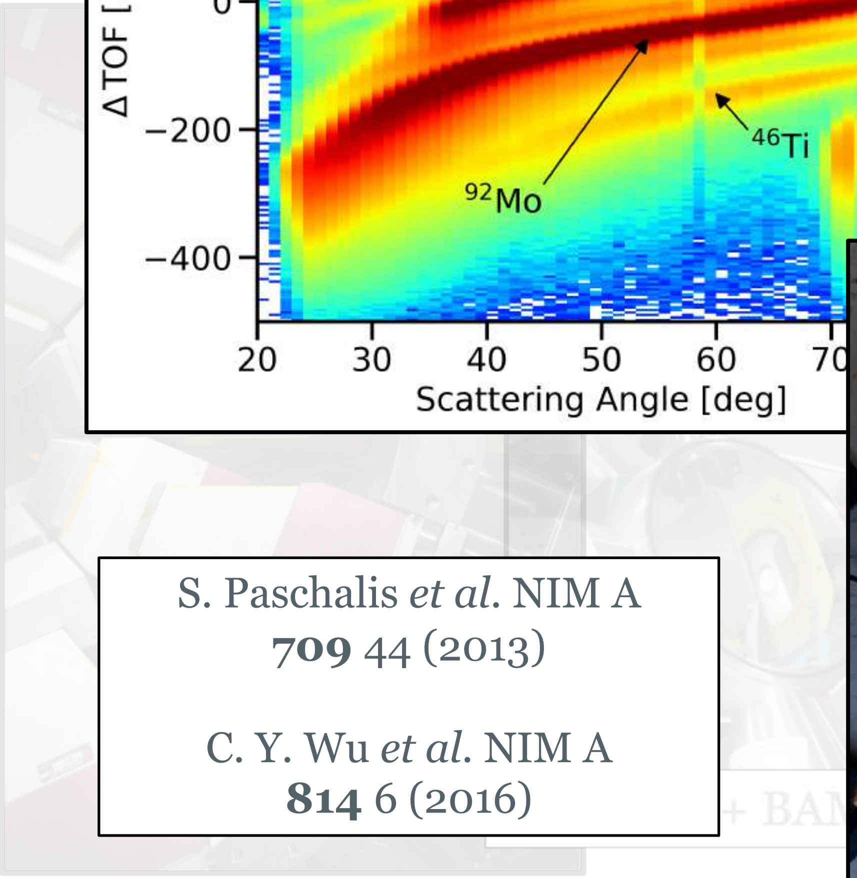
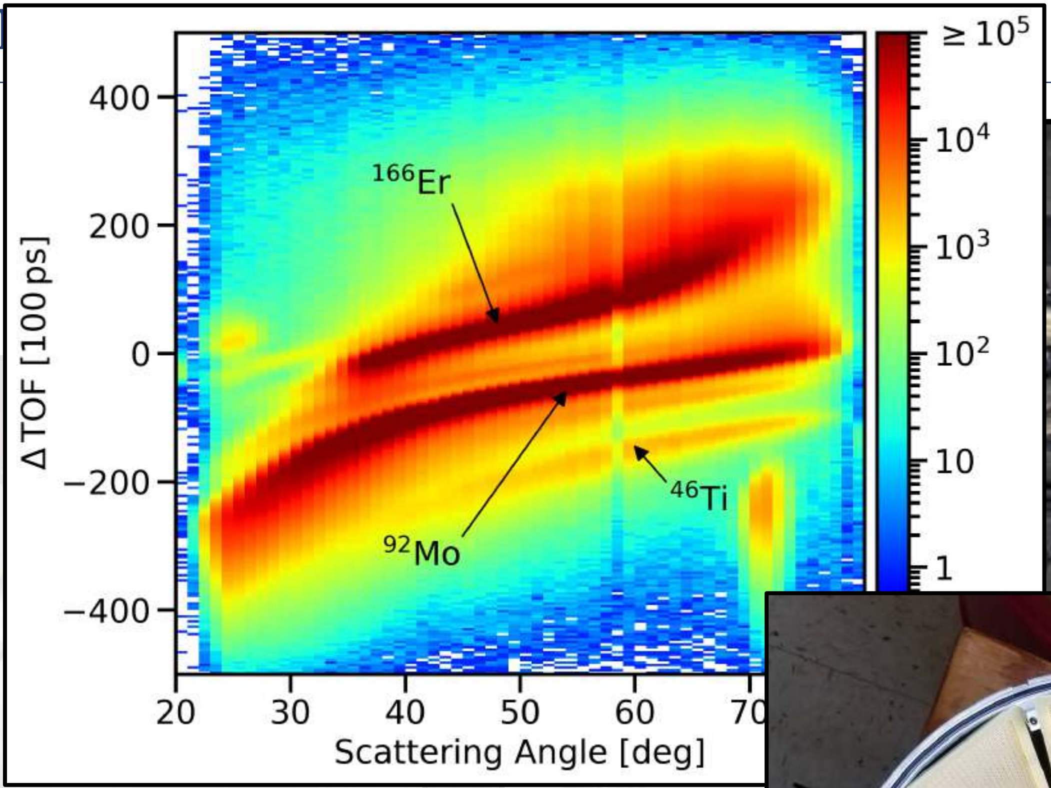
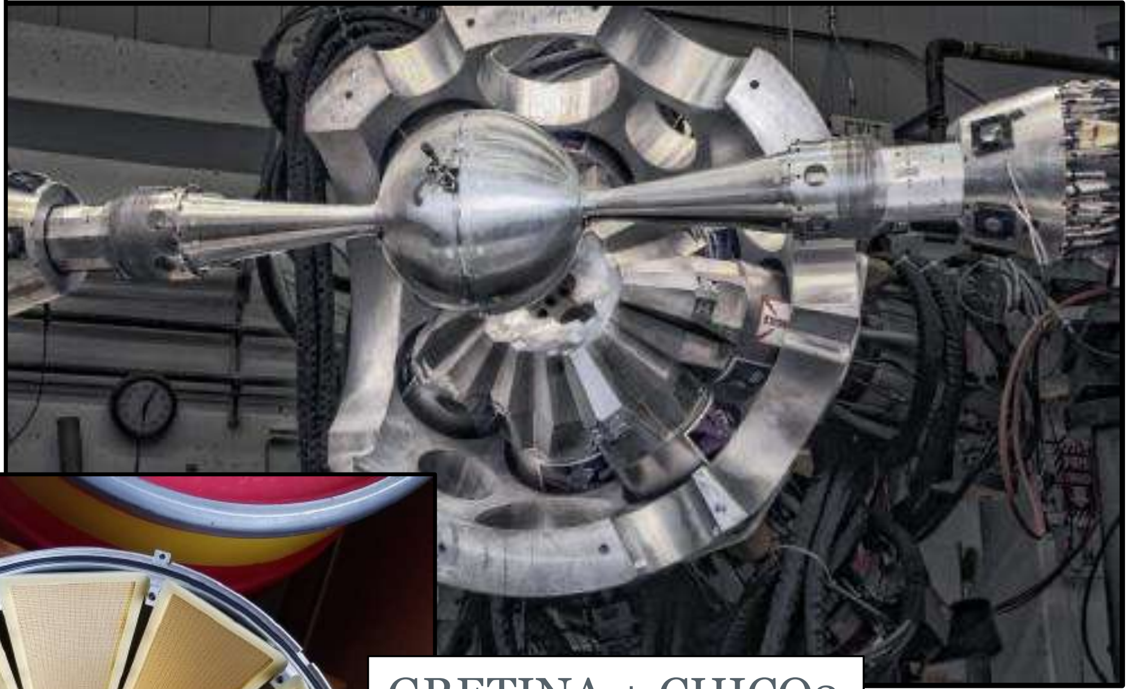


G. Hackman & C. E. Svensson, Hyperfine Interactions **225** 241 (2014)

Resul







GRETINA + CHICO2

S. Paschalis *et al.* NIM A **709** 44 (2013)

C. Y. Wu *et al.* NIM A **814** 6 (2016)

+ BAM

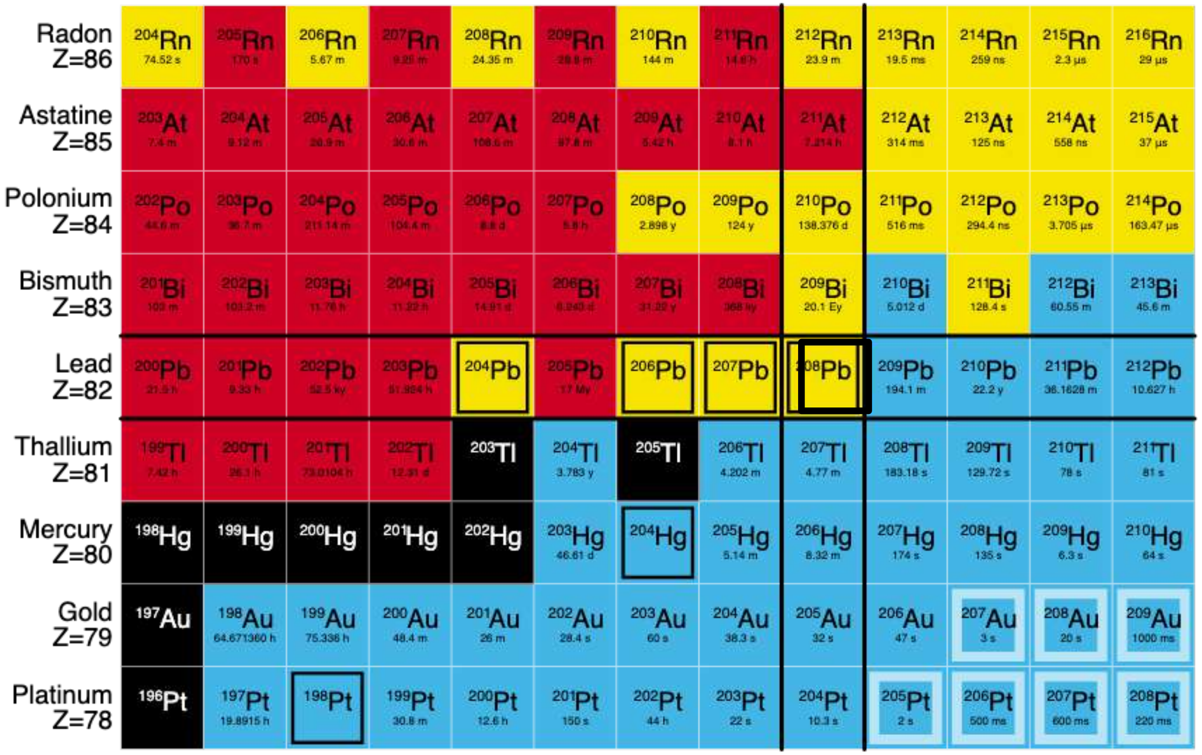
Coulomb excitation of ^{208}Pb

A quintessential doubly-magic system

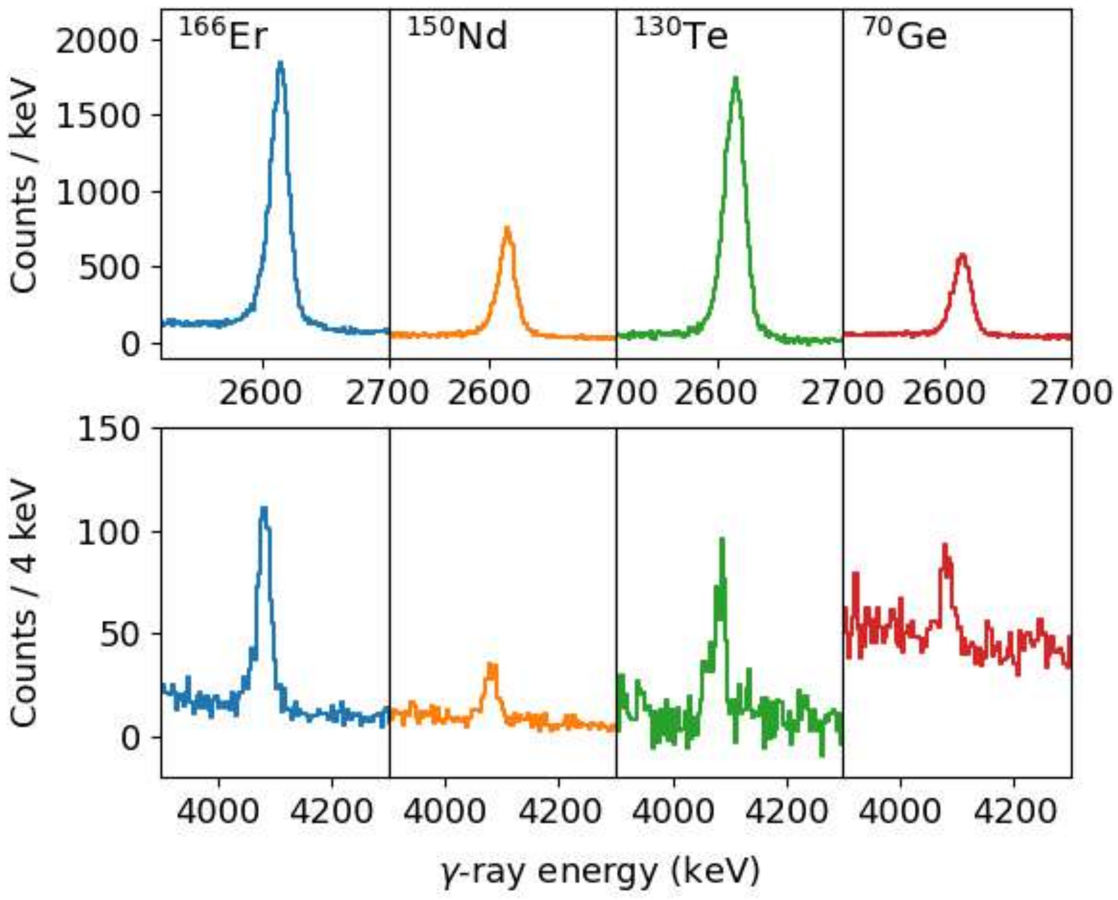
Spherical* ground state
Poves *et al.* PRC **101** 054307 (2020)

First-excited 3^- state, an octupole vibration
D. Goutte *et al.* PRL **45** 1618 (1980)

A key benchmark for models and our understanding of EoS through neutron-skin
B. Hu *et al.* Nature Physics **18** 1196 (2022)
D. Adhikari *et al.* PRL **126** 172502 (2021)



Coulomb excitation of ^{208}Pb



Lead-208 targets often used in Coulomb excitation – clean spectra!

