FLORIDA STATE
UNIVERSITY

Opportunities for studying octupole collectivity at FRIB

M. Spieker

Theoretical Justifications and Motivations
for Early High-Profile FRIB Experiments, FRIB-TA, May 2023

Octupole correlations in atomic nuclei

HOT TOPIC

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Exotic radium-224 atomic nuclei seen at CERN

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Prosthetic limbs with sensory feedback

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Researchers at odds over climate–violence link

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Inflammation links ageing to the hypothalamus

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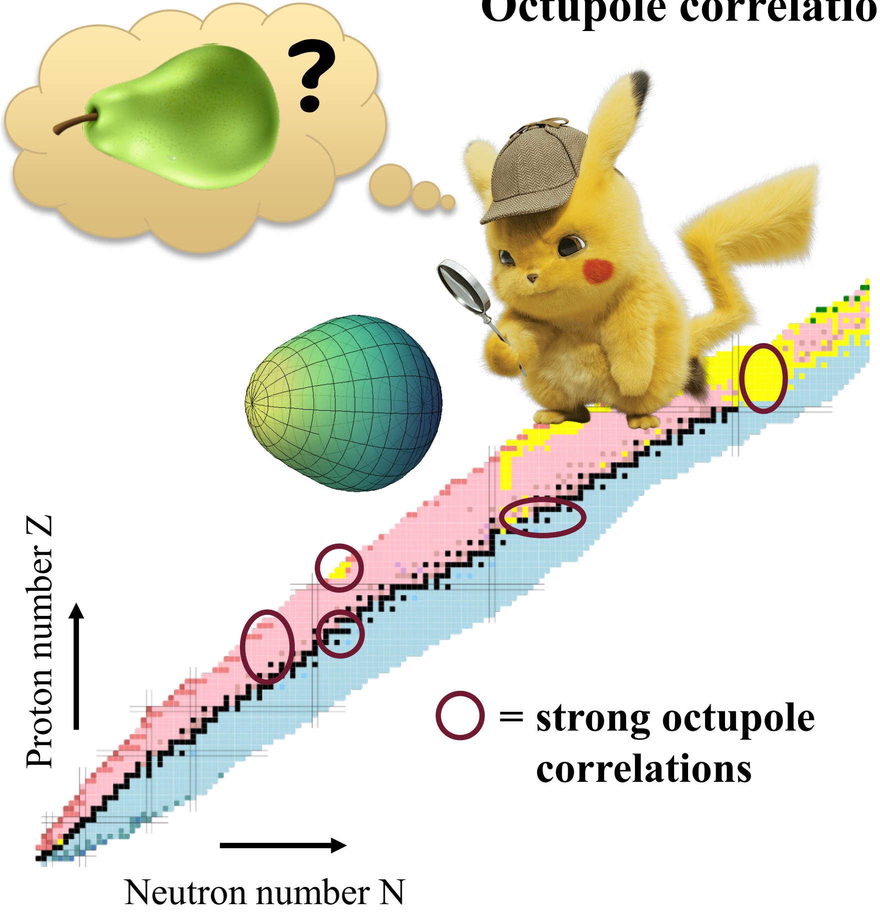
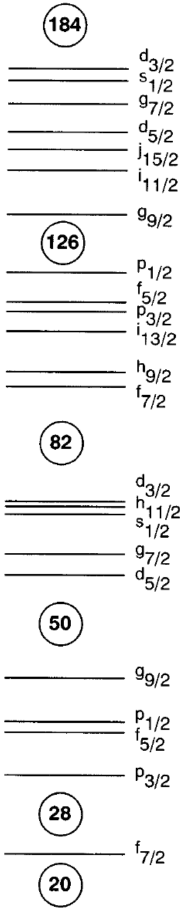
10 years ago and still going!



○ = **strong octupole correlations**



$\Delta j = \Delta l = 3$

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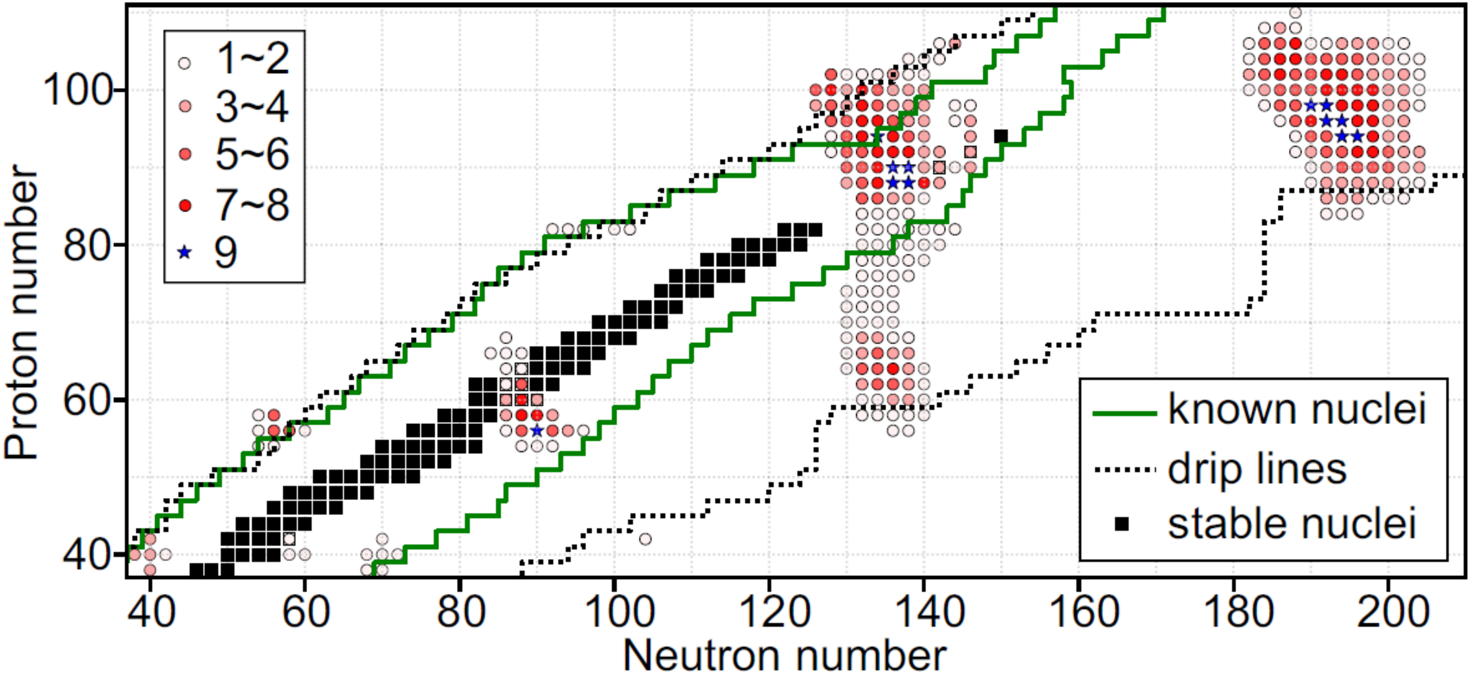
Expected at Z or N equal to 34, 56, 88, 134.

[Butler and Nazarewicz, RMP **68**, 349 (1996)]

Octupole correlations in atomic nuclei (Predictions from DFT at mean-field level)



[Y. Cao *et al.*, PRC **102**, 024311 (2020)]

See also, *e.g.*, S.E. Agbemava *et al.*, PRC **94**, 044304 (2016).

Octupole correlations in atomic nuclei

Part I

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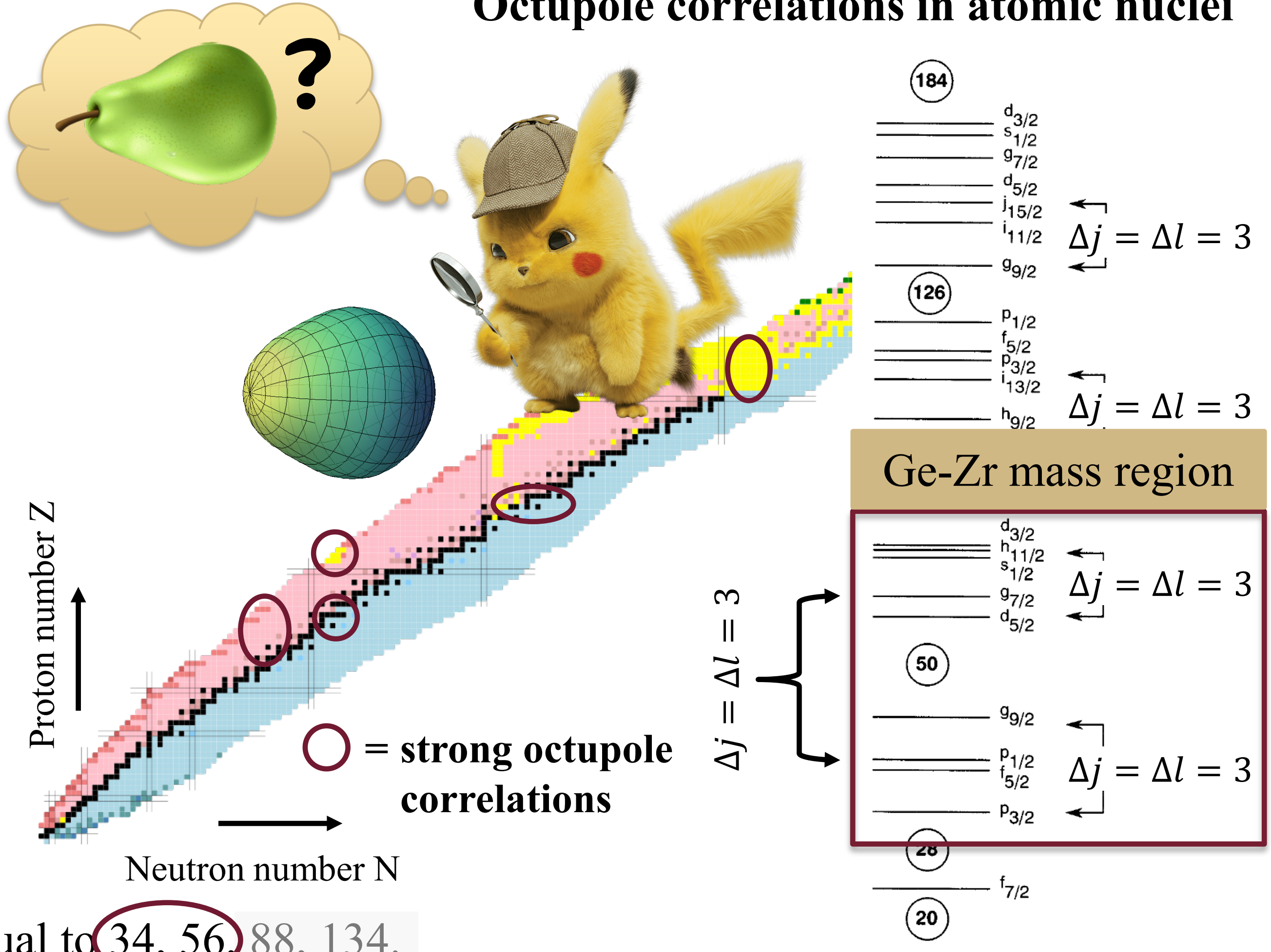