Combine data from four separate Coulomb-excitation measurements: ^{166}Er, ^{150}Nd, ^{130}Te and ^{70}Ge

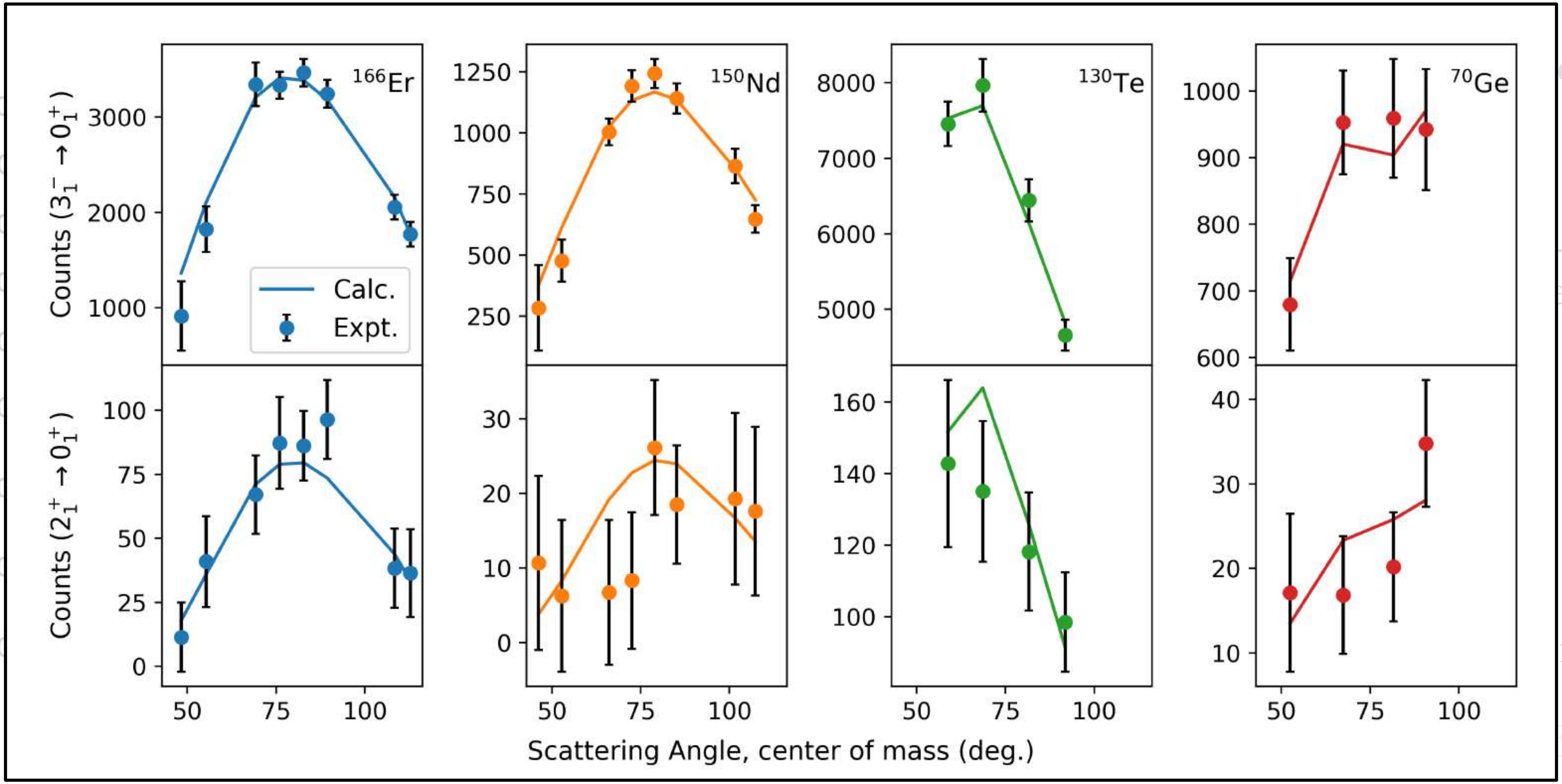
See $3^-_1 \rightarrow 0^+_1$ and $2^+_1 \rightarrow 0^+_1$ transitions

All data taken with CHICO2 and GRETINA in 2022

Data analysed and matrix elements simultaneously minimised using GOSIA
https://github.com/jhenderson88/GOSIAFitter

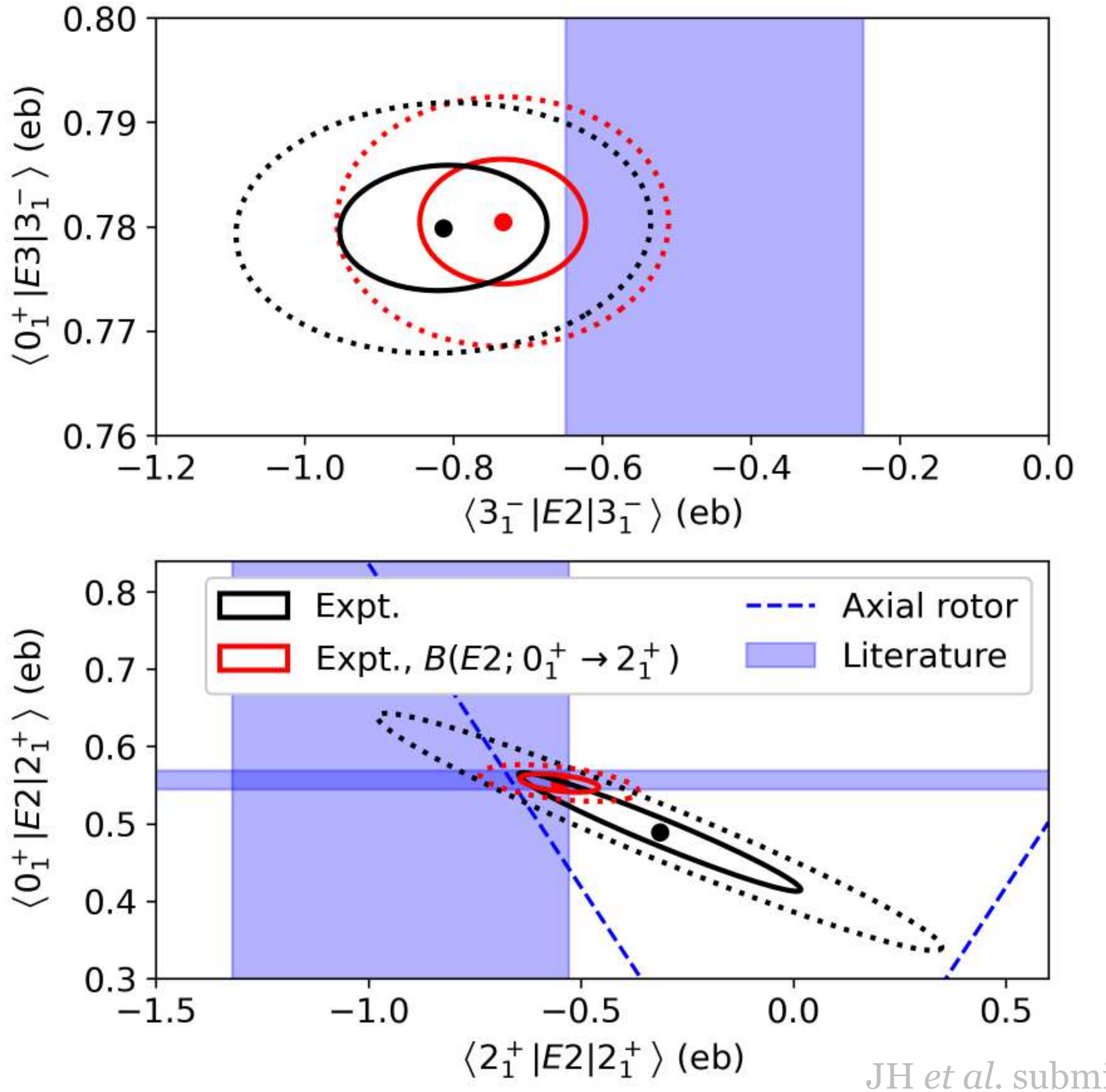
JH *et al.* submitted for publication

Coulomb excitation of ^{208}Pb



JH *et al.* submitted for publication

Coulomb excitation of ^{208}Pb



Extract $\langle 0_1^+|E2|2_1^+\rangle$, $\langle 0_1^+|E3|3_1^-\rangle$, $\langle 2_1^+|E2|2_1^+\rangle$ and $\langle 3_1^-|E2|3_1^-\rangle$ matrix elements and their *correlations*

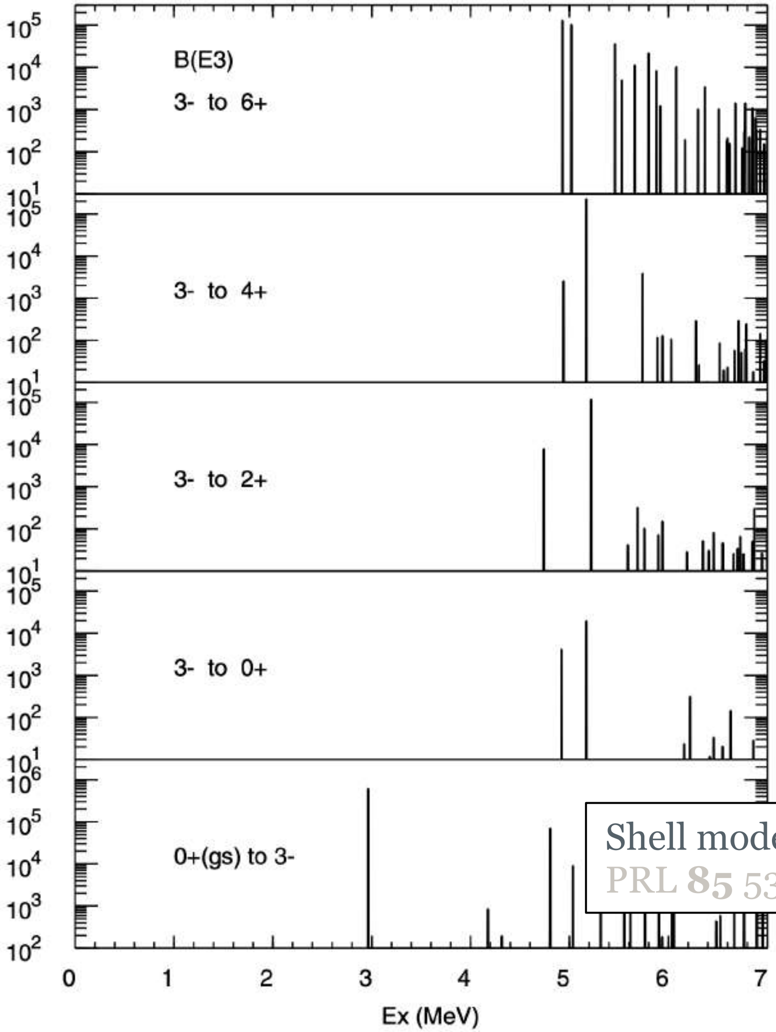
Constrain the data by including literature $\langle 0_1^+|E2|2_1^+\rangle$ [$B(E2;0_1^+\rightarrow 2_1^+)$] and $\langle 0_1^+|E3|3_1^-\rangle$ [$B(E3;0_1^+\rightarrow 3_1^-)$]

Able to tightly constrain both $\langle 2_1^+|E2|2_1^+\rangle$ [$Q_s(2_1^+)$] and $\langle 3_1^-|E2|3_1^-\rangle$ [$Q_s(3_1^-)$]

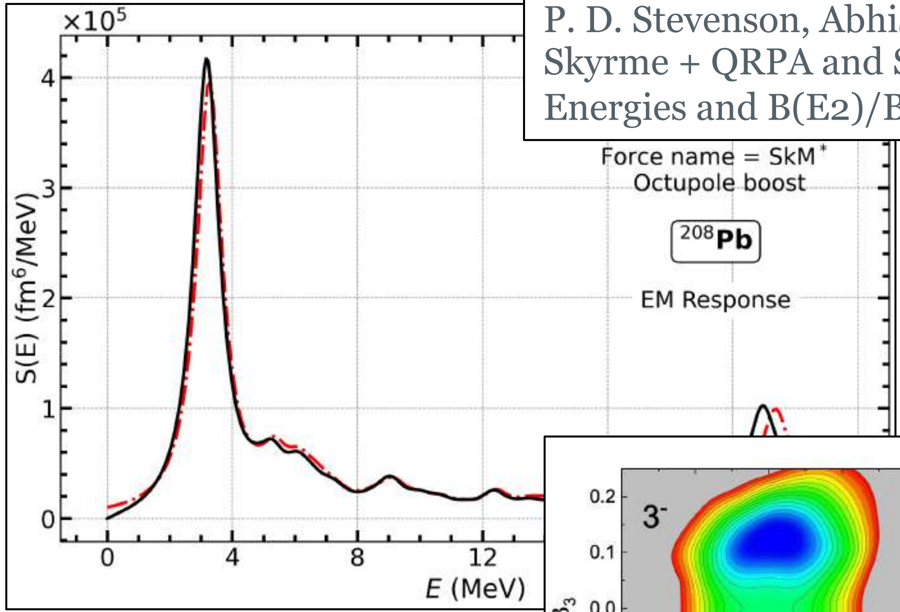
Consistent with Vermeer *et al.* Australian Journal of Physics **37** 123 (1984) but improved uncertainty

JH *et al.* submitted for publication

Coulomb excitation of ^{208}Pb

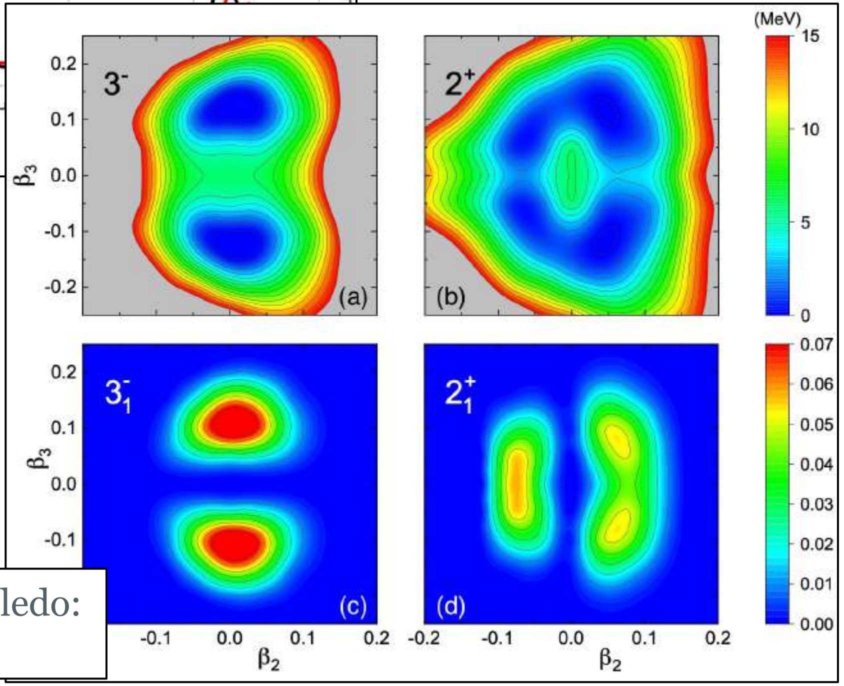


Shell model, B. A. Brown:
PRL **85** 5300 (2020)



P. D. Stevenson, Abhishek, E. Yuksel:
Skyrme + QRPA and Skyrme + TDHF
Energies and B(E2)/B(E3) **only**

Model comparison



T. R. Rodriguez and L. Robledo:
SCCM

JH *et al.* sul

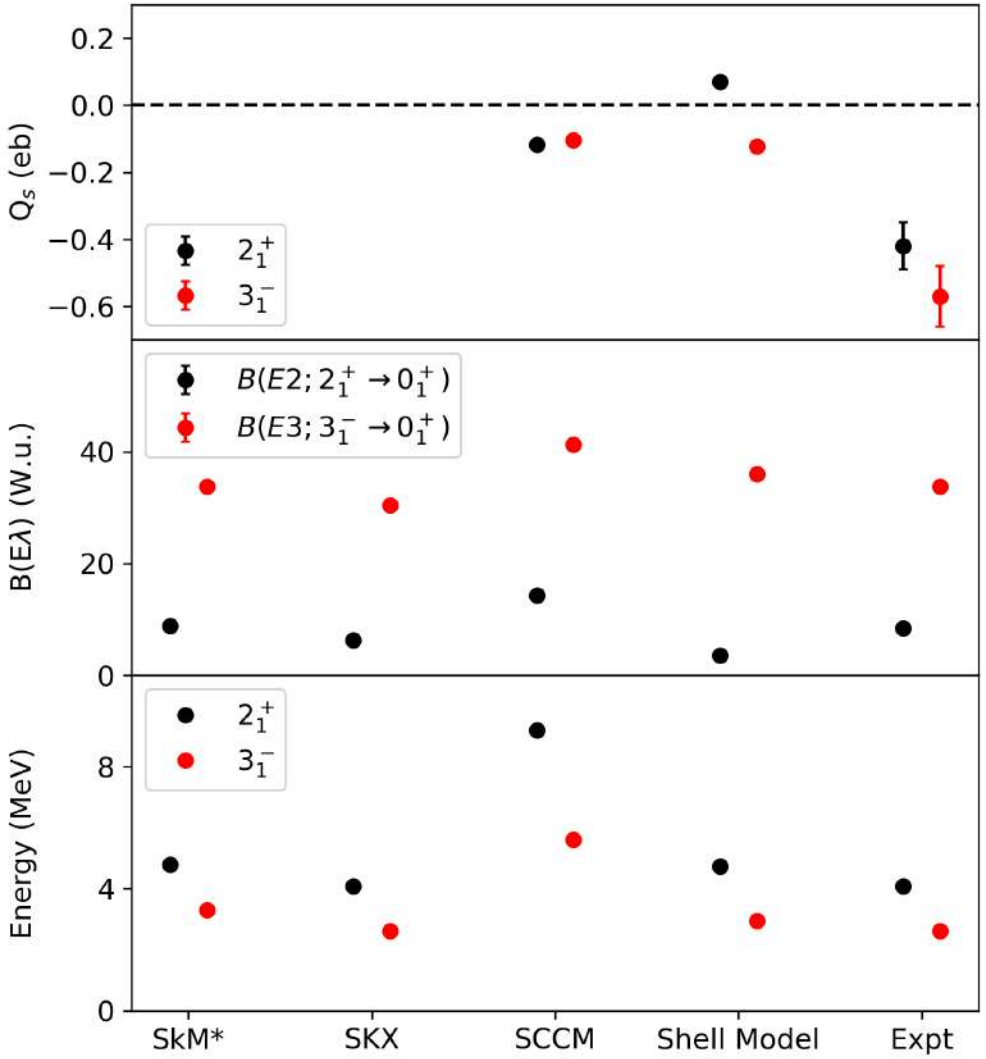
Coulomb excitation of ^{208}Pb

Skyrme models best reproduce B(EL) and energies but **no** Q_s values and **no** indication of preference for prolate deformation

SCCM calculations *over*predict excitation energies and B(EL) values but **do** reproduce signs and similarity of $Q_s(2^+)$ and $Q_s(3^-)$

SM fails to reproduce the signs and magnitudes of the Q_s values but does reproduce energies and B(E3)

No model able to reproduce the electromagnetic observables



JH *et al.* submitted for publication

Coulomb excitation of ^{208}Pb

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SCCM calculations *overp*...
and B(EL) values but **do** ...
similarity of $Q_s(2^+)$ and Q...

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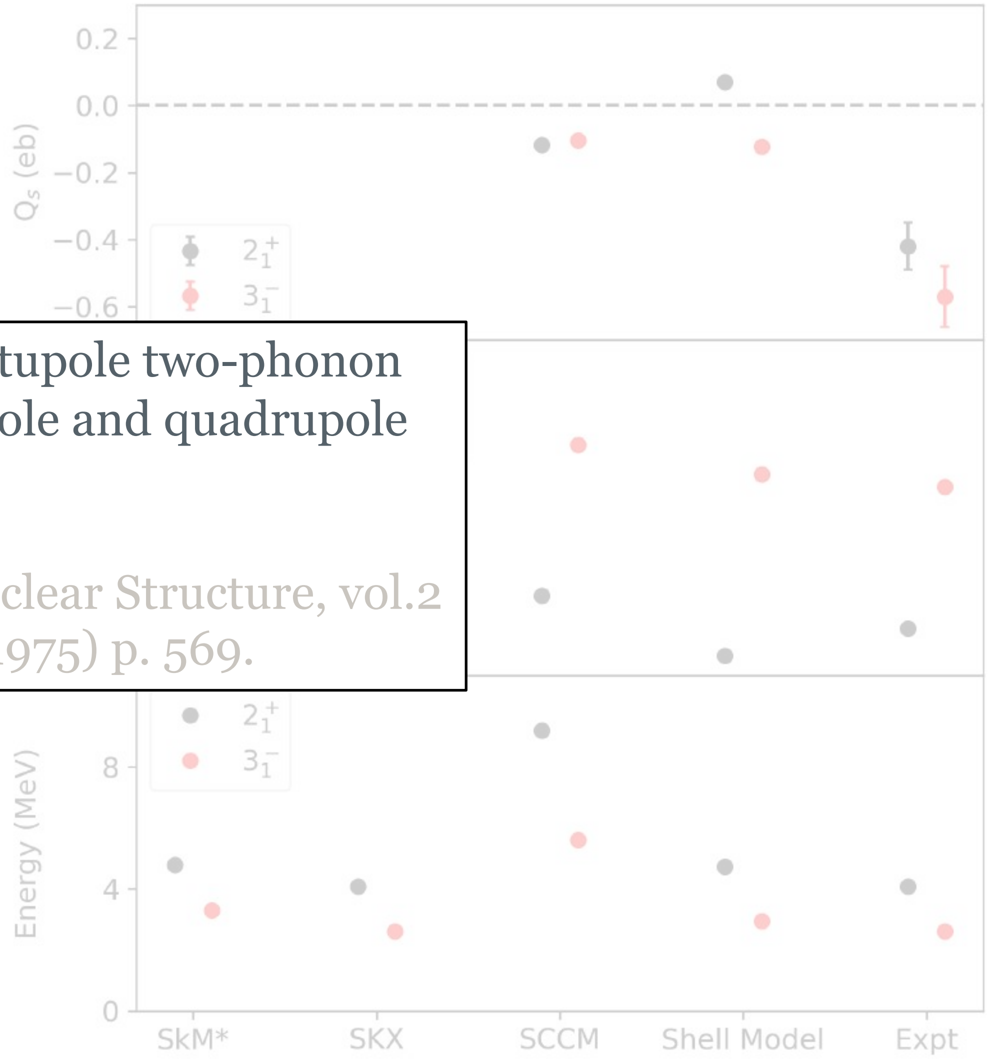
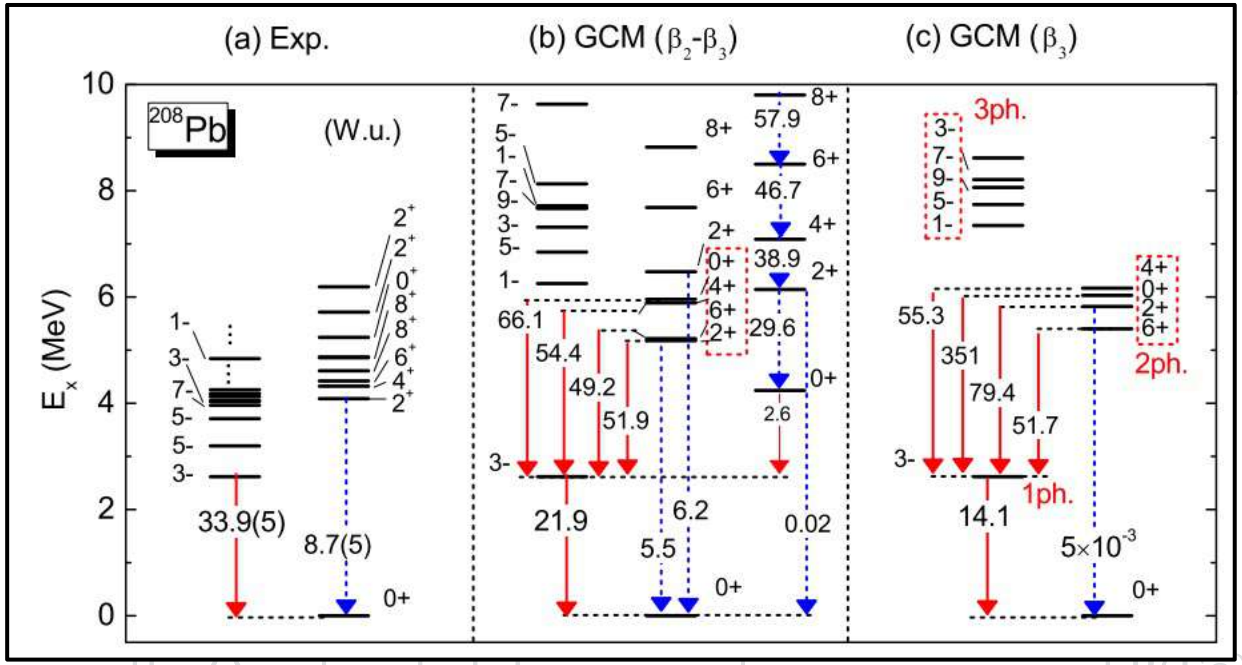


Implications for splitting of octupole two-phonon states due to coupling of octupole and quadrupole modes