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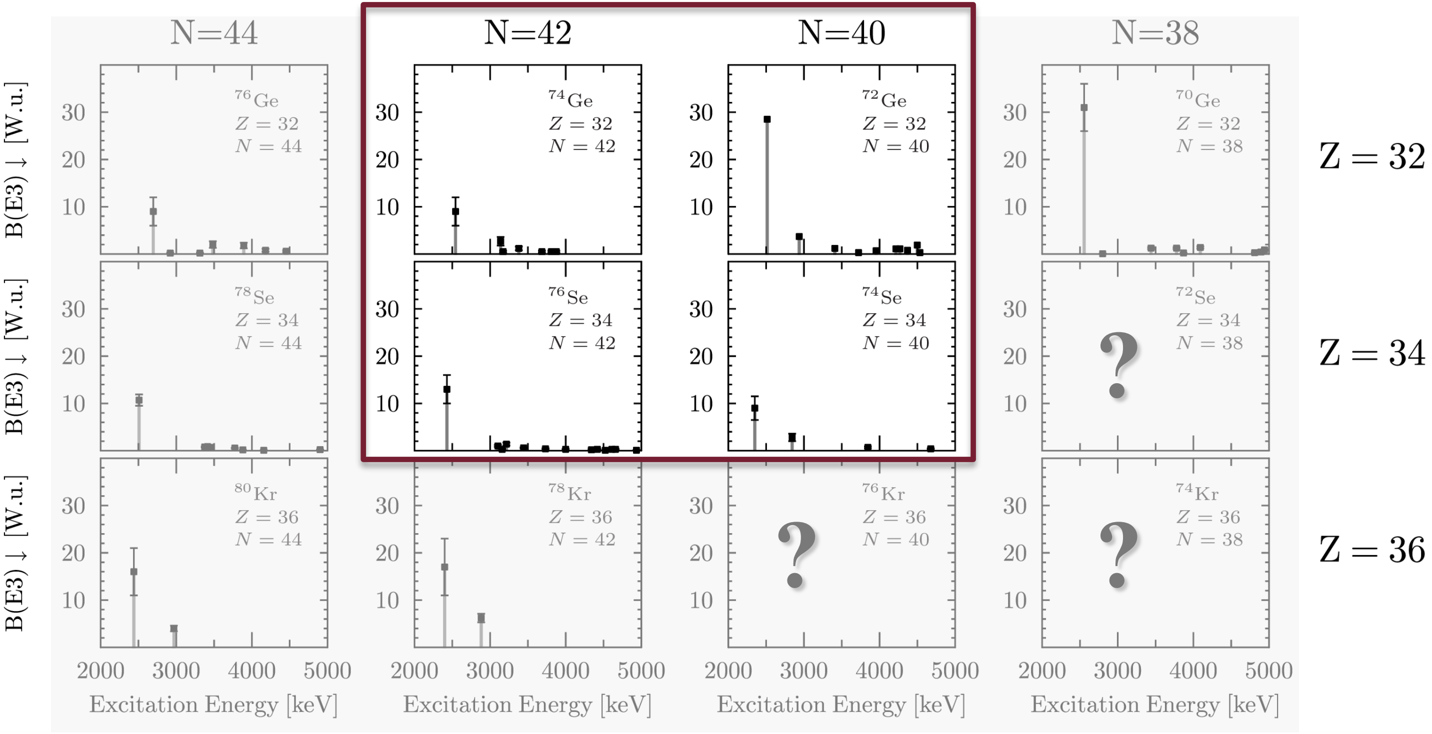
[Butler and Nazarewicz, RMP **68**, 349 (1996)]

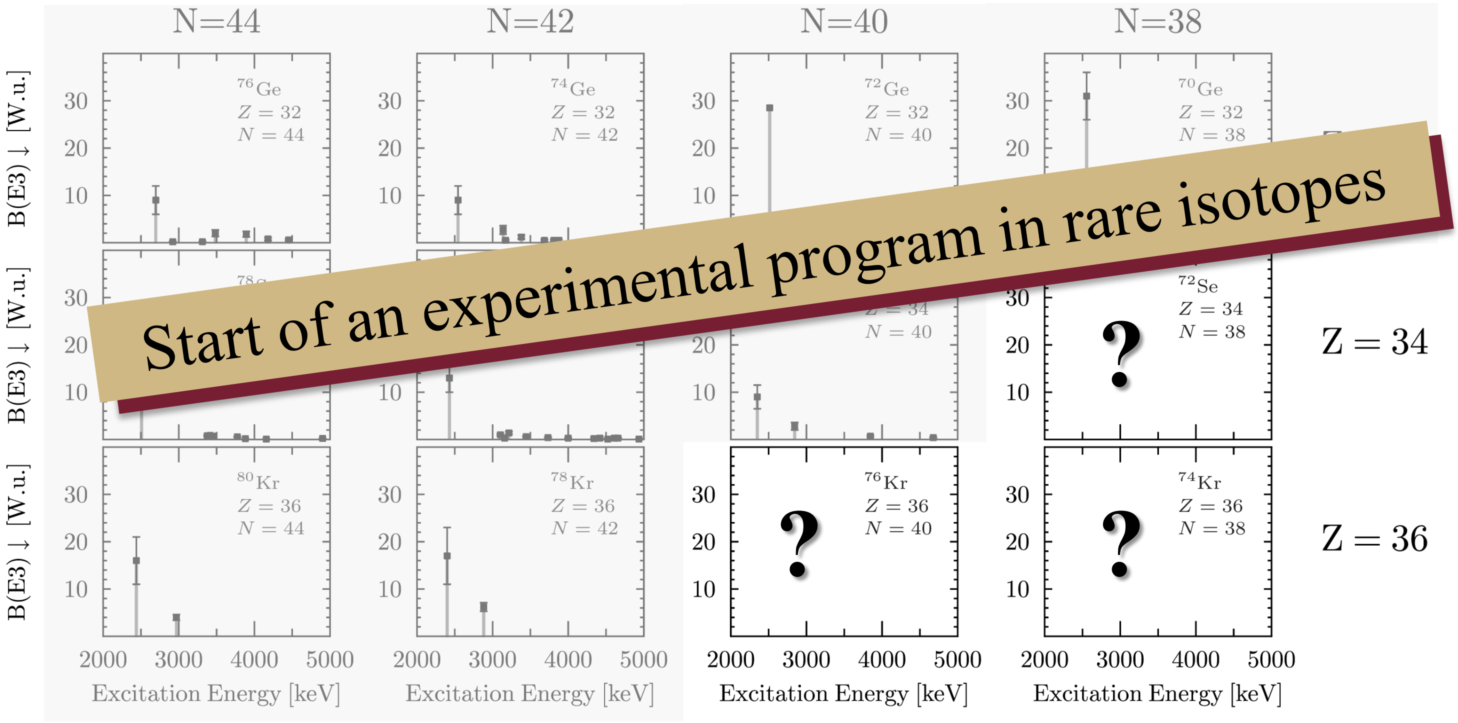
B(E3) systematics in Ge-Kr mass region from light-ion scattering



Sudden strength increase in Ge but not in Se. Why? There seems to be nothing special about Ge in terms of octupole collectivity in the other isotonic chains.

[Rosier *et al.*, NPA **453**, 389 (1986); Schürmann *et al.*, NPA **475**, 361 (1987); Ogino, PRC **33**, 71 (1986); Matsuki *et al.*, PLB **113**, 21 (1982)]

B(E3) systematics in Ge-Kr mass region from light-ion scattering

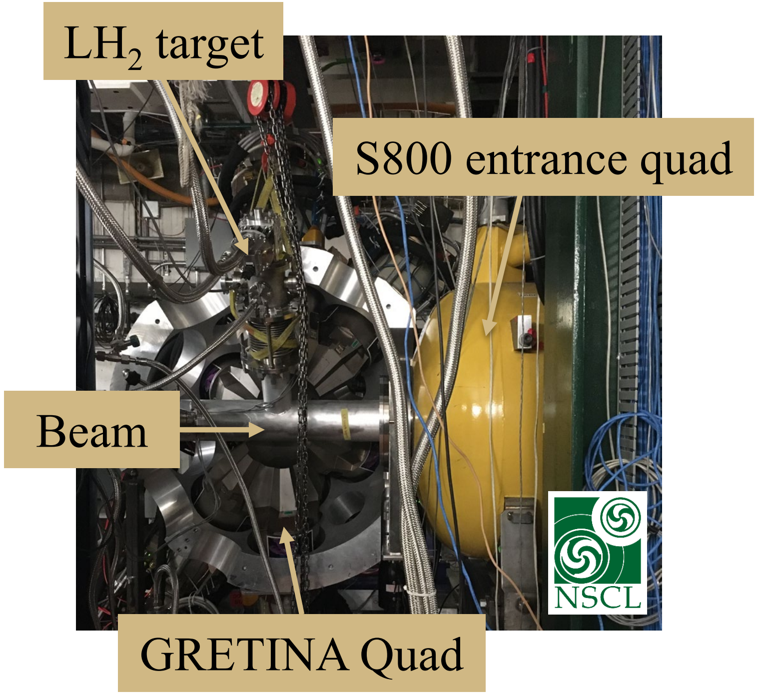


Start of an experimental program in rare isotopes

Strength increase delayed in the other isotopic chains? Ge or Se special?

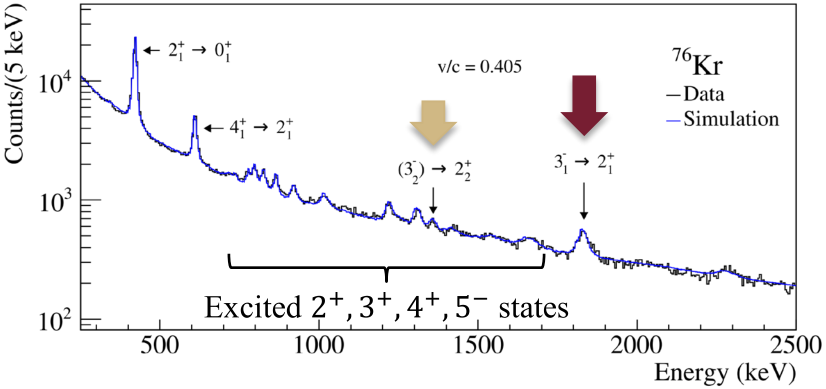
[Rosier *et al.*, NPA **453**, 389 (1986); Schürmann *et al.*, NPA **475**, 361 (1987); Ogino, PRC **33**, 71 (1986); Matsuki *et al.*, PLB **113**, 21 (1982)]

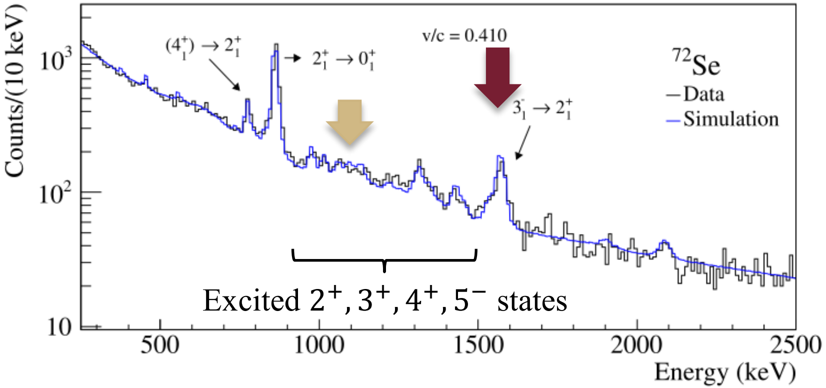
Experiment with combined GRETINA-S800-LH$_2$ setup at NSCL

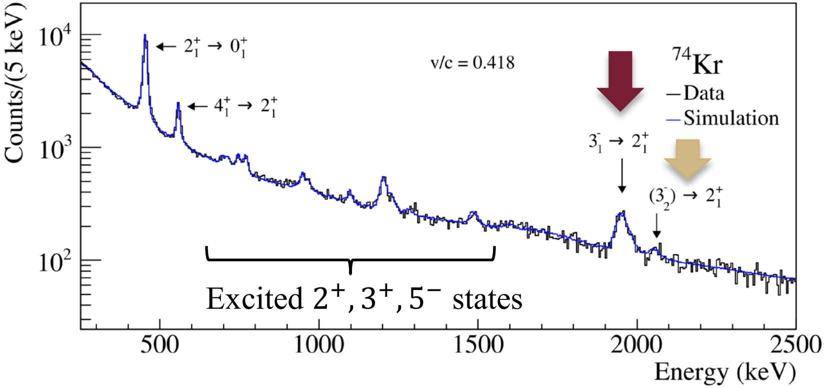


- **Inelastic proton scattering in inverse kinematics**
  - Powerful probe to populate 3^- states
- **NSCL/Ursinus LH$_2$ target**
  - “Thin” cell was used (50 mg/cm^2)
- **Secondary beam energies corresponding to proton energies of 100 MeV in c.m. frame**
  - Enhanced sensitivity to both proton and neutron contributions
- **Beam purities:** 79% for ^{76}Kr, 51% for ^{74}Kr, 6% for ^{72}Se
- 8 GRETINA Quads mounted in north hemisphere (3rd campaign had nominally 12 Quads).