A. Bohr and B. R. Mottelson, Nuclear Structure, vol.2 (Benjamin, New York, 1975) p. 569.

JH *et al.* submitted for publication

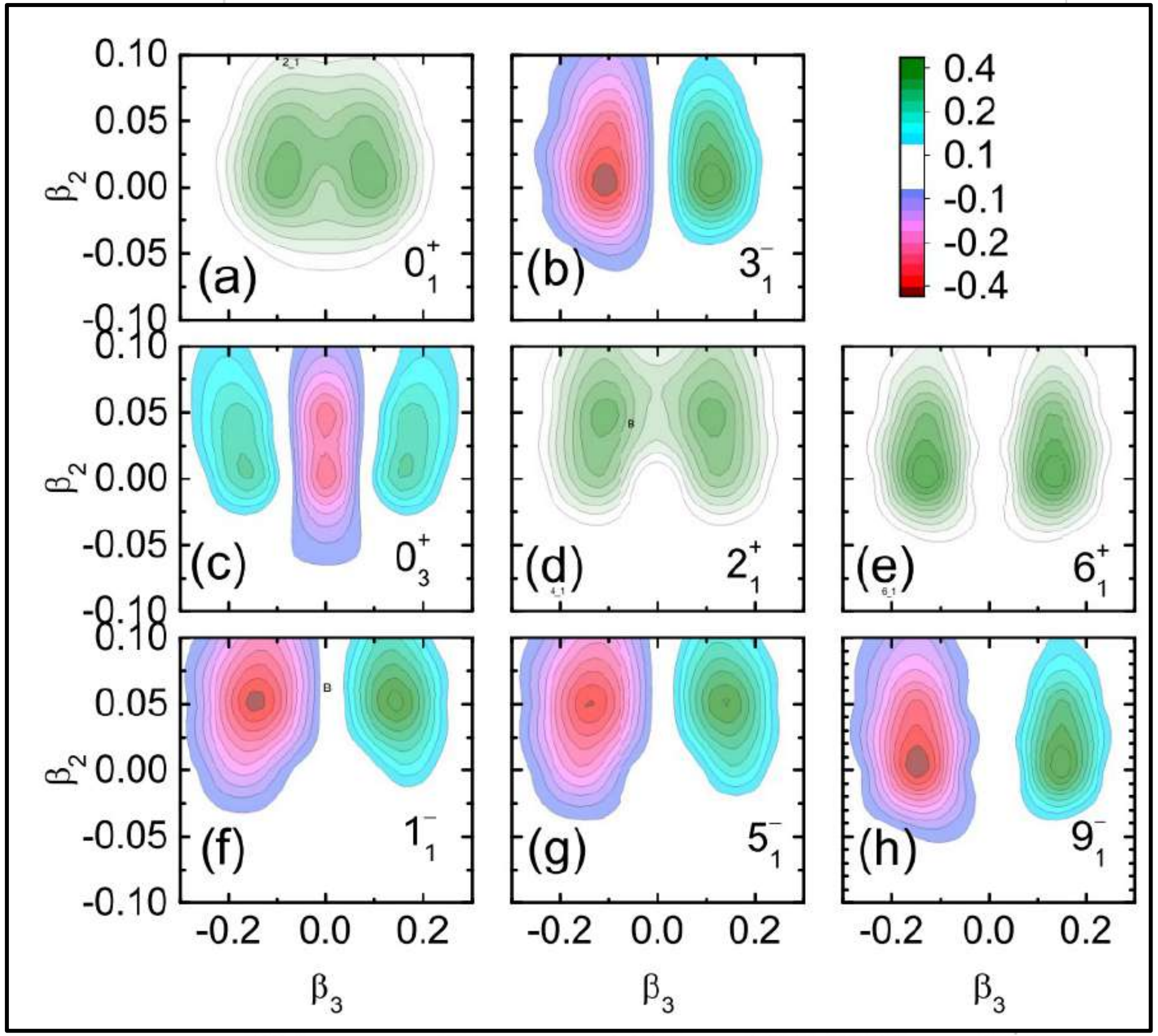
Coulomb excitation of ^{208}Pb



the Q_s values but does reproduce energies and B(E3)

Yao and Hagino [PRC **94** 011303(R) (2016)]

Investigated quadrupole-octupole mixing in GCM



JH *et al.* submitted for publication

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A. Nannini,[2] C. O'Shea,[1] S. Pascu,[1,25] C. Paxman,[1] A. Perkoff,[26] E. E. Peters,[20] Zs. Podolyák,[1] A. Radich,[3]
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J. R. Vanhoy,[19] G. L. Wilson,[4,28,**] K. Wrzosek-Lipska,[18] S. Yates,[5,6] S. W. Yates,[20] and I. Zanon[29]

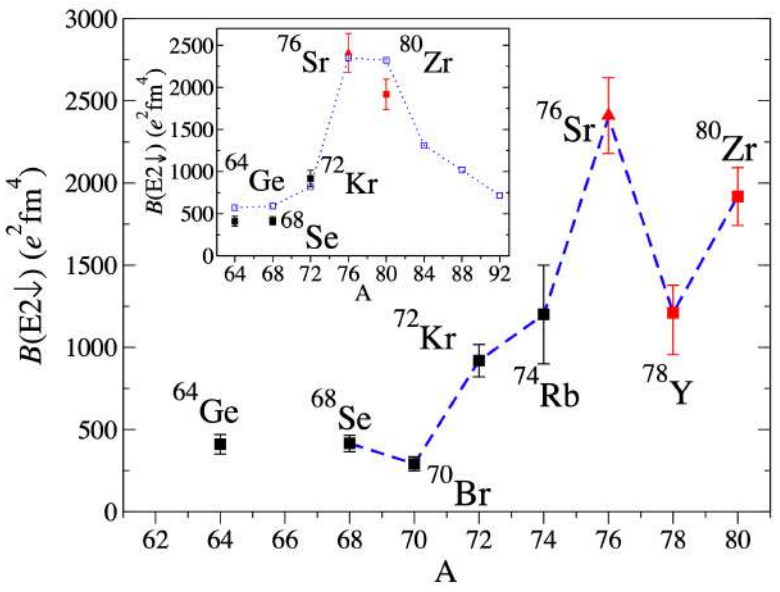
Strontium-80 Coulomb excitation

Region around N=Z=40 (^{80}Zr) associated with strong deformation

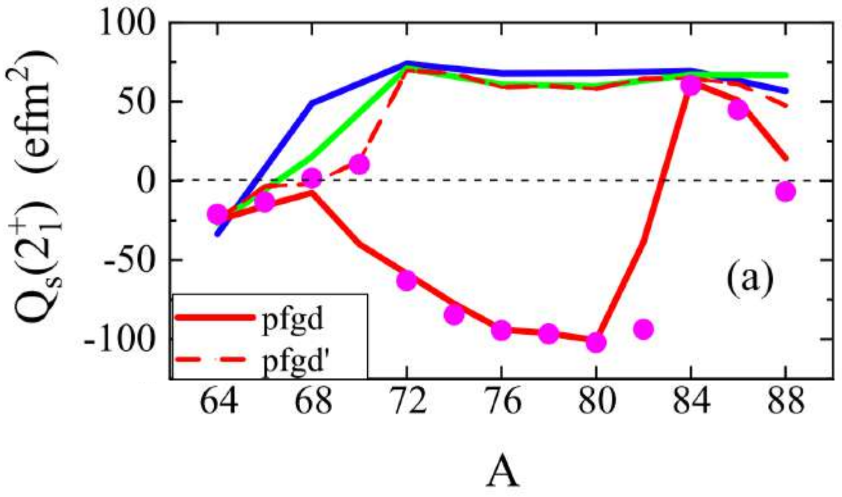
Driven by quasi-SU3 symmetry - strong $\langle Q \cdot Q \rangle$ interaction between $g_{9/2}$ and $d_{5/2}$ orbitals

Completely erases the influence of the HO shell closure (i.e. ^{90}Zr)

Predictions from PMMU interaction of a region of *prolate* deformation



R. Llewellyn *et al.* PRL **124** 152501 (2020)



K. Kaneko *et al.* PLB **817** 136286 (2021)

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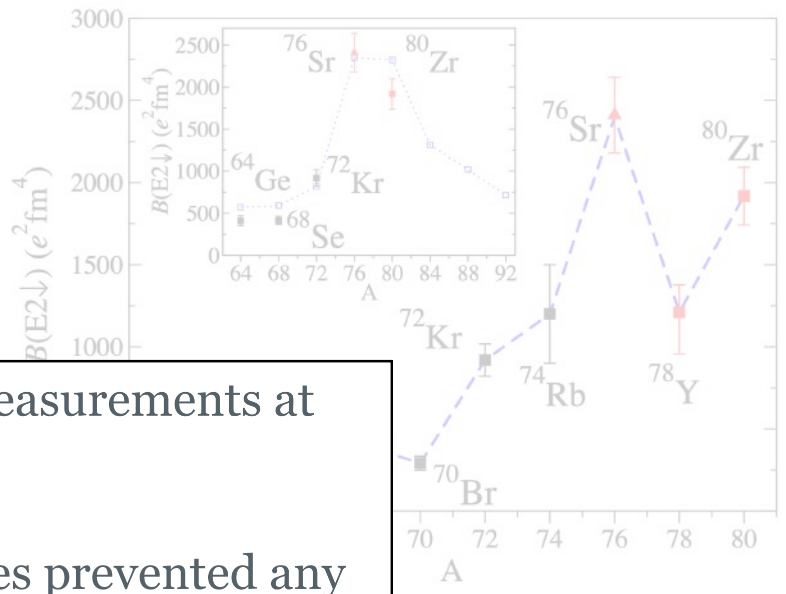
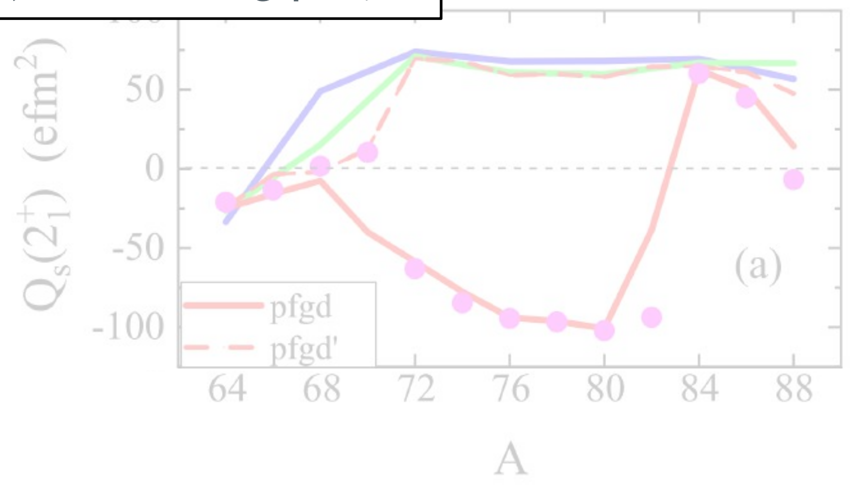
Predictions from PMMU interaction of a region of *prolate* deformation

Motivated Coulomb excitation measurements at TRIUMF

Goals were ^{78,80}Sr - beam difficulties prevented any attempt at ^{78}Sr (JANUS @ ReA6, FRIB PAC~~3~~4 🤞)