Doppler-corrected in-beam γ-ray spectra for ^{74,76}Kr and ^{72}Se



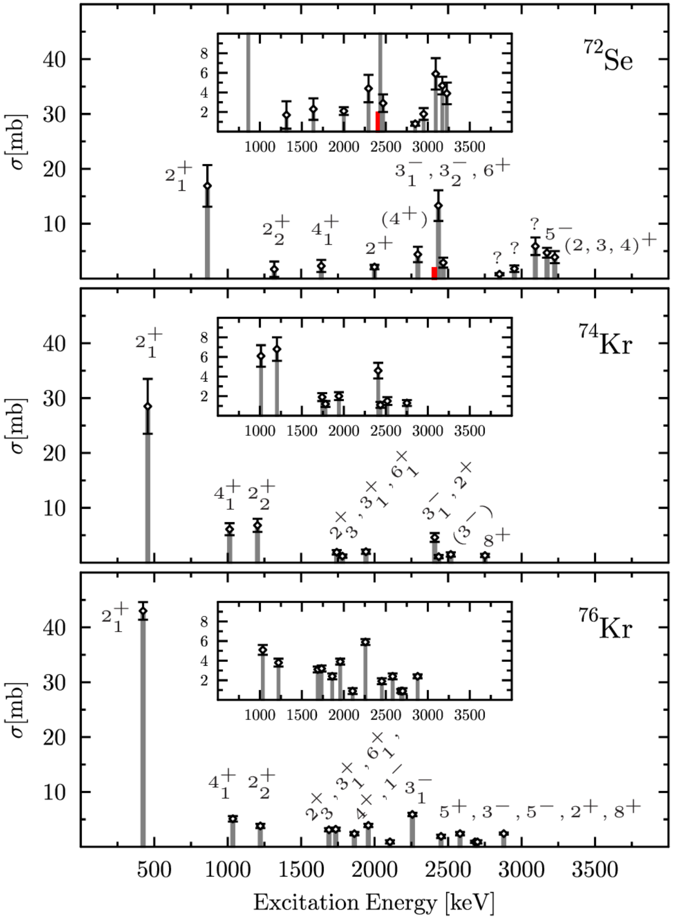




- Excellent resolution with GRETINA.
- 3_1^- and 3_2^- states (candidates) are strongly populated in (p,p')
- In addition, several low-spin states are populated for which scattering lengths and, thus, reduced transition probabilities can be determined.

[Results: MS *et al.*, PRC **106**, 054305 (2022); UCGRETINA: Riley *et al.*, NIM A **1003**, 165305 (2021)]

(p,p') cross sections for ^{72}Se and ^{74,76}Kr

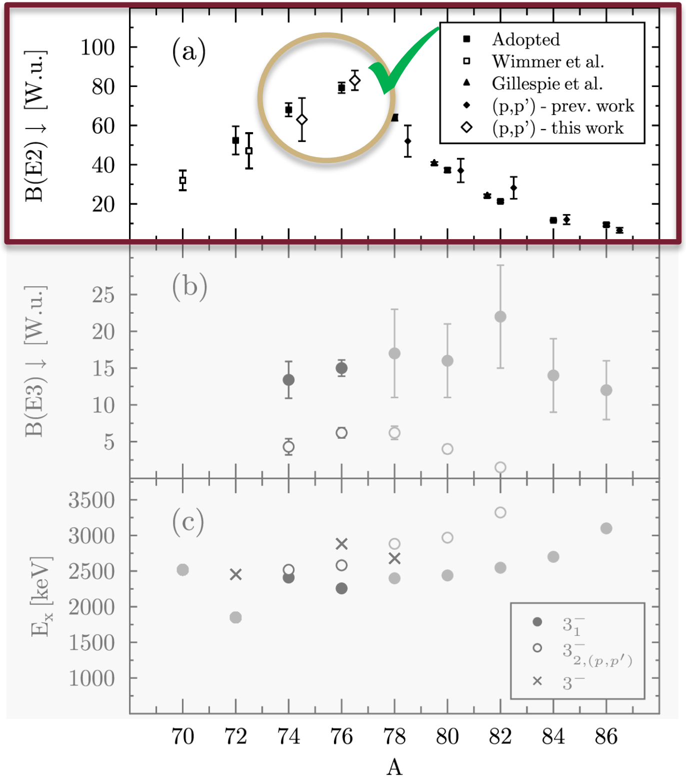


- **Direct observable:** (p,p') cross sections.
- (p,p') cross sections allow model-dependent determination of deformation parameters β_λ. $\rightarrow B\left(E\lambda; 0_1^+ \rightarrow J_f^\pi\right)$ can be calculated.

Disclaimer

[MS *et al.*, PRC **106**, 054305 (2022) and PLB **841**, 137932 (2023)]

Systematics in the Kr isotopes with $N \leq 50$



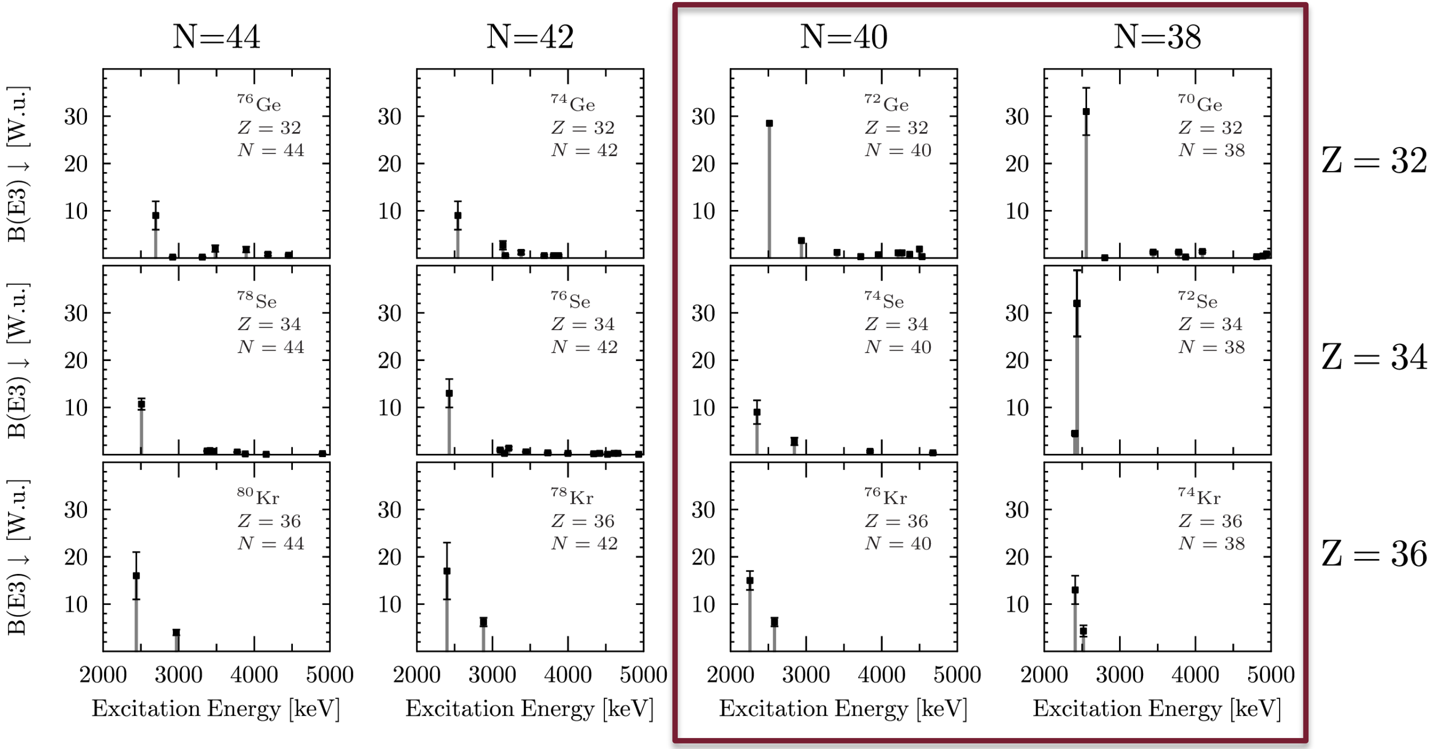
[MS *et al.*, PRC **106**, 054305 (2022)] and other data from: [Wimmer *et al.*, EPJA **56**, 159 (2020); Wimmer *et al.*, PRL **126**, 072501 (2021); Pritychenko *et al.*, Nuclear Data Sheets **120**, 112 (2014); Gillespie *et al.*, PRC **104**, 044313 (2021); Matsuki *et al.*, PLB **113**, 21 (1982)]

- **Direct observable:** (p,p') cross sections.
- (p,p') cross sections allow model-dependent determination of deformation parameters β_λ.
  → $B\left(E\lambda; 0_1^+ \rightarrow J_f^\pi\right)$ can be calculated.

Results:

- Excellent agreement of $B(E2; 2_1^+ \rightarrow 0_1^+)$ to values determined with other probes. ✓
- $B(E3; 3_1^- \rightarrow 0_1^+)$ strengths fit well into systematics.
- $B\left(E3; 3^-_{2,(p,p')} \rightarrow 0_1^+\right)$ strengths, even though assigned tentatively in ^{74,76}Kr, show that strength remains fragmented.
  → Fragmentation appears nontrivial as 2nd 3^- is not necessarily 2nd strongest fragment.

B(E3) strength distribution in Ge-Kr mass region

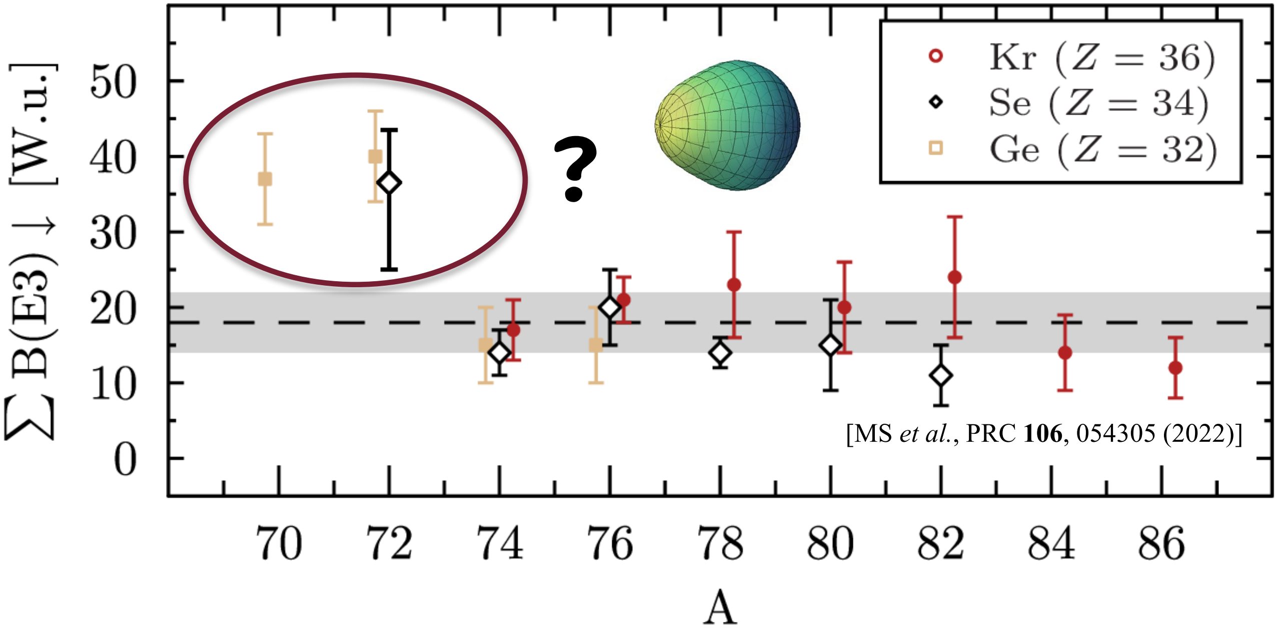


Strength increase observed for ^{72}Se but not for ^{74,76}Kr. What determines strength increase?

[Rosier *et al.*, NPA **453**, 389 (1986); Schürmann *et al.*, NPA **475**, 361 (1987); Ogino, PRC **33**, 71 (1986); Matsuki *et al.*, PLB **113**, 21 (1982); MS *et al.*, PRC **106**, 054305 (2022)]

Summed B(E3) strengths in Ge-Kr mass region

Two distinct regions with sudden strength increase at A = 72



[MS *et al.*, PRC **106**, 054305 (2022)]

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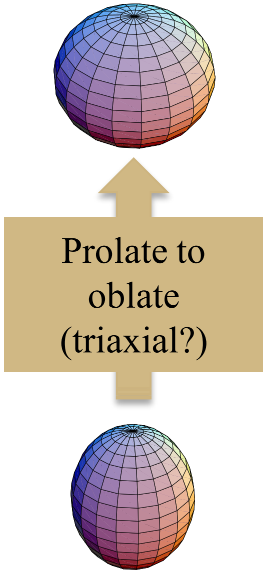
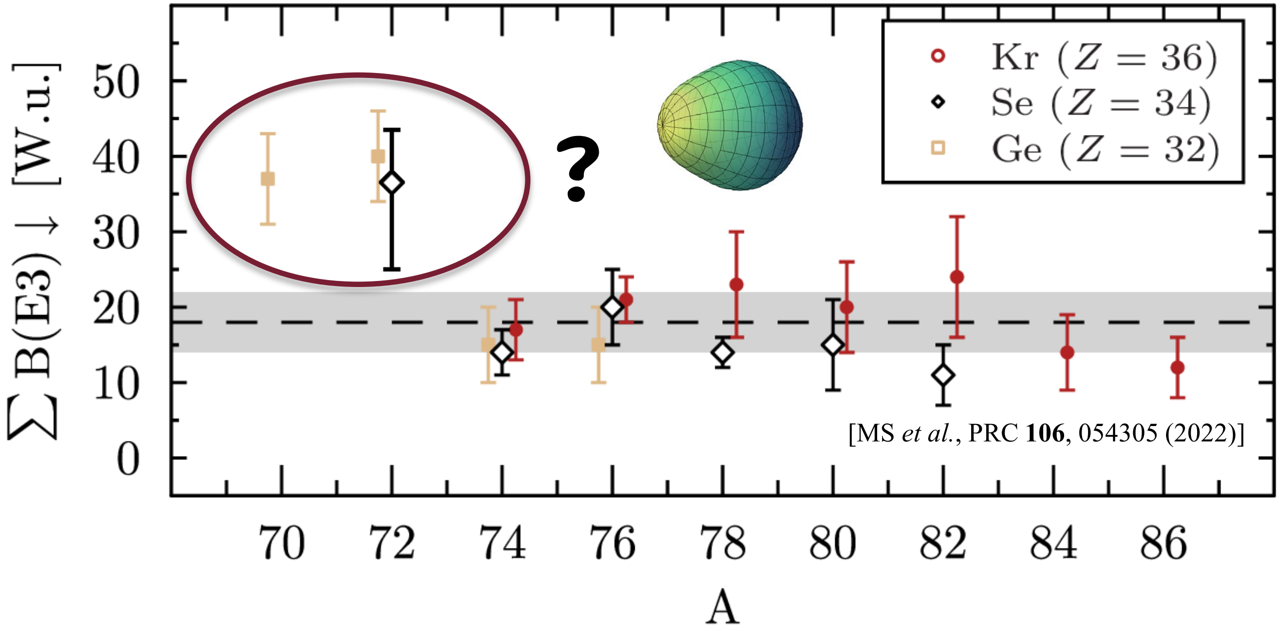


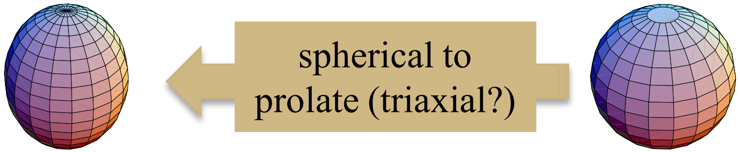
Prolate to oblate (triaxial?)



[MS *et al.*, PRC **106**, 054305 (2022)]

Some recent work on "shapes":

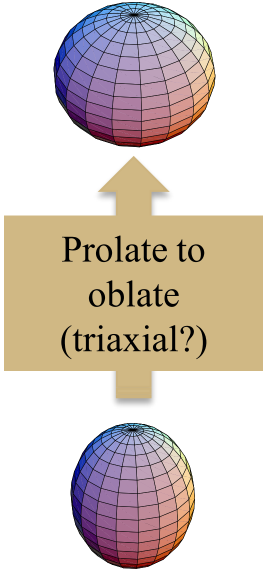
- [Ayangeakaa *et al.*, PLB **754**, 254 (2016)]
- [Henderson *et al.*, PRL **121**, 082502 (2018)]
- [Gillespie *et al.*, PRC **104**, 044313 (2021)]
- [Wimmer *et al.*, PRL **126**, 072501 (2021)]

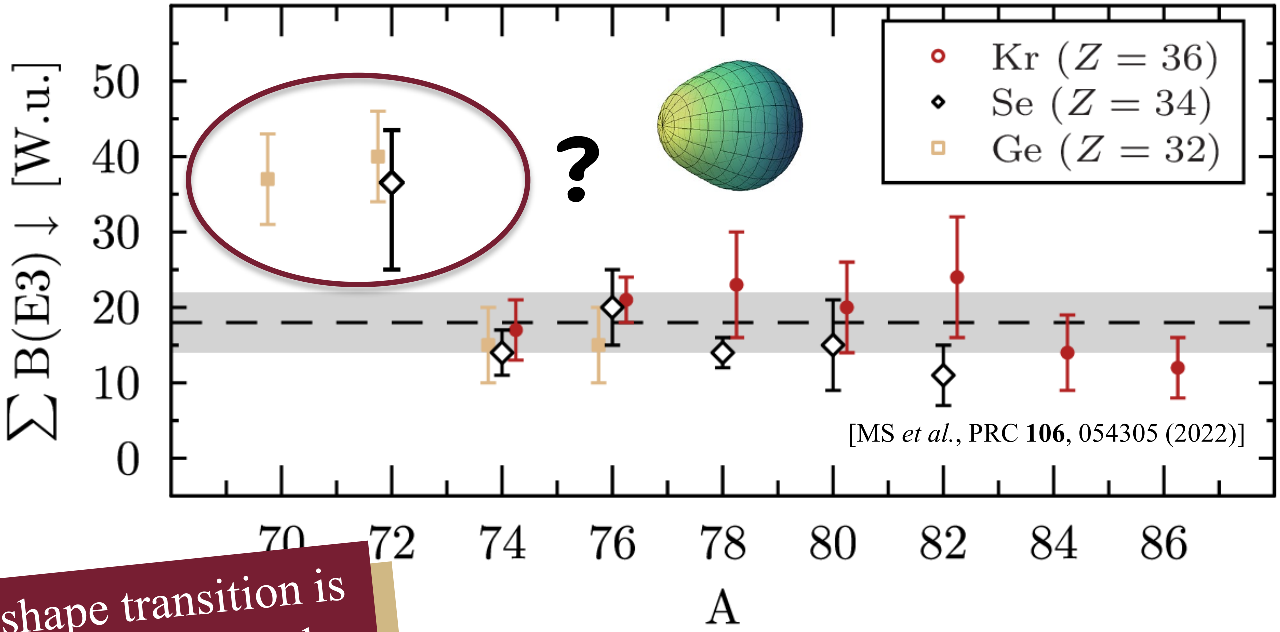


spherical to prolate (triaxial?)

Summed B(E3) strengths in Ge-Kr mass region

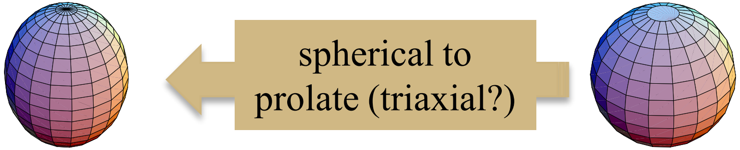
Two distinct regions with sudden strength increase at A = 72


Prolate to oblate (triaxial?)

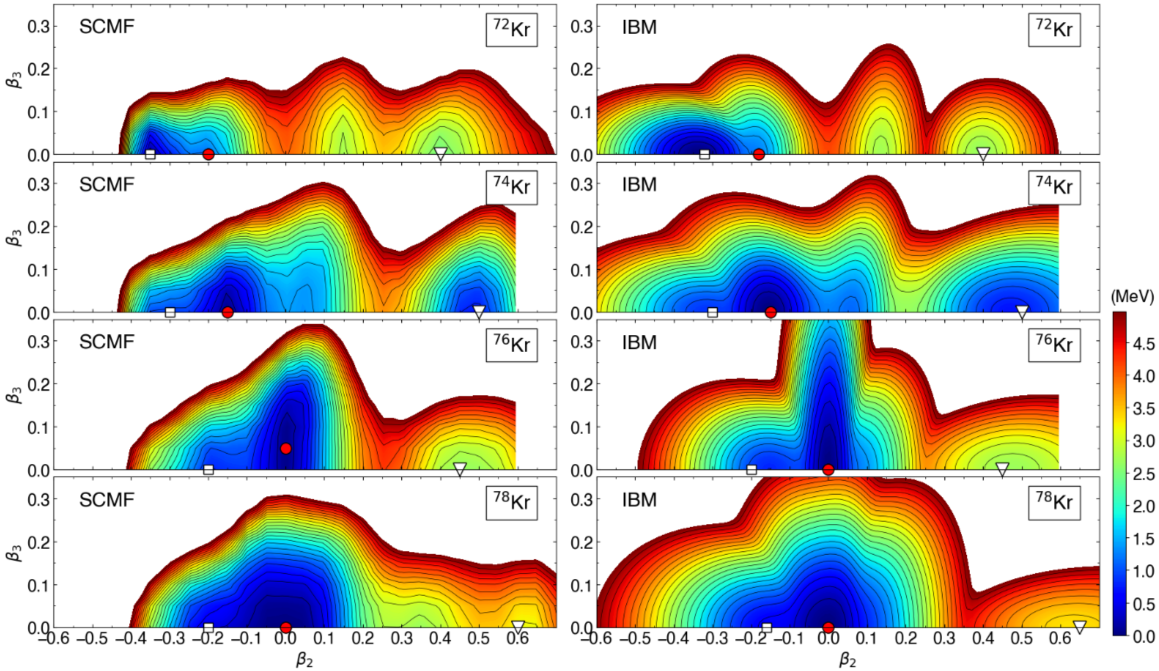


[MS *et al.*, PRC **106**, 054305 (2022)]

If connection to shape transition is true, should we expect enhanced strength in ^{70}Se and ^{70,72}Kr?


spherical to prolate (triaxial?)

Octupole and quadrupole "correlations" from SCMF+IBM calculations

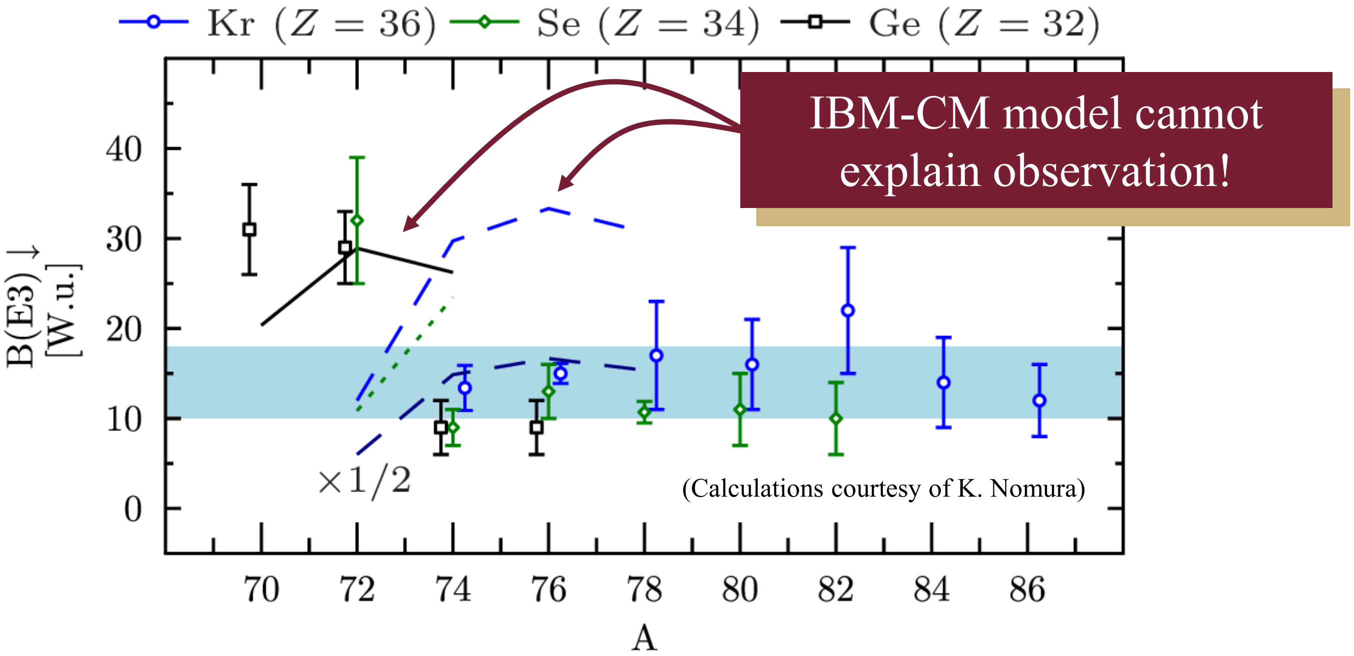


The minima associated with the 0p-0h, 2p-2h, and 4p-4h unperturbed configurations are identified by the circle, square, and triangle, respectively. The red solid symbol denotes the global minimum. Octupole softness is predicted to decrease from ^{76}Kr to ^{72}Kr.