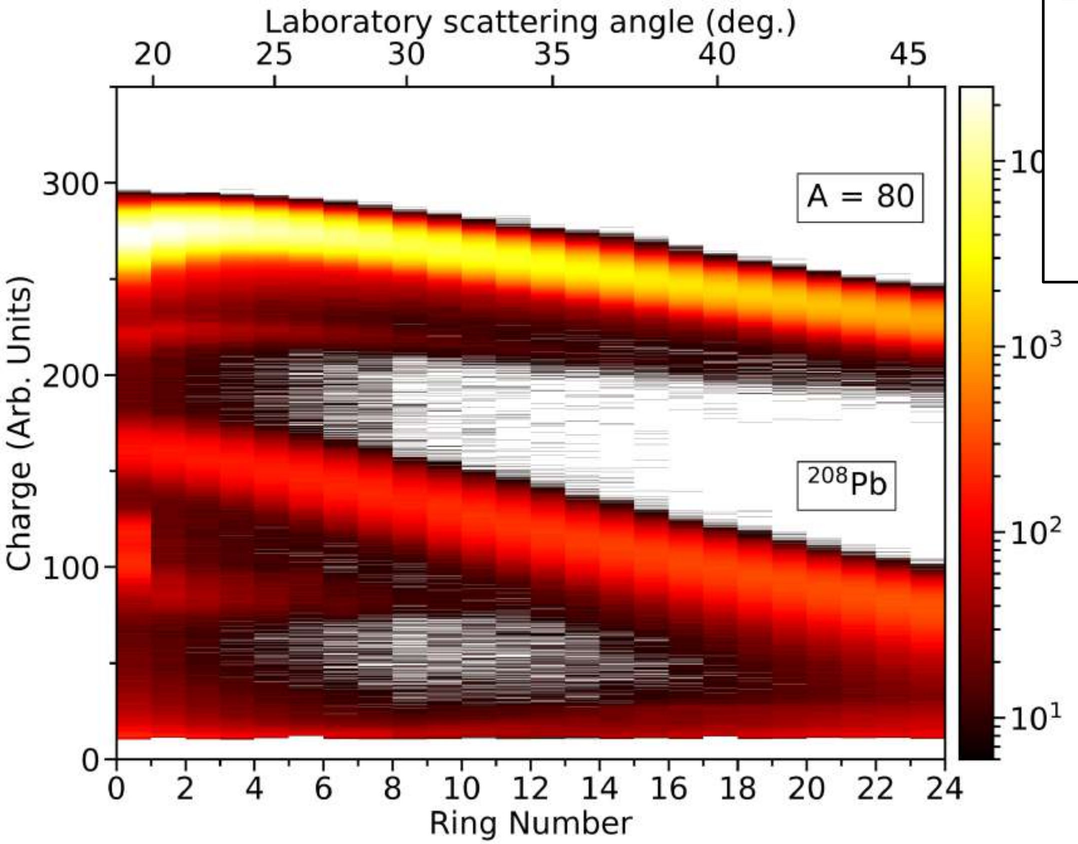


R. Llewellyn *et al.* PRL **124** 152501 (2020)

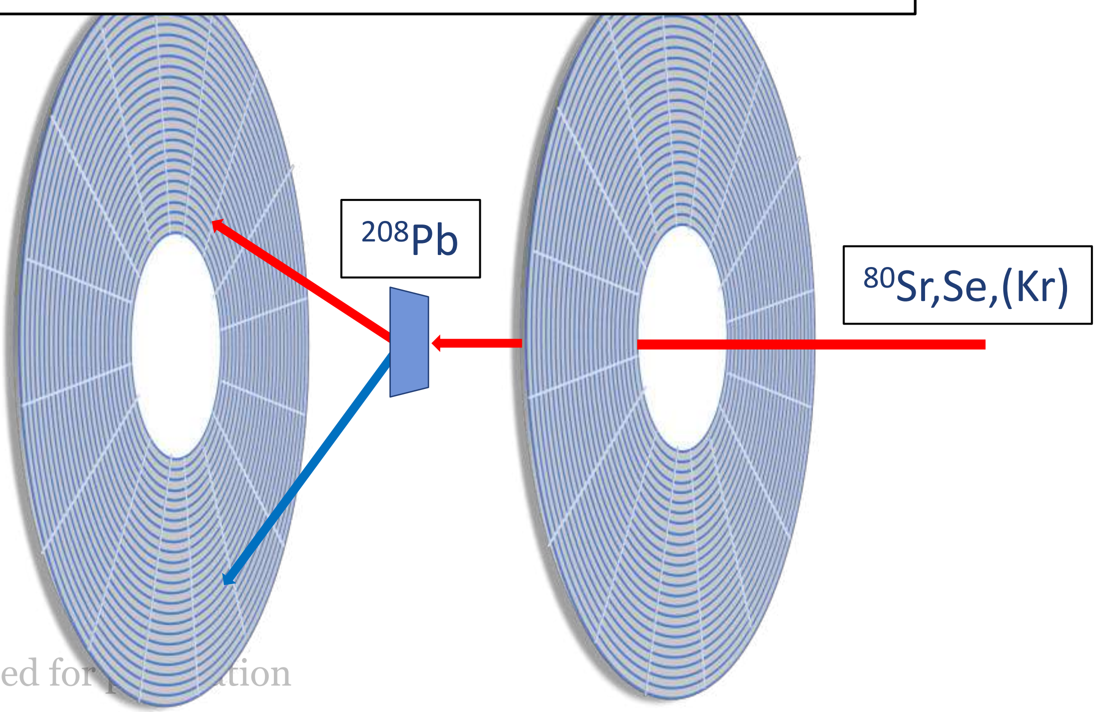


K. Kaneko *et al.* PLB **817** 136286 (2021)

Strontium-80 Coulomb excitation

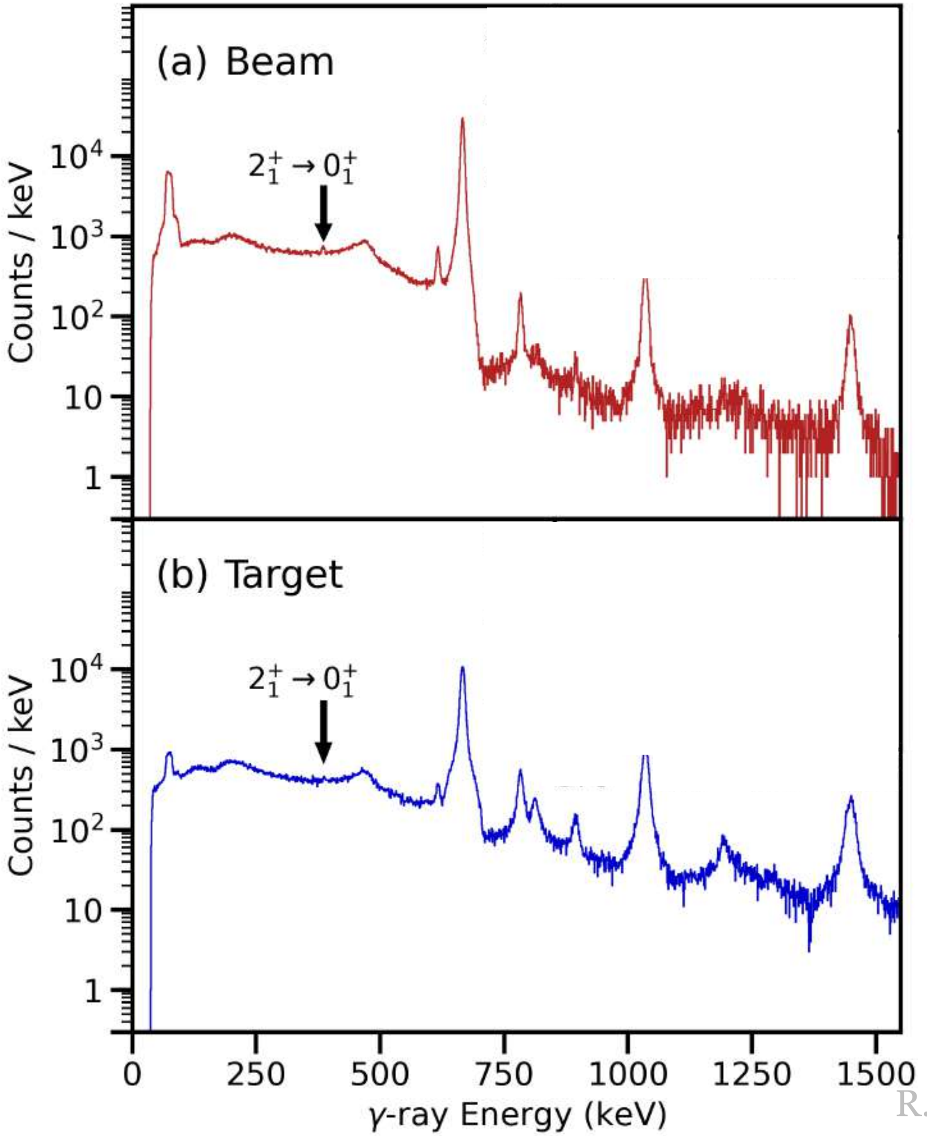


A=80 (Sr, Se, Kr) impinged upon ^{208}Pb target



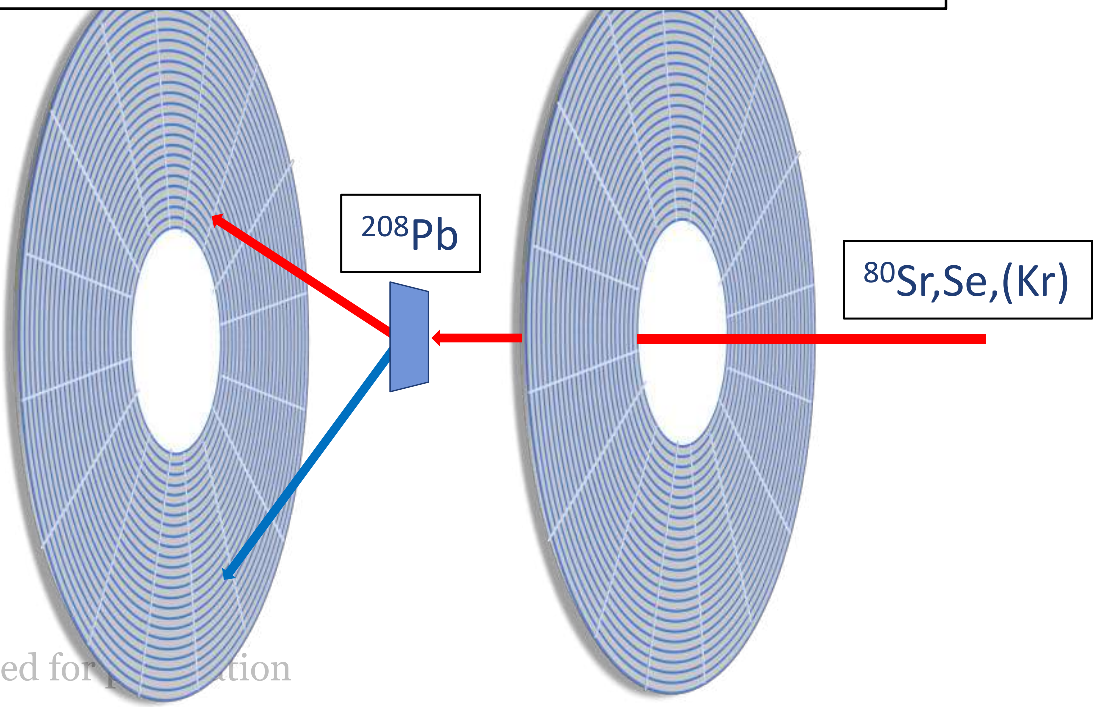
R. Russell *et al.* submitted for publication

Strontium-80 Coulomb excitation



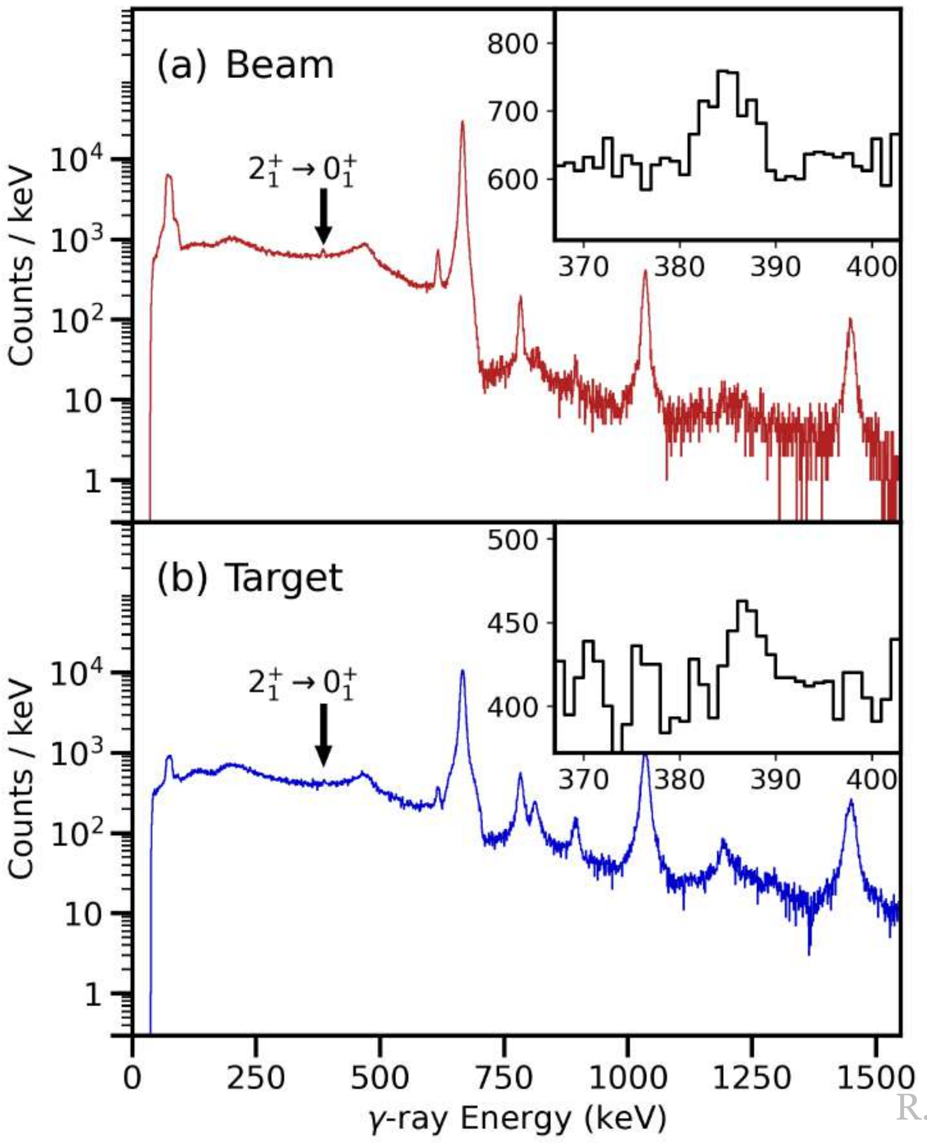
A=80 (Sr, Se, Kr) impinged upon ^{208}Pb target