(Calculations courtesy of K. Nomura)

Summed B(E3) strengths in Ge-Kr mass region

Experimentally, two distinct regions with sudden strength increase at A = 72.



IBM-CM model cannot explain observation!

(Calculations courtesy of K. Nomura)

So, what is going on here? Are the sudden shape transitions in this region affecting octupole collectivity? What should we expect for ^{70,72}Kr and ^{70}Se? These nuclei could be studied at FRIB. But can theory even reliably inform experiment in this mass region?

Recent work from the arXiv

- Recently posted on the arXiv: RPA/QRPA study of $B(E3; 3_1^- \rightarrow 0_1^+)$ strength using different Skyrme functionals at mean-field level.

[Bui *et al.*, arXiv:2303.10928 [nucl-th]]

→ Observed huge model dependency for excitation energy and reduced transition probability.

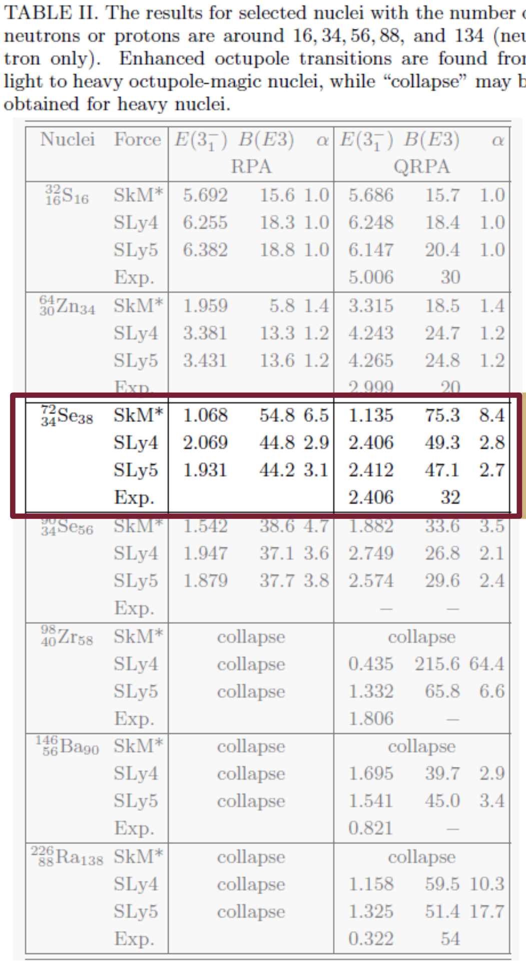


TABLE II. The results for selected nuclei with the number of neutrons or protons are around 16, 34, 56, 88, and 134 (neutron only). Enhanced octupole transitions are found from light to heavy octupole-magic nuclei, while "collapse" may be obtained for heavy nuclei.

Nuclei	Force	$E(3_1^-)$	$B(E3)$	α	$E(3_1^-)$	$B(E3)$	α
		RPA			QRPA		
$^{32}_{16}\mathrm{S}_{16}$	SkM*	5.692	15.6	1.0	5.686	15.7	1.0
	SLy4	6.255	18.3	1.0	6.248	18.4	1.0
	SLy5	6.382	18.8	1.0	6.147	20.4	1.0
	Exp.				5.006	30	
$^{64}_{30}\mathrm{Zn}_{34}$	SkM*	1.959	5.8	1.4	3.315	18.5	1.4
	SLy4	3.381	13.3	1.2	4.243	24.7	1.2
	SLy5	3.431	13.6	1.2	4.265	24.8	1.2
	Exp.				2.999	20	
$^{72}_{34}\mathrm{Se}_{38}$	SkM*	1.068	54.8	6.5	1.135	75.3	8.4
	SLy4	2.069	44.8	2.9	2.406	49.3	2.8
	SLy5	1.931	44.2	3.1	2.412	47.1	2.7
	Exp.				2.406	32	
$^{90}_{34}\mathrm{Se}_{56}$	SkM*	1.542	38.6	4.7	1.882	33.6	3.5
	SLy4	1.947	37.1	3.6	2.749	26.8	2.1
	SLy5	1.879	37.7	3.8	2.574	29.6	2.4
	Exp.				–	–	
$^{98}_{40}\mathrm{Zr}_{58}$	SkM*	collapse			collapse		
	SLy4	collapse			0.435	215.6	64.4
	SLy5	collapse			1.332	65.8	6.6
	Exp.				1.806	–	
$^{146}_{56}\mathrm{Ba}_{90}$	SkM*	collapse			collapse		
	SLy4	collapse			1.695	39.7	2.9
	SLy5	collapse			1.541	45.0	3.4
	Exp.				0.821	–	
$^{226}_{88}\mathrm{Ra}_{138}$	SkM*	collapse			collapse		
	SLy4	collapse			1.158	59.5	10.3
	SLy5	collapse			1.325	51.4	17.7
	Exp.				0.322	54	

Huge model dependency!

Kr isotopes and strength evolution in Kr-Ge mass region not discussed. Not clear whether "model" gets trend right.

Bui *et al.* state:

"The results for octupole-magic nuclei are extremely sensitive to the choice of Skyrme force. […] The difference between SLy5 and SLy4 is from the terms which depend on the spin-orbit densities. It is well-known that the spin-orbit interaction plays a key point in the single-particle spectrum which, as we saw, largely determines the octupole magic numbers. A small change in the spin-orbit component makes a significant change in the result."

[Table: Bui *et al.*, arXiv:2303.10928 [nucl-th]]

The challenges? (The example of the $B(E3;3_1^- \rightarrow 0_1^+) = 42(3)$ W.u. in ^{96}Zr)

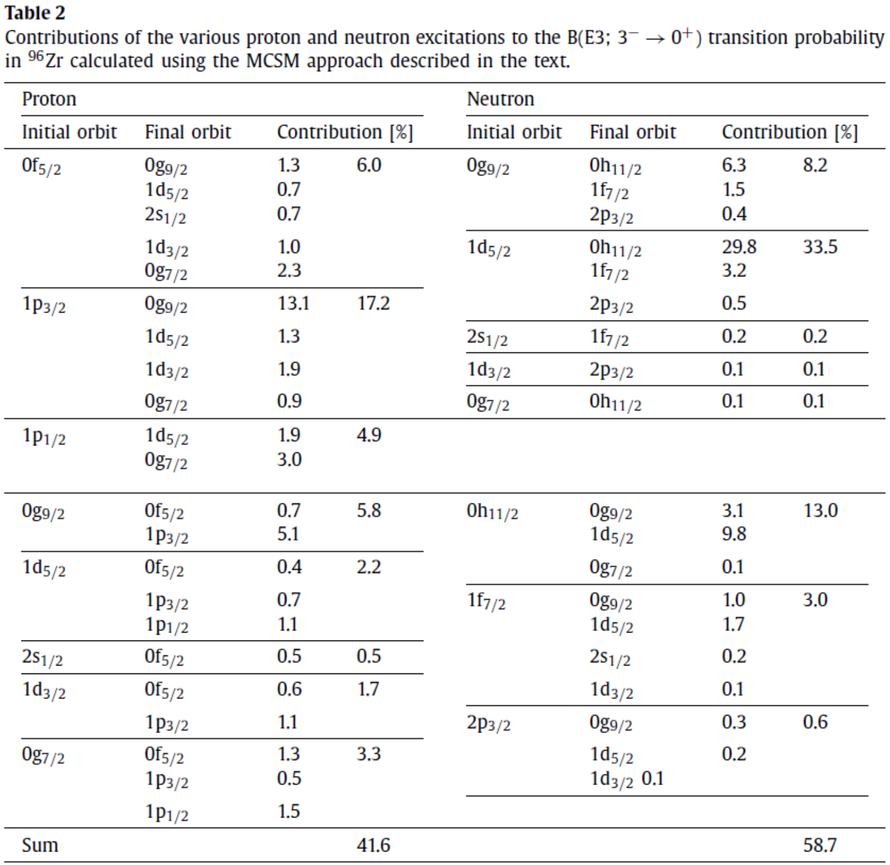
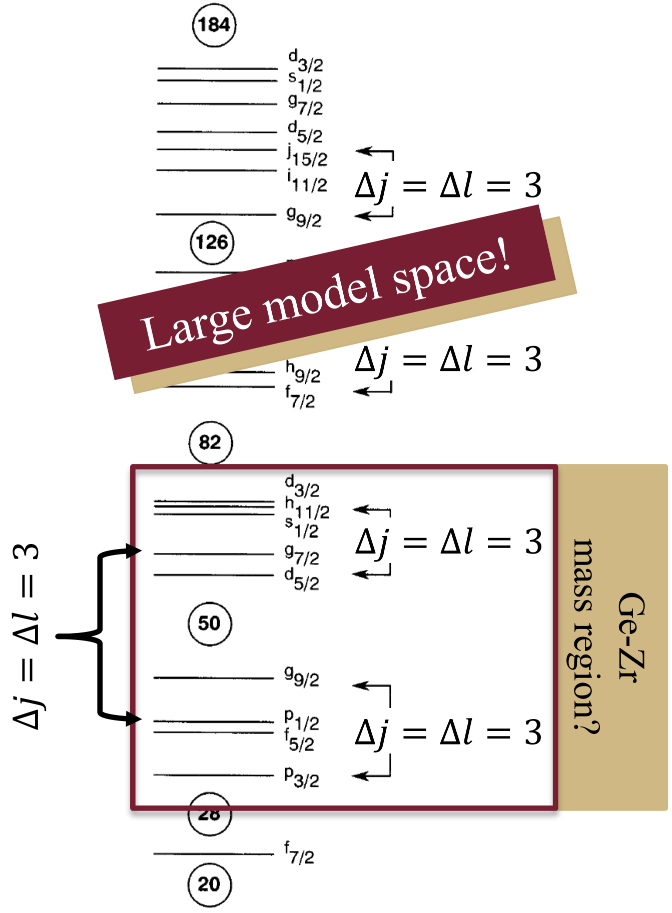


Table 2

Contributions of the various proton and neutron excitations to the B(E3; $3^- \rightarrow 0^+$) transition probability in ^{96}Zr calculated using the MCSM approach described in the text.

Proton				Neutron			
Initial orbit	Final orbit	Contribution [%]		Initial orbit	Final orbit	Contribution [%]	
$0f_{5/2}$	$0g_{9/2}$	1.3	6.0	$0g_{9/2}$	$0h_{11/2}$	6.3	8.2
	$1d_{5/2}$	0.7			$1f_{7/2}$	1.5	
	$2s_{1/2}$	0.7			$2p_{3/2}$	0.4	
	$1d_{3/2}$	1.0		$1d_{5/2}$	$0h_{11/2}$	29.8	33.5
	$0g_{7/2}$	2.3			$1f_{7/2}$	3.2	
$1p_{3/2}$	$0g_{9/2}$	13.1	17.2		$2p_{3/2}$	0.5	
	$1d_{5/2}$	1.3		$2s_{1/2}$	$1f_{7/2}$	0.2	0.2
	$1d_{3/2}$	1.9		$1d_{3/2}$	$2p_{3/2}$	0.1	0.1
	$0g_{7/2}$	0.9		$0g_{7/2}$	$0h_{11/2}$	0.1	0.1
$1p_{1/2}$	$1d_{5/2}$	1.9	4.9				
	$0g_{7/2}$	3.0					
$0g_{9/2}$	$0f_{5/2}$	0.7	5.8	$0h_{11/2}$	$0g_{9/2}$	3.1	13.0
	$1p_{3/2}$	5.1			$1d_{5/2}$	9.8	
$1d_{5/2}$	$0f_{5/2}$	0.4	2.2		$0g_{7/2}$	0.1	
	$1p_{3/2}$	0.7		$1f_{7/2}$	$0g_{9/2}$	1.0	3.0
	$1p_{1/2}$	1.1			$1d_{5/2}$	1.7	
$2s_{1/2}$	$0f_{5/2}$	0.5	0.5		$2s_{1/2}$	0.2	
$1d_{3/2}$	$0f_{5/2}$	0.6	1.7		$1d_{3/2}$	0.1	
	$1p_{3/2}$	1.1		$2p_{3/2}$	$0g_{9/2}$	0.3	0.6
$0g_{7/2}$	$0f_{5/2}$	1.3	3.3		$1d_{5/2}$	0.2	
	$1p_{3/2}$	0.5			$1d_{3/2}$	0.1	
	$1p_{1/2}$	1.5					
Sum			41.6				58.7

[Ł.W. Iskra *et al.*, PLB **788**, 396 (2019)]



$\Delta j = \Delta l = 3$

Large model space!