Spectra dominated by ^{80}Se Coulomb excitation



R. Russell *et al.* submitted for publication

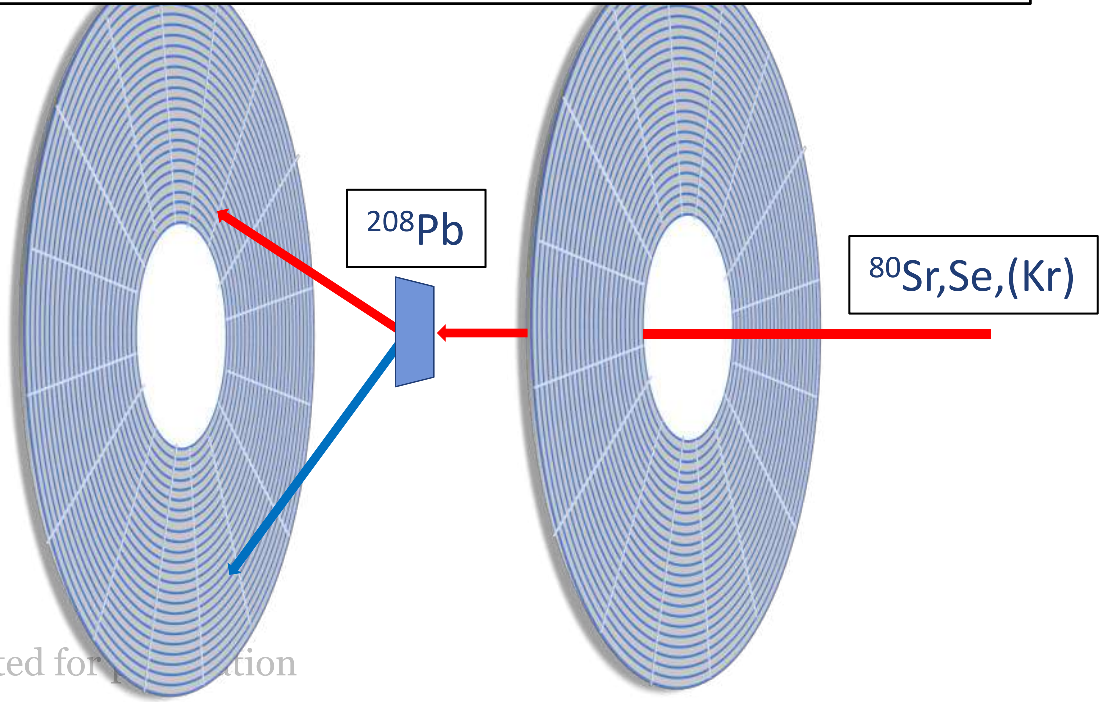
Strontium-80 Coulomb excitation



A=80 (Sr, Se, Kr) impinged upon ^{208}Pb target

Spectra dominated by ^{80}Se Coulomb excitation

^{80}Sr $2_1^+ \rightarrow 0_1^+$ visible on ^{80}Se Compton background



R. Russell *et al.* submitted for p ation

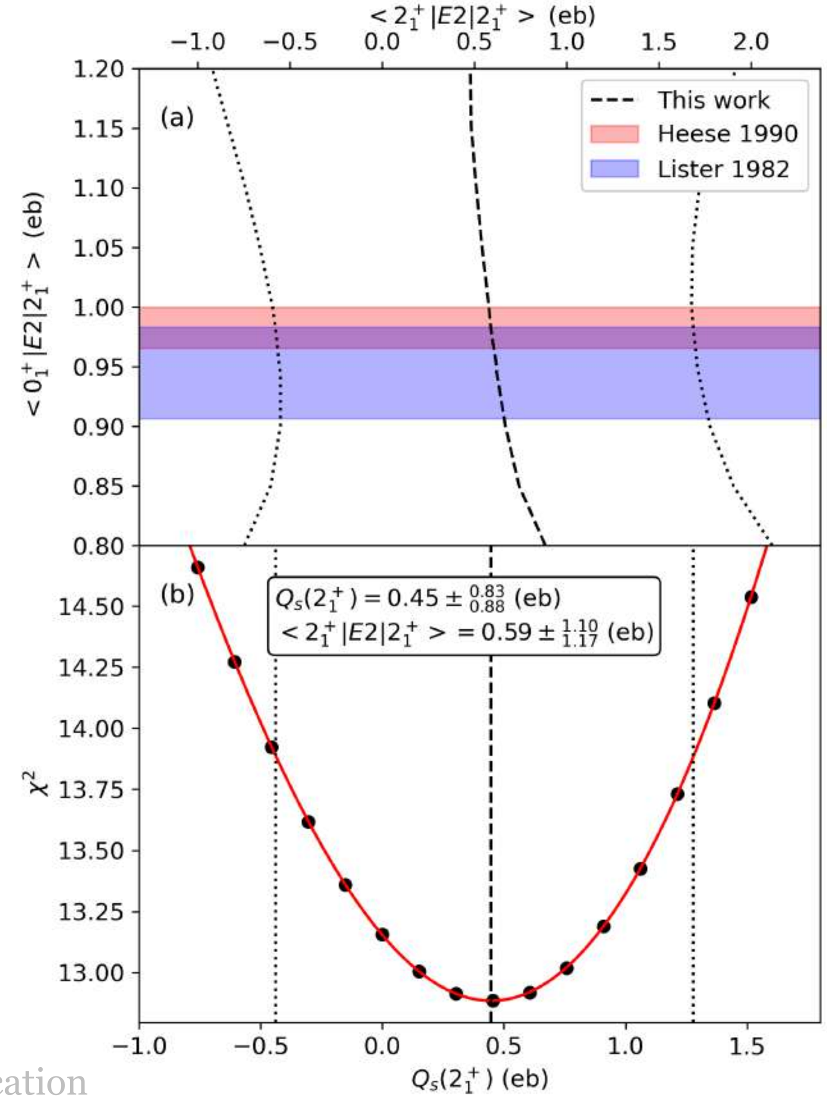
Strontium-80 Coulomb excitation

Strontium-80 quadrupole moment extracted from angular distribution

Verified consistency with both literature 2_1^+ state lifetimes

Limited correlation between $\langle 0_1^+|E2|2_1^+\rangle$ and $\langle 2_1^+|E2|2_1^+\rangle$

Large uncertainty dominated by background from ^{80}Se Coulomb excitation

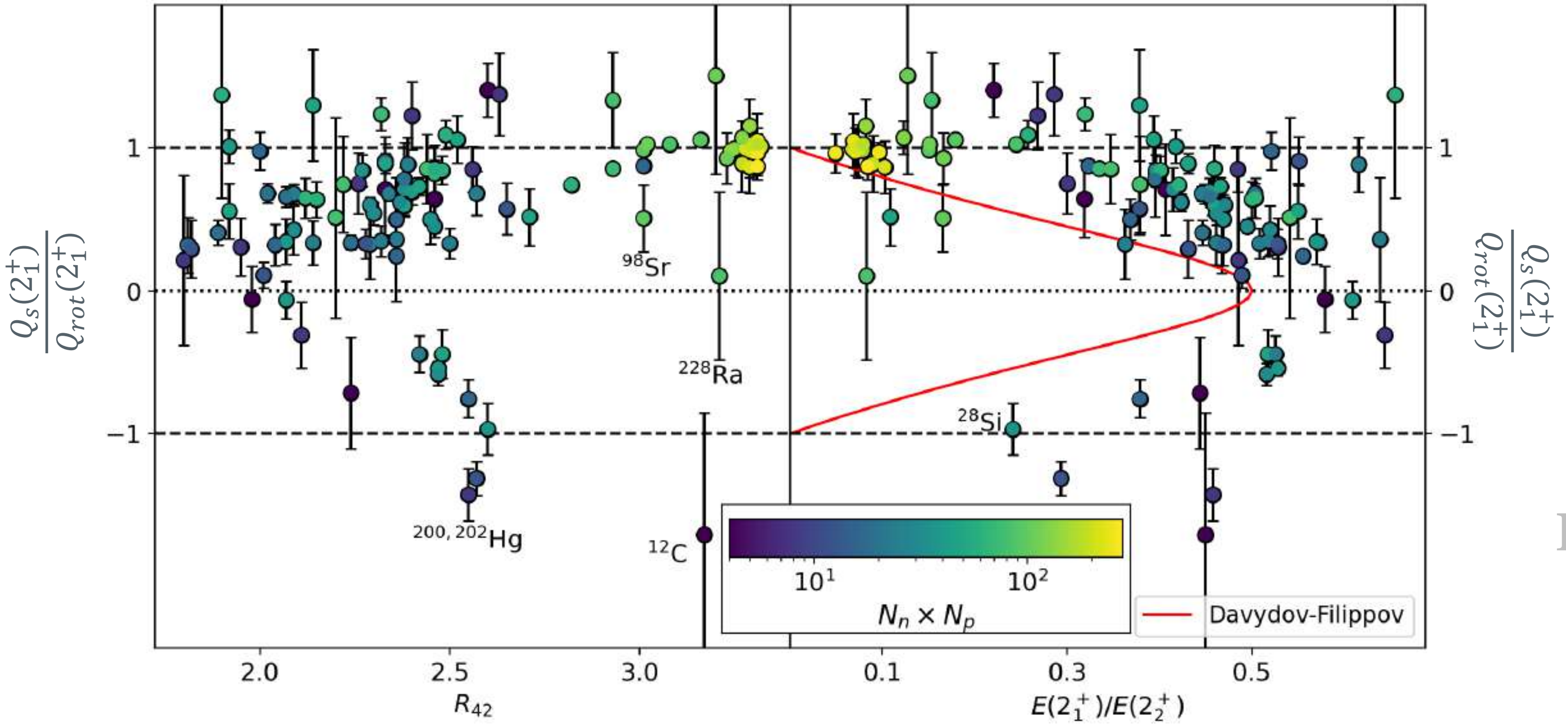


R. Russell *et al.* submitted for publication

Use a simple metric for the form of the nuclear deformation

$$Q_{rot}(2_1^+) - \frac{2}{7}\sqrt{\frac{16\pi}{5}B(E2;0_1^+ \rightarrow 2_1^+)}$$

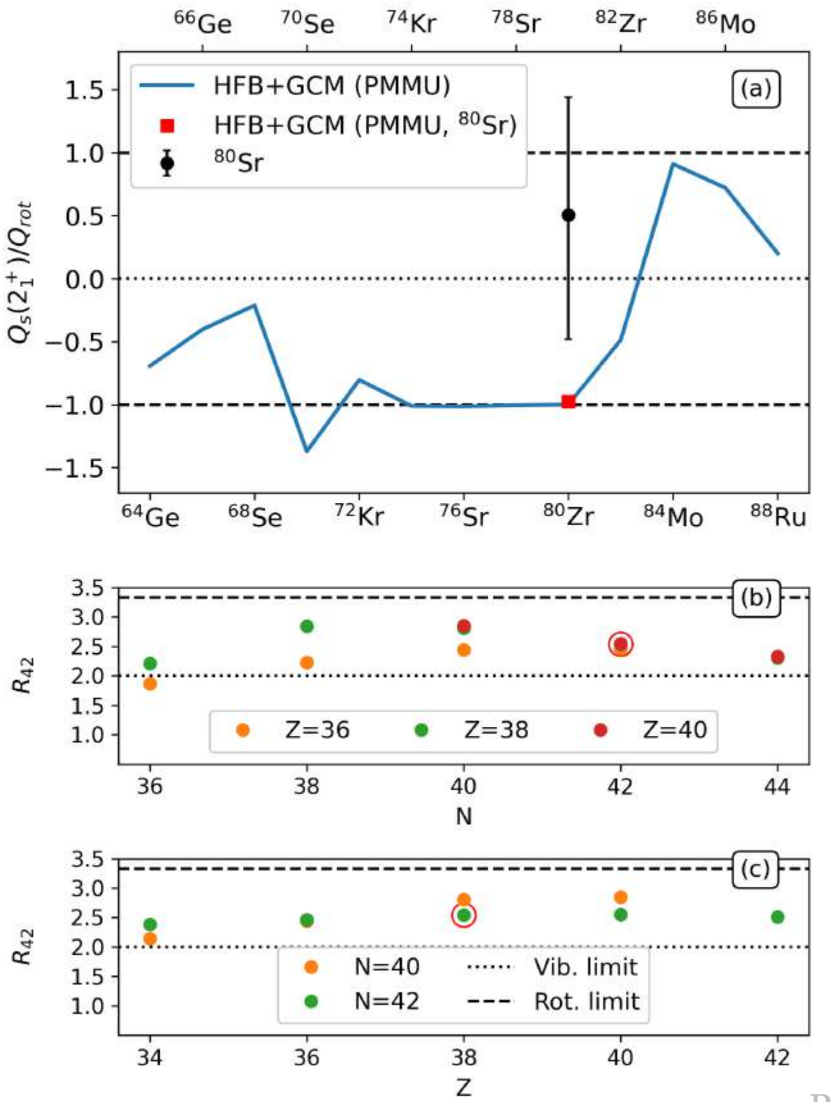
$$\cos(3\gamma) \approx -\frac{Q_s(2_1^+)}{Q_{rot}(2_1^+)} = q_s$$



JH, PRC **102** 054306 (2020)

Rhodes *et al*. PRC **103** L051301 (2021)

Strontium-80 Coulomb excitation



Kaneko *et al.* PLB **817** 136286 (2021)

Comparison with PMMU calculations

Predict near-axial, prolate systems around N=Z=40

$$\frac{Q_s(2_1^+)}{Q_{s,rot}(2_1^+)} \approx -1$$

Even with large uncertainty, experimental $Q_s(2_1^+)$ is **inconsistent** with this prediction

More consistent with *triaxial* or *oblate* deformations

R. Russell *et al.* submitted for publication

Strontium-80 Coulomb excitation

Contrary to PMMU calculation predictions, ^{80}Sr appears to be *triaxial* or *oblate*

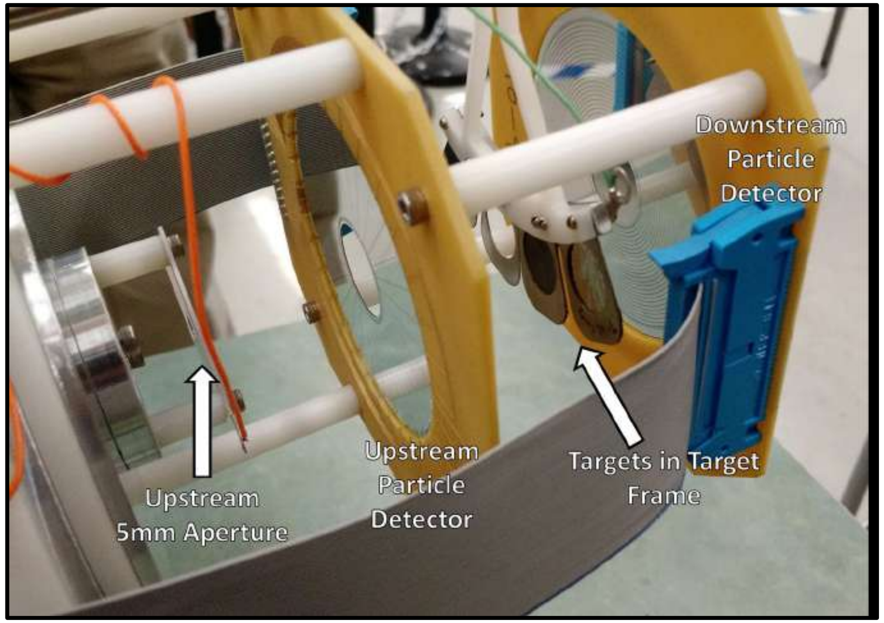
Any island of strong, prolate, axial deformation around N=Z=40 is confined to ^{76,78}Sr and ^{78,80}Zr

Recently presented (as-yet unpublished) SM results imply a different mechanism – more varied shapes