$\Delta j = \Delta l = 3$

$\Delta j = \Delta l = 3$

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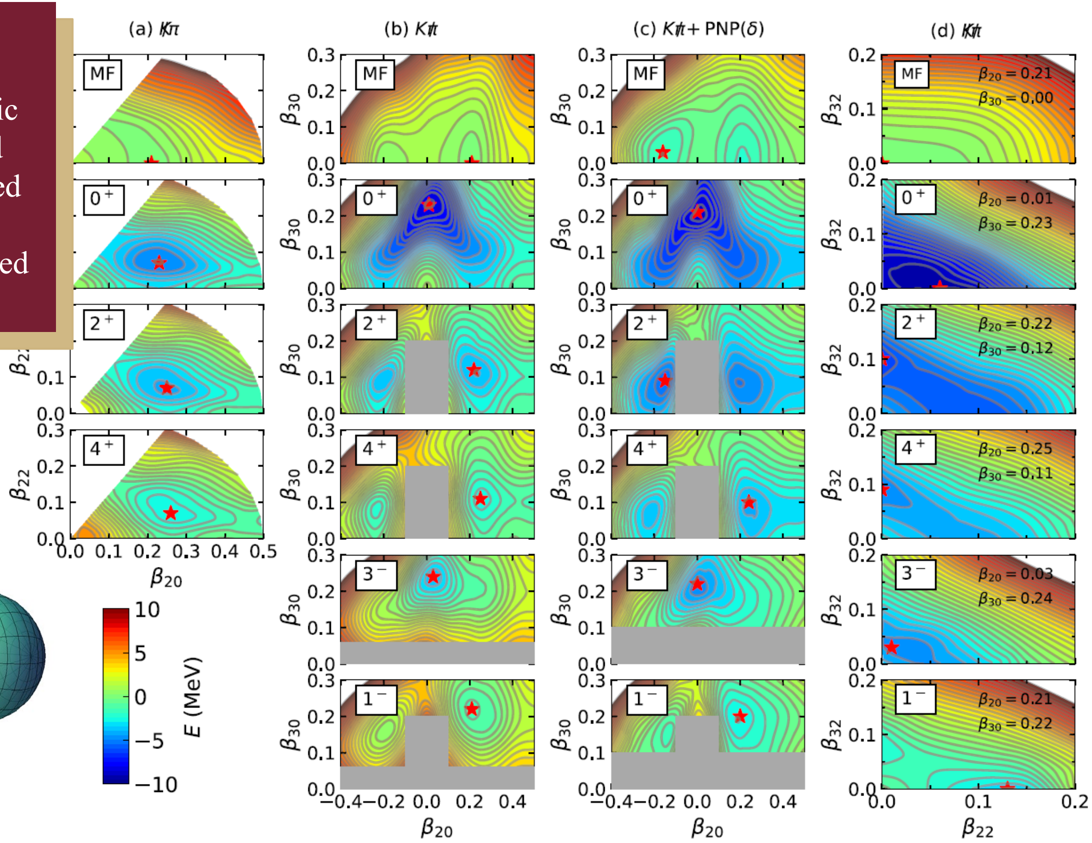
Ge-Zr mass region?

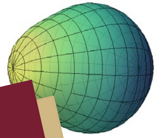
[Butler and Nazarewicz, RMP **68**, 349 (1996)]

The challenges? (The example of the $B(E3; 3_1^- \to 0_1^+) = 42(3)$ W.u. in ^{96}Zr)

Rong *et al.* performed projection-after-variation calculations for ^{96}Zr based on a multidimensionally constrained relativistic Hartree-Bogoliubov model. They showed that an octupole deformed shape is favored in energy after symmetry restoration, and that this phenomenon cannot be reproduced in the pure mean-field calculations.



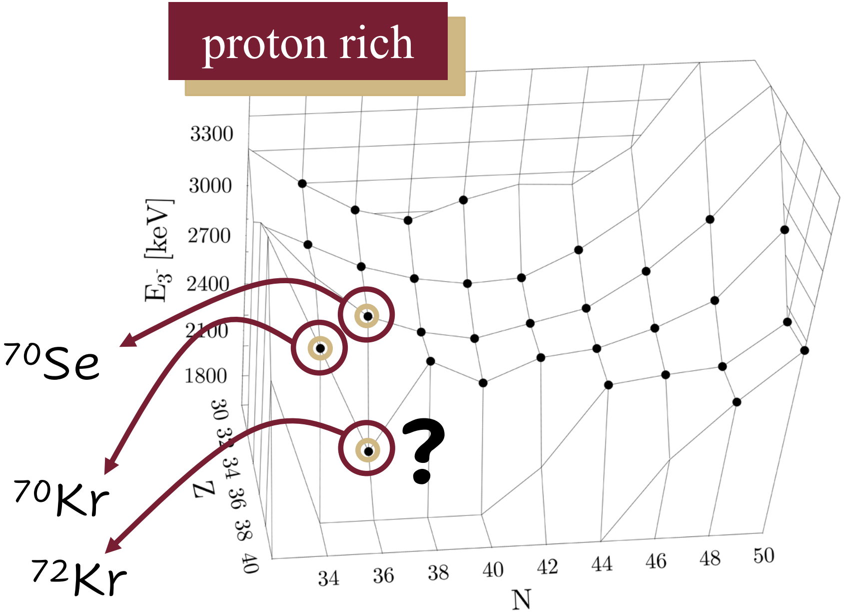
(b) non-axial but reflection symmetry with (β_{20}, β_{22}), (c) axial symmetry but reflection asymmetry with (β_{20}, β_{30}), and (d) non-axial and reflection asymmetry with $(\beta_{20}, \beta_{22}, \beta_{30}, \beta_{32})$.

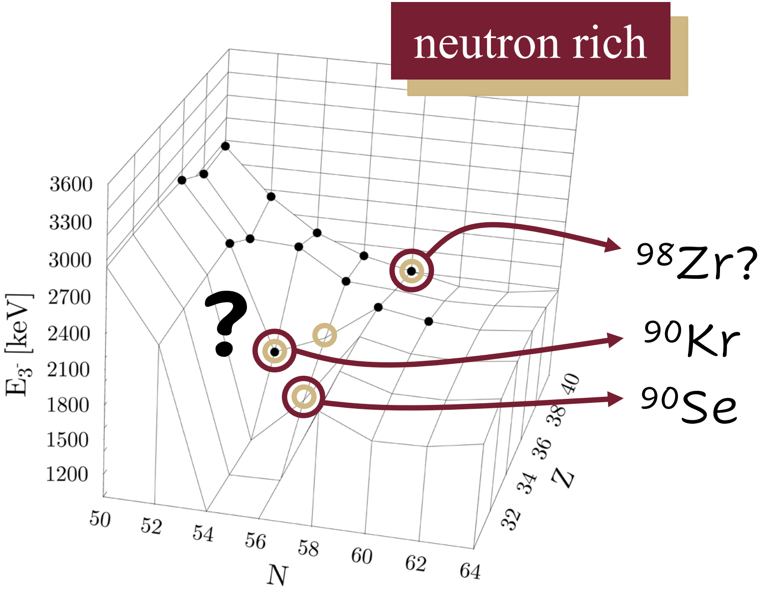


^{96}Zr could be octupole deformed?

[Rong *et al.*, PLB **840**, 137896 (2023)]

… and coming back to the Ge-Zr mass region





Should we also expect enhanced $B(E3) \sim 40$ W.u. strengths in the neutron-rich isotopes? Can we really claim that they could be octupole deformed? What about ^{90}Se (Z=34, N=56)? 5-kW (^{238}U) rate is 10^4 pps for ^{90}Se. That is feasible!

Octupole correlations in atomic nuclei

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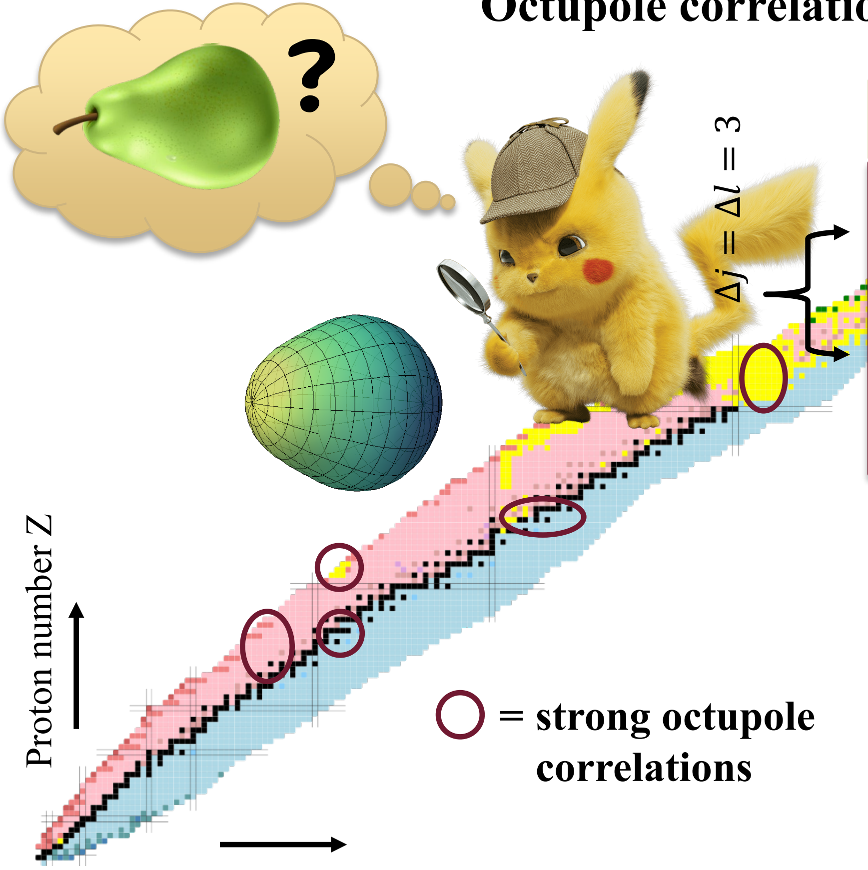
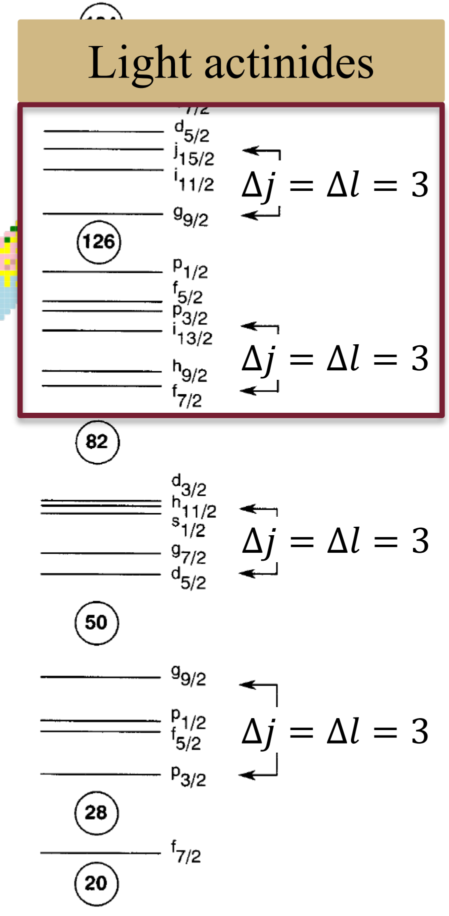


○ = **strong octupole correlations**

Light actinides

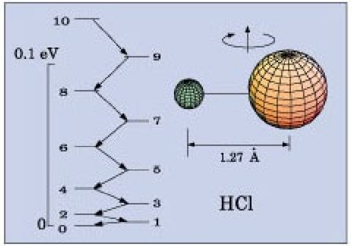


Expected at Z or N equal to 34, 56, 88, 134

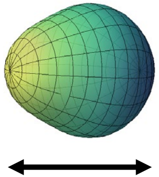
[Butler and Nazarewicz, RMP **68**, 349 (1996)]

^{224}Ra – The textbook example?