JANUS — A setup for low-energy Coulomb excitation at ReA3 ☆

E. Lunderberg [a,b], J. Belarge [a,1], P.C. Bender [a], B. Bucher [c], D. Cline [d], B. Elman [a,b], A. Gade [a,b], S.N. Liddick [a,e], B. Longfellow [a,b], C. Prokop [a,e], D. Weisshaar [a], C.Y. Wu [c]

Neutron-deficient Sr (should be) accessible at FRIB-ReA6: a priority to perform safe Coulomb excitation

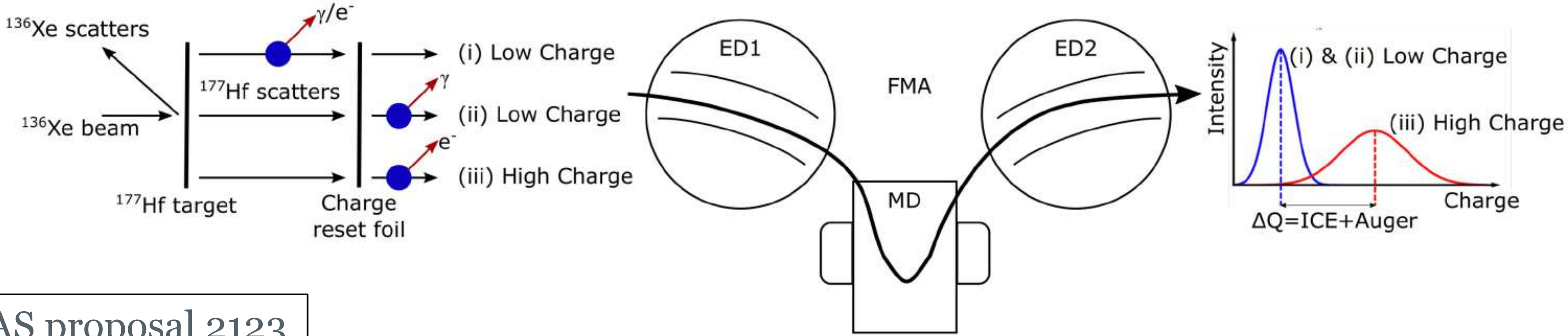


With thanks to:

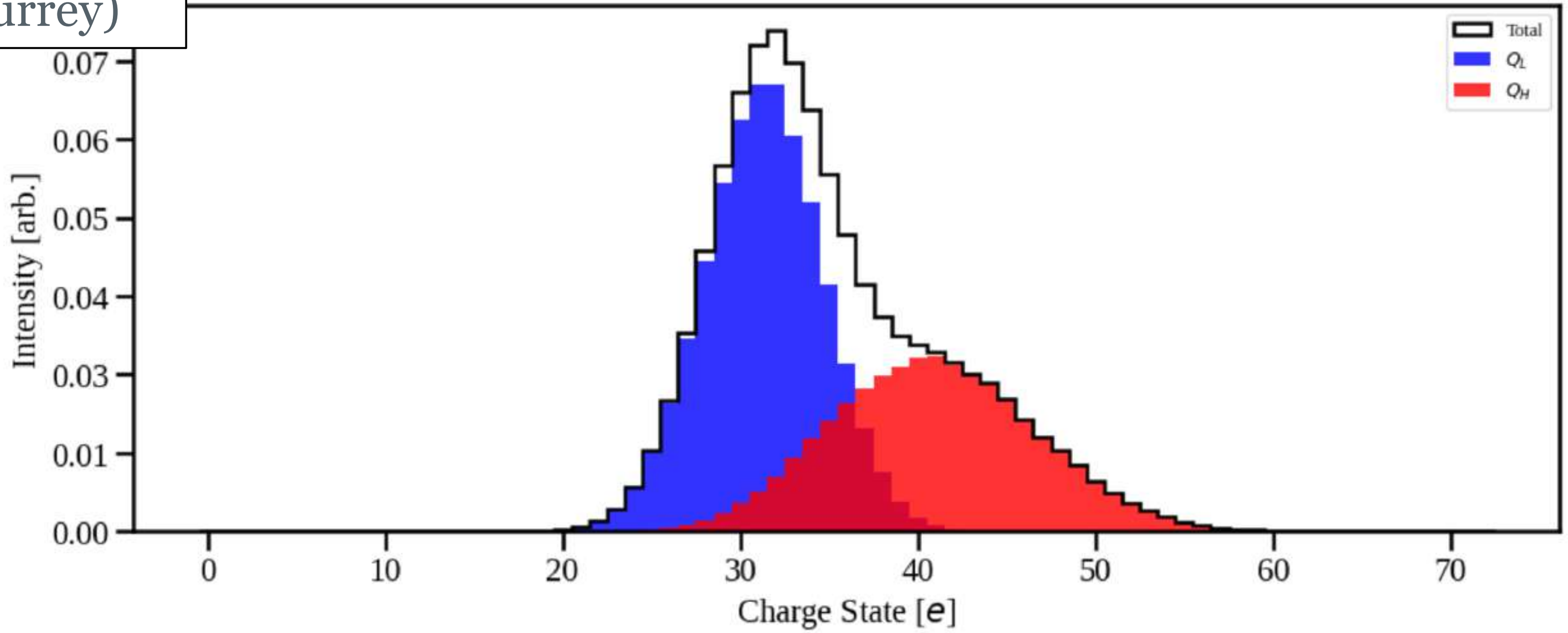
R. Russell[a], J. Heery[a], J. Henderson[a,*], R. Wadsworth[b], K. Kaneko[c], N. Shimizu[d], T. Mizusaki[e], Y. Sun[f], C. Andreoiu[h], D. W. Annen[h], A. A. Avaa[i], G. C. Ball[i], V. Bildstein[j], S. Buck[j], C. Cousins[a], A. B. Garnsworthy[i], S. A. Gillespie[k], B. Greaves[j], A. Grimes[i], G. Hackman[i], R. O. Hughes[l], D. G. Jenkins[b], T. M. Kowalewski[m,n], M. S. Martin[g], C. Müller-Gatermann[o], J. R. Murias[i], S. Murillo-Morales[i], S. Pascu[a,p], D. M. Rhodes[i,l], J. Smallcombe[q], P. Spagnoletti[h], C. E. Svensson[i,j], B. Wallis[b], J. Williams[i], C. Y. Wu[l], D. Yates[i,r]

Coulomb excitation as a tool for nuclear medicine

Coulomb excitation as a tool for nuclear medicine



ANL ATLAS proposal 2123
PI: Jacob Heery (Surrey)



Charge-state distribution measurements

Scattered beam from ^{136}Xe caused issues at FMA focal plane – challenging to interpret online data

Changed the beam/target combination to ^{40}Ar/^{197}Au

Almost a repeat of the FMA/EMMA commissioning experiments

Lighter beam + heavier target massively reduced scattered beam at FMA focal plane

S3-detector at backwards angles to provide normalisation (potential for CoulEx measurement of ^{40}Ar?)

Charge-state distribution measurements

Method:

Reset foil (carbon) located at ~1 cm from target

Recoiling Au ions at ~80 MeV (~0.9 cm/ns)

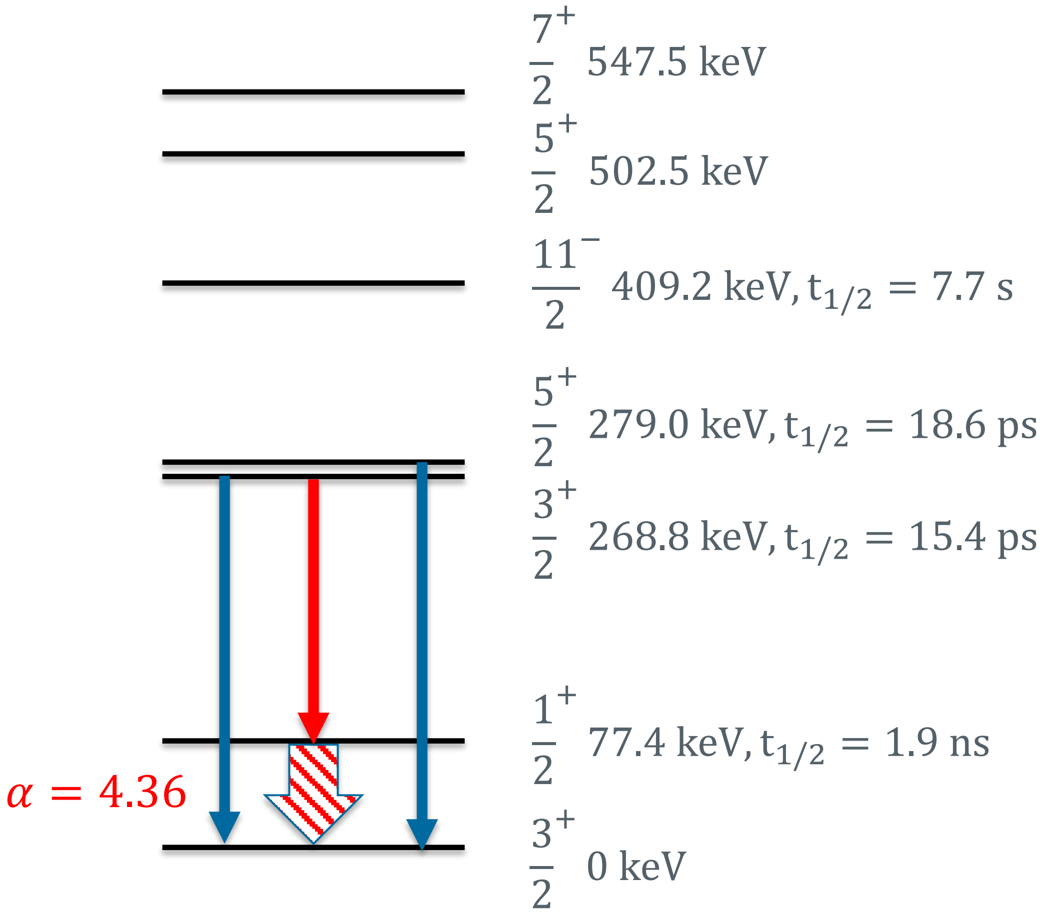
All states above 77 keV have half-lives ~10 ps or lower

Gate on 191-keV gamma-ray populating 77-keV state

Measure charge state

Will have low-charge (gamma-decay and IC before reset) and high-charge (IC after foil) component

Centroid difference between HC and LC gives mean Auger-electron multiplicity



Charge-state distribution measurements

Method:

Reset foil (

Recoiling

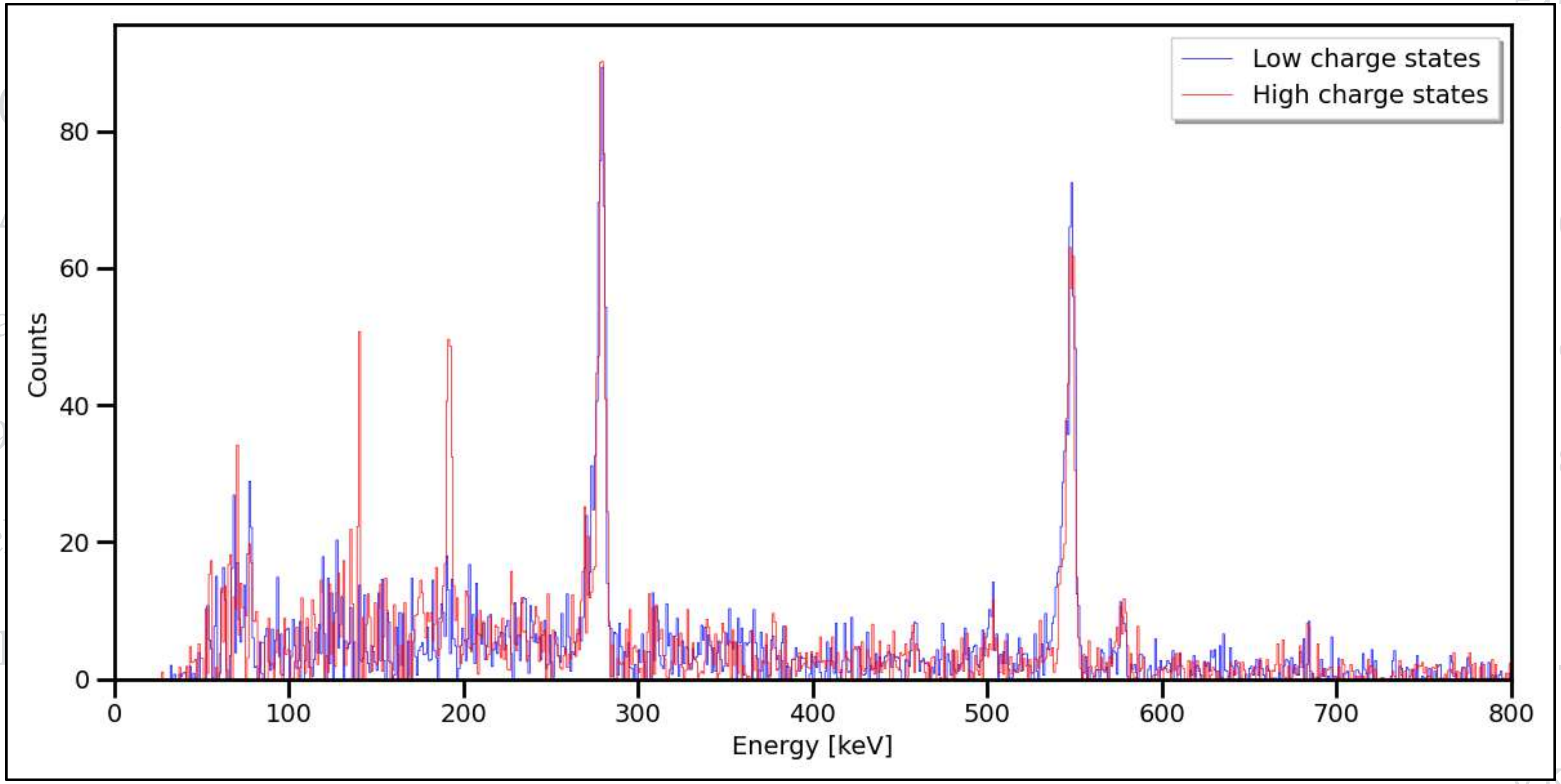
All states a

Gate on 19

Measure c

Will have l
reset) and

Centroid difference between HC and LC gives mean Auger-electron multiplicity



7^+
7.5 keV
2.5 keV
09.2 keV, $t_{1/2} = 7.7$ s
9.0 keV, $t_{1/2} = 18.6$ ps
8.8 keV, $t_{1/2} = 15.4$ ps
.4 keV, $t_{1/2} = 1.9$ ns
keV
2