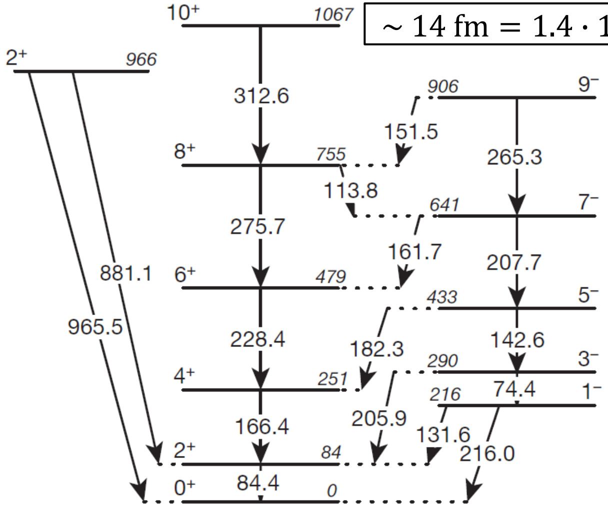
Appearance of alternating-parity band at low spin and low excitation energy

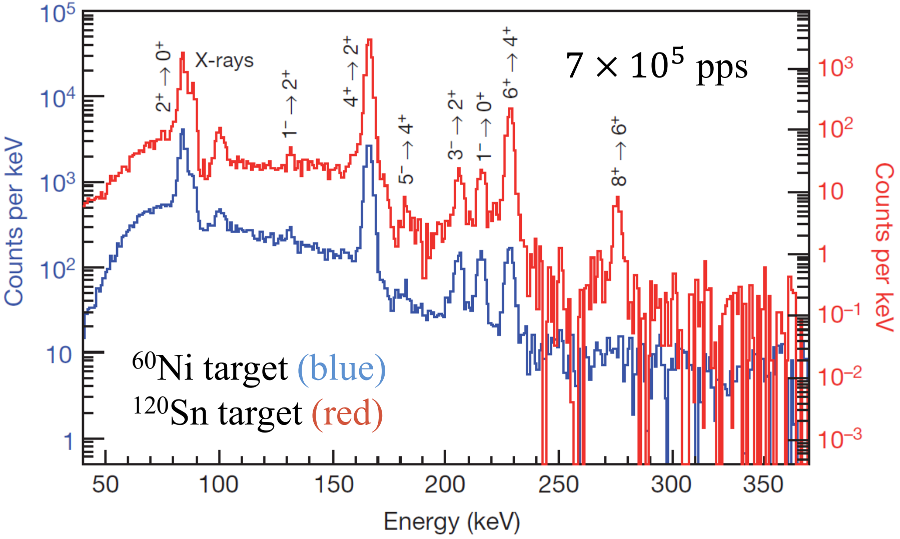


^{224}Ra



~ 14 fm = 1.4 · 10^{-4}Å

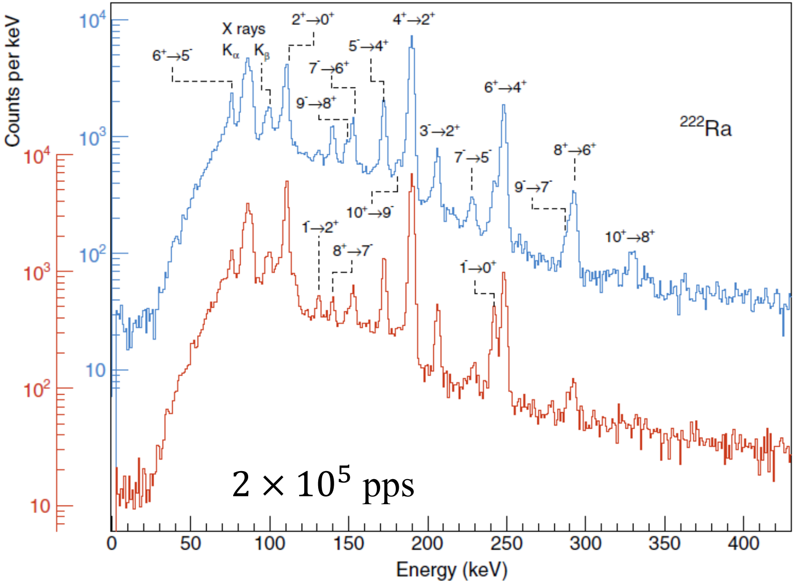




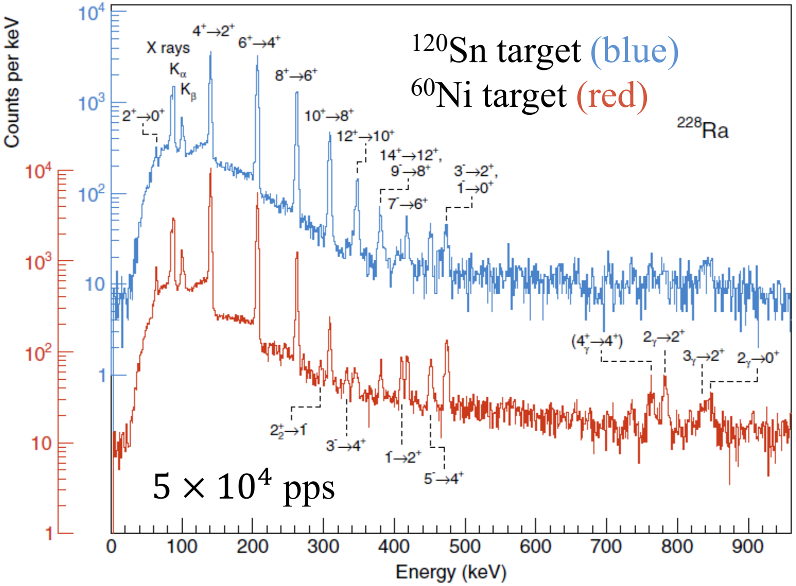
$$B(E3;3_1^- \to 0_1^+) = 42 \pm 3 \text{ W.u.}$$

[L.P. Gaffney *et al.*, Nature **497**, 199 (2013)]

Safe Coulomb excitation of ^{222,228}Ra at HIE-ISOLDE



2×10^5 pps



^{120}Sn target (blue)

^{60}Ni target (red)

5×10^4 pps

$B(E3; 3^-_1 \rightarrow 0^+_1) = 62 \pm 5$ W.u.

$B(E3; 3^-_1 \rightarrow 0^+_1) = 33 \pm 6$ W.u.

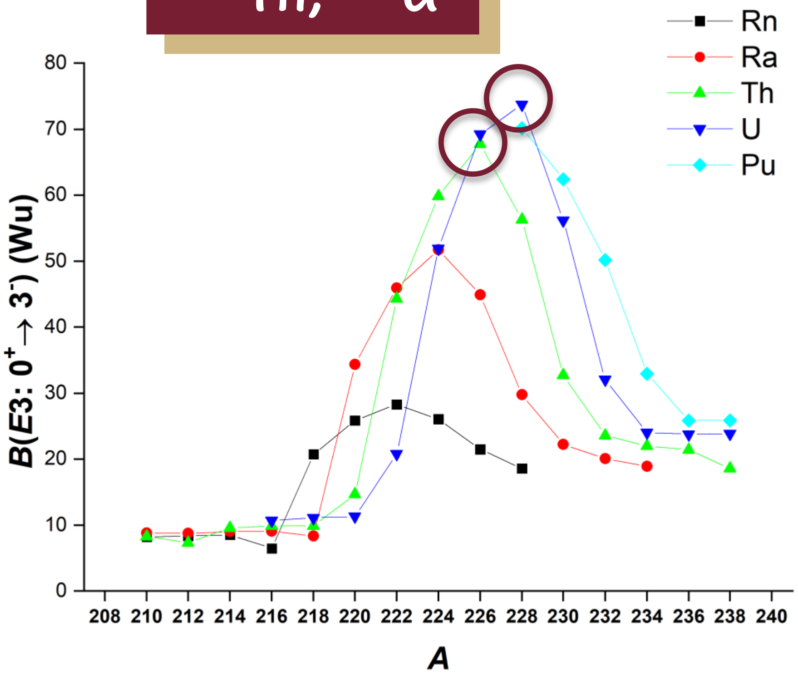
Statically octupole deformed

Octupole vibrational

[P.A. Butler *et al.*, Phys Rev Lett. **124**, 042503 (2020)]

What's new at FRIB?

^{226}Th, ^{228}U

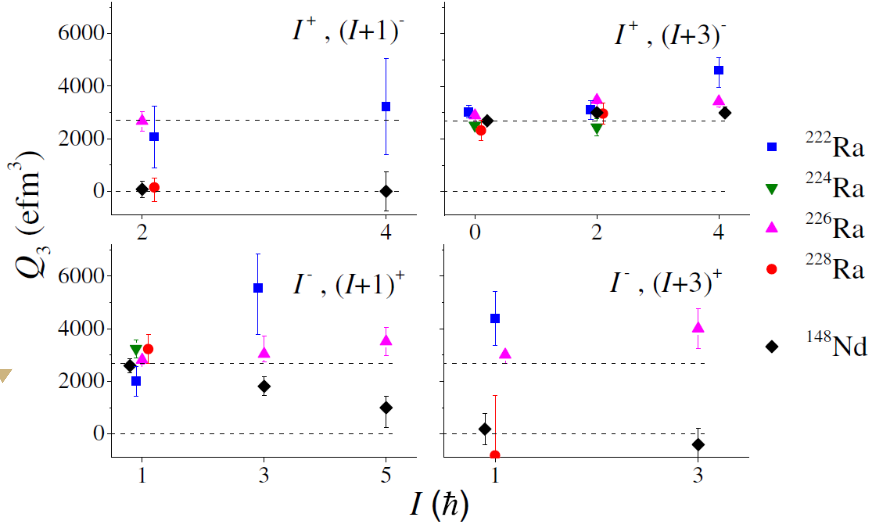


[L.M. Robledo and G.F. Bertsch, Phys. Rev. C **86**, 054306 (2012)]

Rates of 10^5 to 10^6 pps expected for reaccelerated beam experiments! Those are the rates previously available for $^{222\text{-}228}$Ra.

→ LoI has already been submitted to PAC1 for beam development.

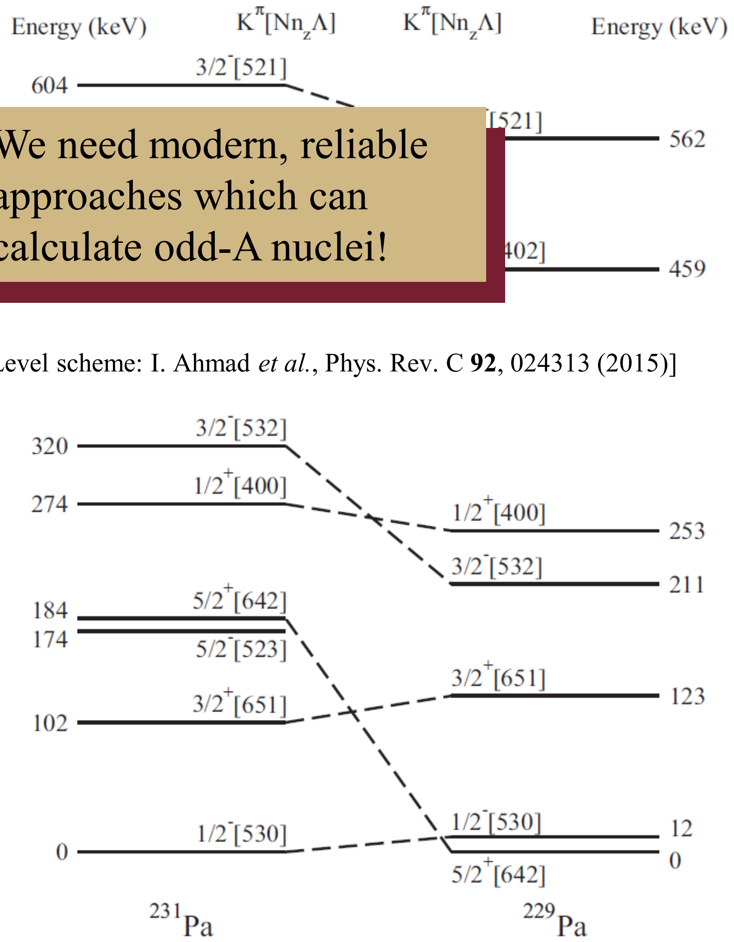
Electric octupole moments



What it takes!

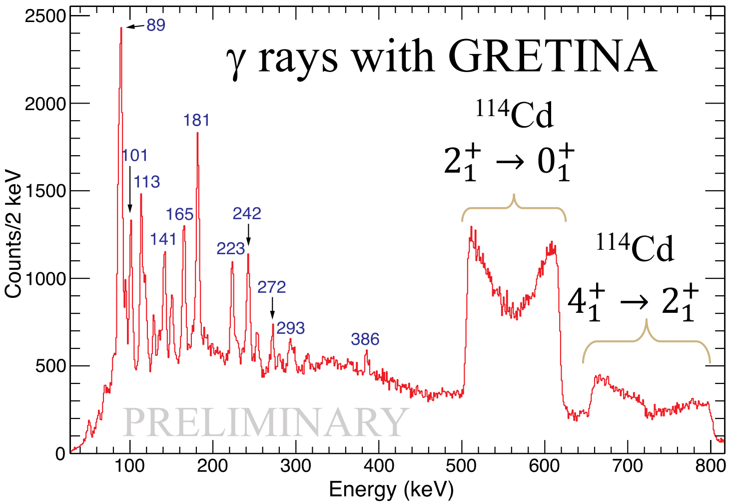
[P.A. Butler *et al.*, Phys. Rev. Lett. **124**, 042503 (2020)]

Octupole collectivity and EDM? ^{225}Ra and ^{229}Pa – The holy grails



We need modern, reliable approaches which can calculate odd-A nuclei!