Charge-state distribution measurements

Method:

Reset foil (carb

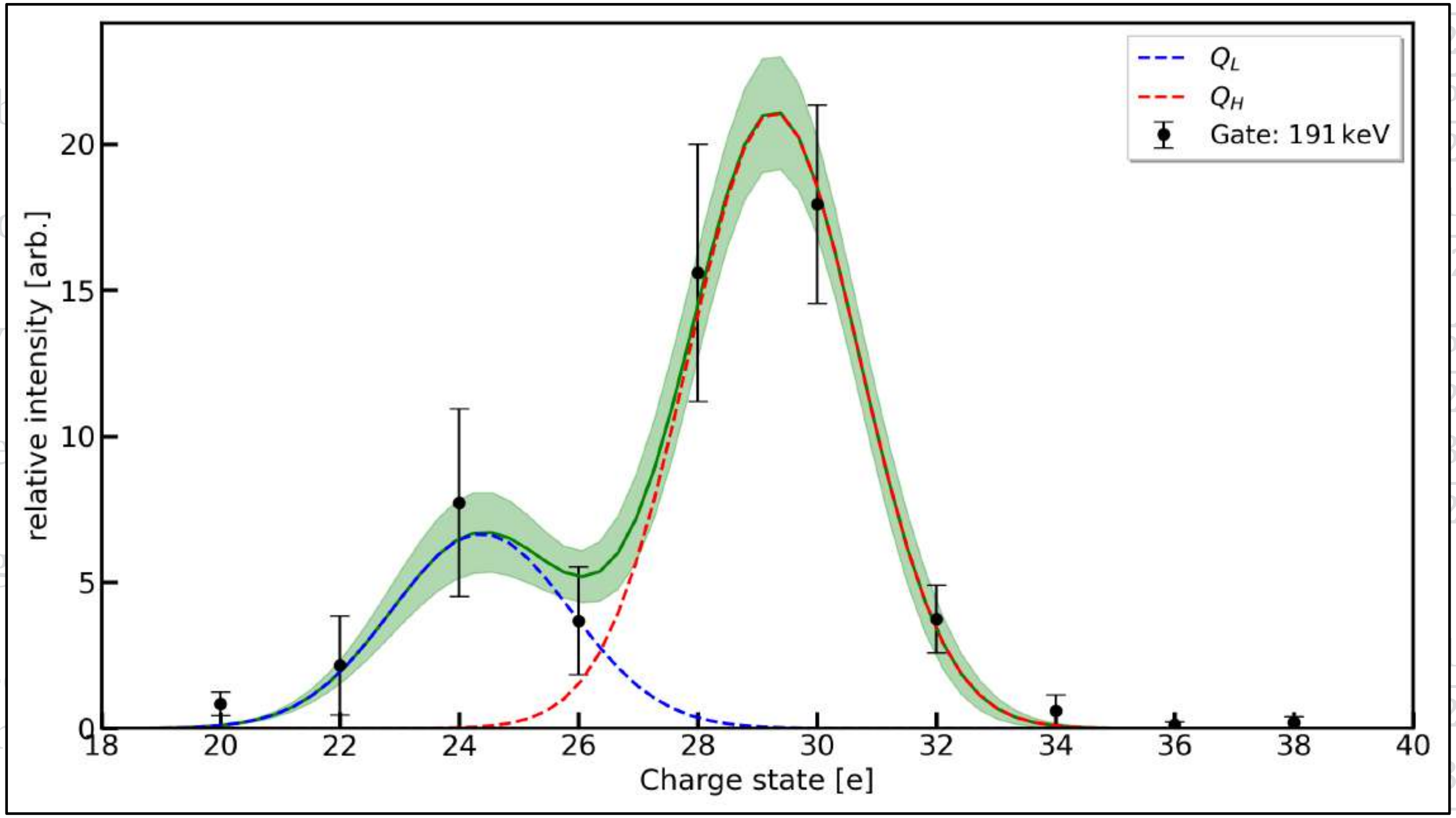
Recoiling Au i

All states abov

Gate on 191-ke

Measure charg

Will have low-
reset) and high



Centroid difference between HC and LC gives mean Auger-electron multiplicity

547.5 keV

502.5 keV

409.2 keV, $t_{1/2} = 7.7$ s

279.0 keV, $t_{1/2} = 18.6$ ps

268.8 keV, $t_{1/2} = 15.4$ ps

77.4 keV, $t_{1/2} = 1.9$ ns

0 keV

Charge-state distribution measurements

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Reset foil (carb

Recoiling Au i

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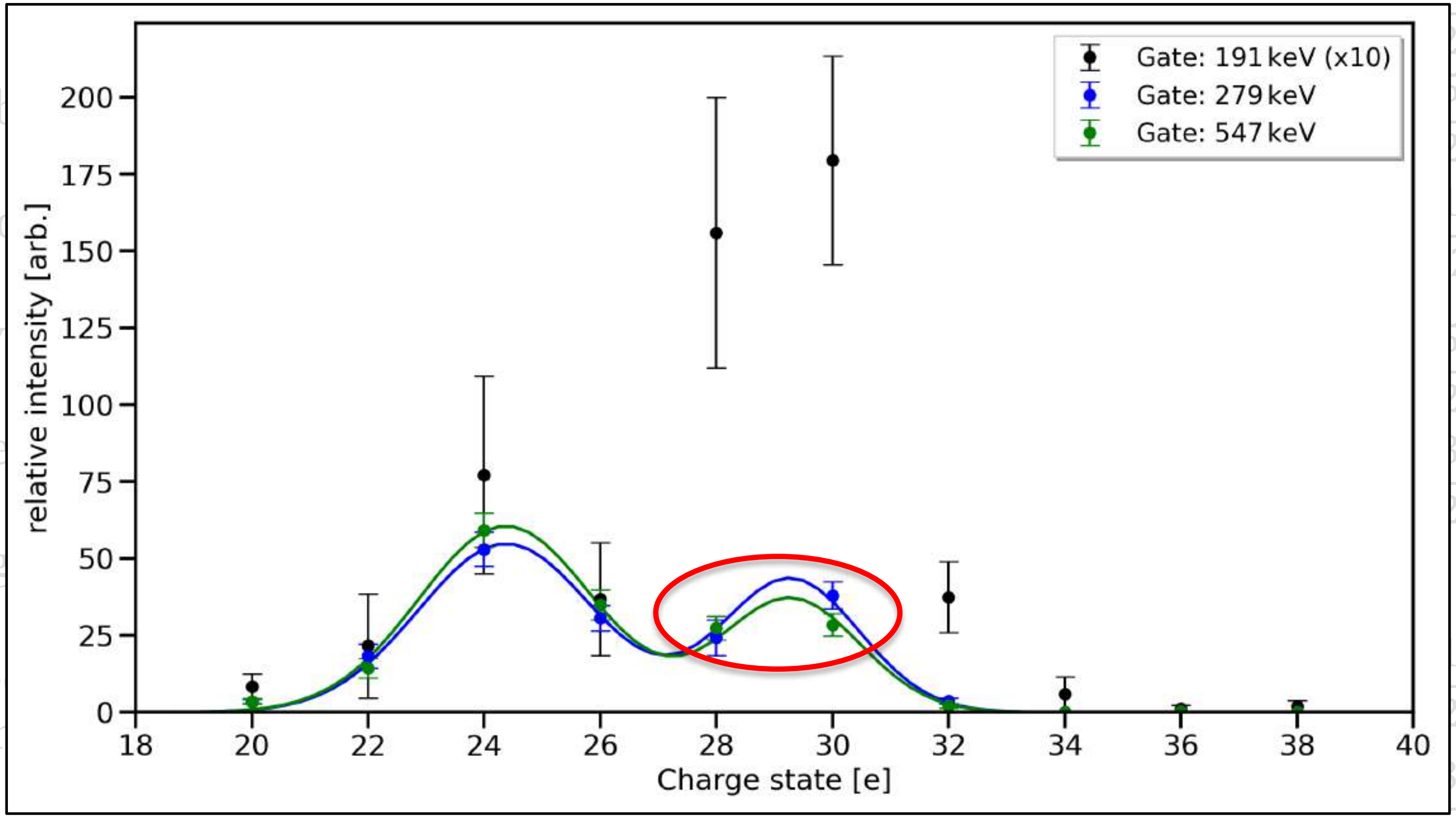

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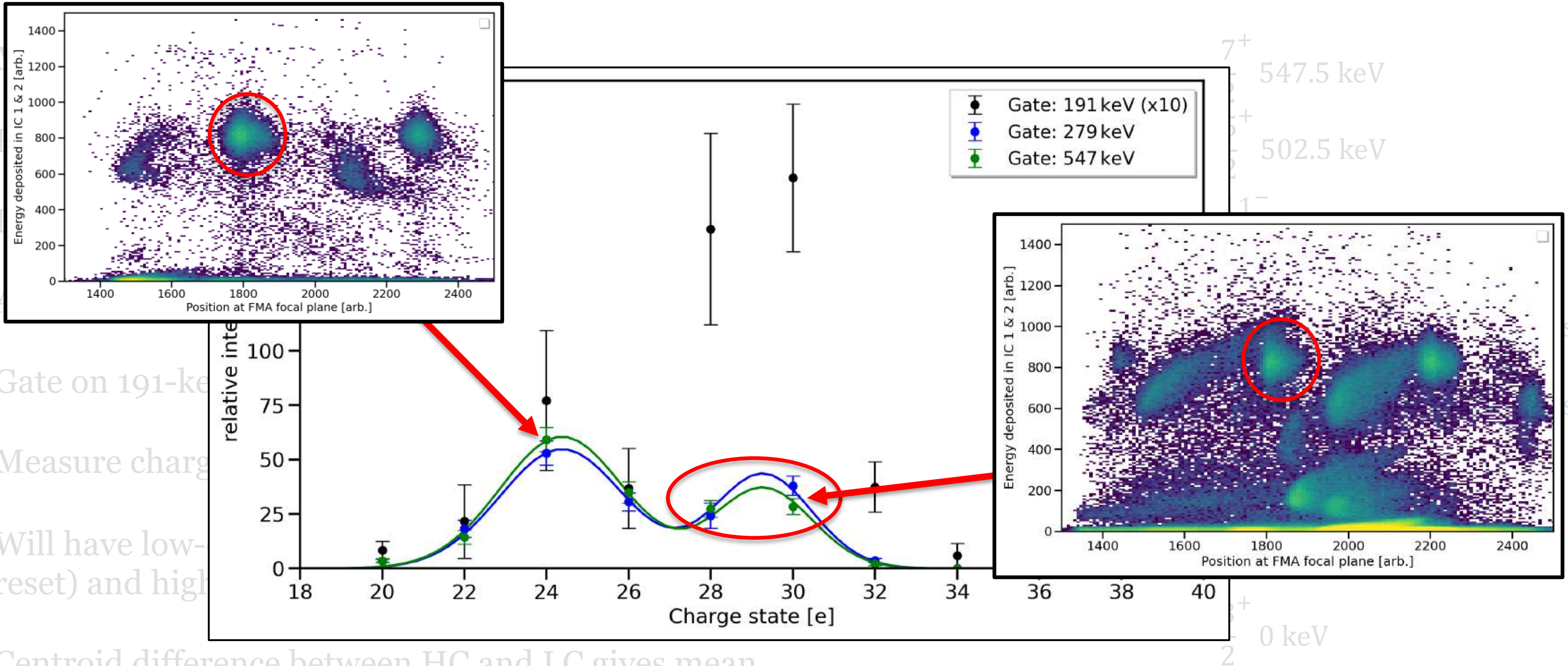
Charge-state distribution measurements



Gate on 191-ke

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Auger-electron multiplicity

Auger multiplicity

With thanks to:

J. Heery[1,2], J. Henderson[1], T. Budner[3], M.P. Carpenter[3], W. Catford[1], J. Chadderton[4], R. Chakma[3], S. Collins[2], C. Cousins[1], J. Cubiss[5], A. Dewald[6], D. Doherty[1], F. Dunkel[6], S. Dutta[7], A. Ertoprak[3], C. Fransen[6], R.-D. Herzberg[4], V. Karayoncev[3], B. Kay[3], T. Kibédi[8], F. G. Kondev[3], C.-D. Lakenbrink[6], T. Lauritsen[3], G. Lorusso[2], G. Lotay[1], C. Müller-Gatermann[3], B. S. Nara Singh[7], J. Nolan[3], D O'Donnell[7], E. O'Sullivan[1,2], S. Pascu[1], Z. Podolyák[1], P. H. Regan[1,2], A. Renne[3], W. Reviol[3], R. Russell[1], J. Sarén[9], N. Sensharma[3], D. Seweryniak[3], R. Shearman[2], M. Siciliano[3], F. von Spee[6], P. Stollenberg[3], S. Suman[10], S.K. Tandel[10], J. Uusitalo[9], J. Vilhena[7], M. Williams[1], G. Willmott[1]


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