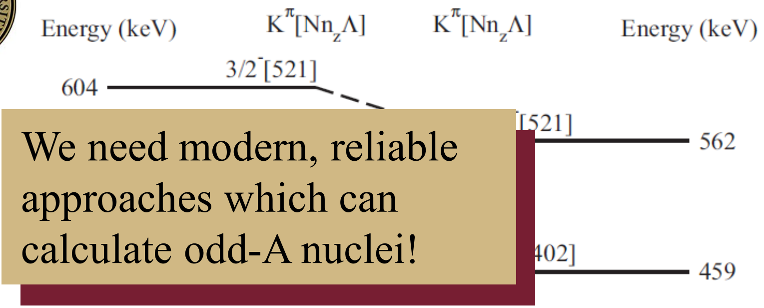
[Level scheme: I. Ahmad *et al.*, Phys. Rev. C **92**, 024313 (2015)]



Highlighted experiment: Coulomb excitation of ^{223}Ra with GRETINA and CHICO-2 at ANL to test whether ^{223}Ra is statically octupole deformed (parity doublet ΔE=50 keV). Experiment used 400 ng $Ra(NO_3)_2$ target (70% enriched sample; dose rate of 60 mR/hr). Experiment happened during last GRETINA campaign. Analysis is ongoing.

[R.V.F. Janssens and A.D. Ayangeakaa, private communication]

Octupole collectivity and EDM? ^{225}Ra and ^{229}Pa – The holy grails



We need modern, reliable approaches which can calculate odd-A nuclei!

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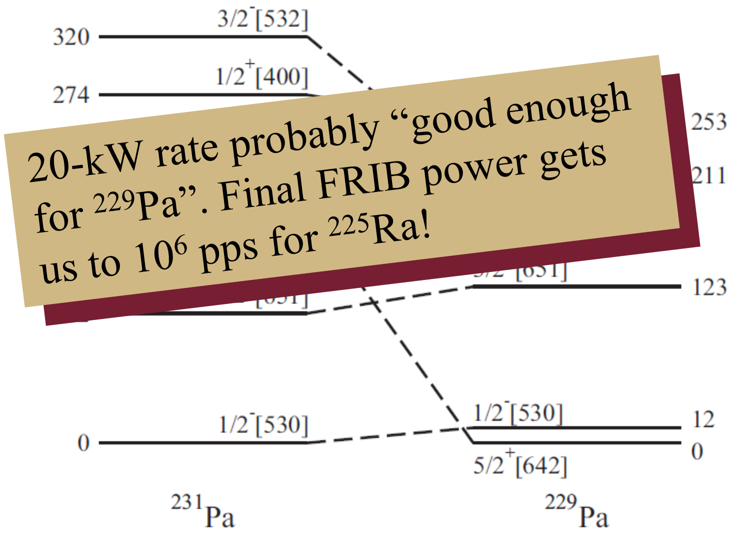
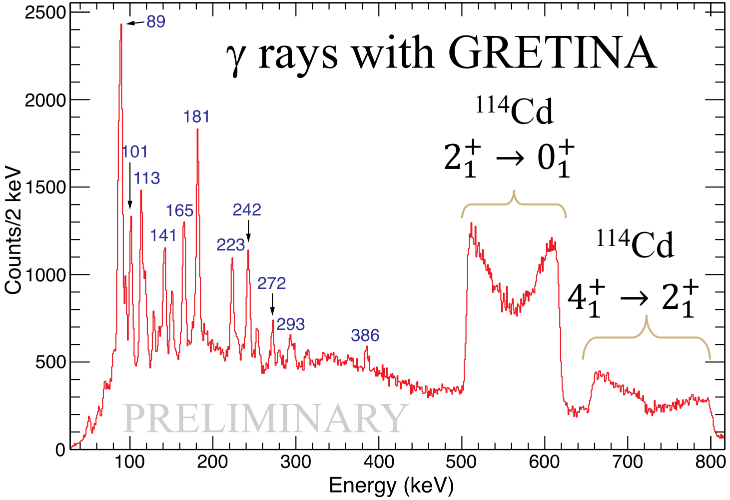


20-kW rate probably "good enough for ^{229}Pa". Final FRIB power gets us to 10^6 pps for ^{225}Ra!



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[R.V.F. Janssens and A.D. Ayangeakaa, private communication]

Octupole correlations in atomic nuclei

HOT TOPIC

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

GOING PEAR-SHAPED

Exotic radium-224 atomic nuclei seen at CERN

PAGES 190 & 199

BIOMEDICINE

STAYING IN TOUCH

Prosthetic limbs with sensory feedback

PAGE 176

CIVIL CONFLICT

HEATED ARGUMENT

Researchers at odds over climate–violence link

PAGE 179

NEUROSCIENCE

THE AGE OF THE BRAIN

Inflammation links ageing to the hypothalamus

PAGES 197 & 211

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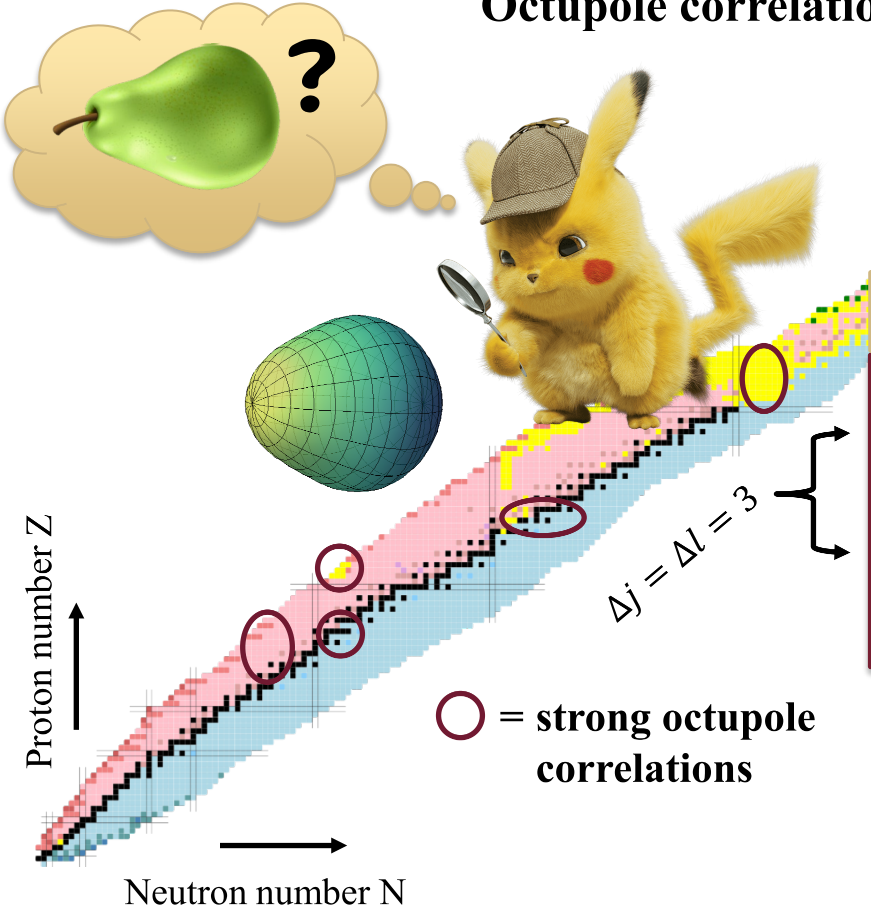
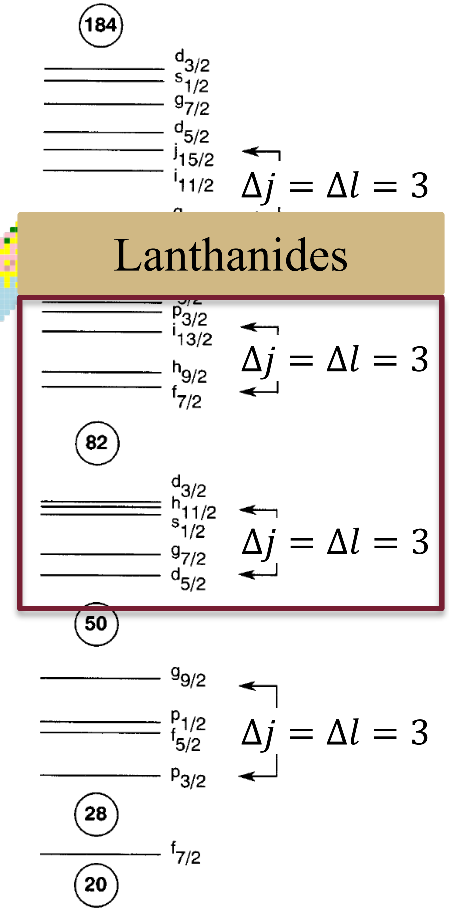
9 May 2013 £10

Vol. 497, No. 7448

10 years ago and still going!



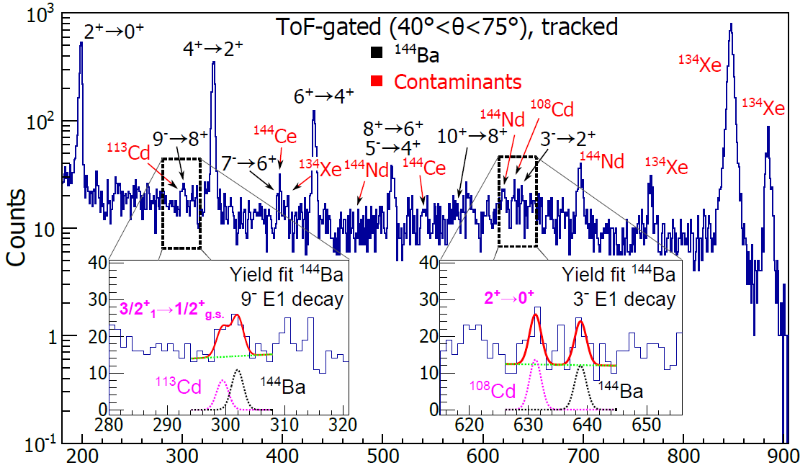
= strong octupole correlations

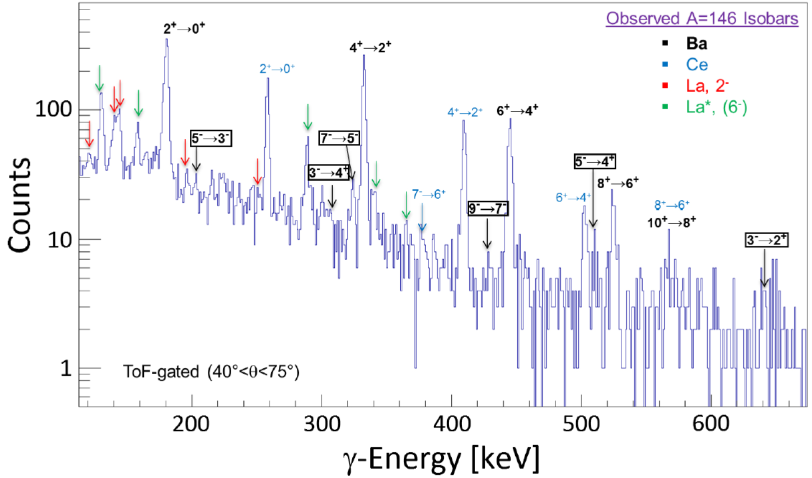


Expected at Z or N equal to 34, 56, 88, 134.

[Butler and Nazarewicz, RMP **68**, 349 (1996)]

^{144,146}Ba – What we know from ANL experiments





$B(E3;3_1^- \rightarrow 0_1^+) = 48^{+25}_{-34}$ W.u. for ^{144}Ba

$B(E3;3_1^- \rightarrow 0_1^+) = 48^{+21}_{-29}$ W.u. for ^{146}Ba

[B. Bucher *et al.*, PRL **116**, 112503 (2016) & PRL **118**, 152504 (2017)]

Rate at ANL was less than 10^4 pps.

→ Projected 400-kW rate is more than 10^6 pps for ^{144}Ba and around 10^5 pps for ^{146}Ba.

These higher rates will then allow to perform meaningful safe CoulEx experiments for ^{146,148}Ce (200-kW, too).

^{144,146}Ba – What we know from ANL experiments

^{146}Ba

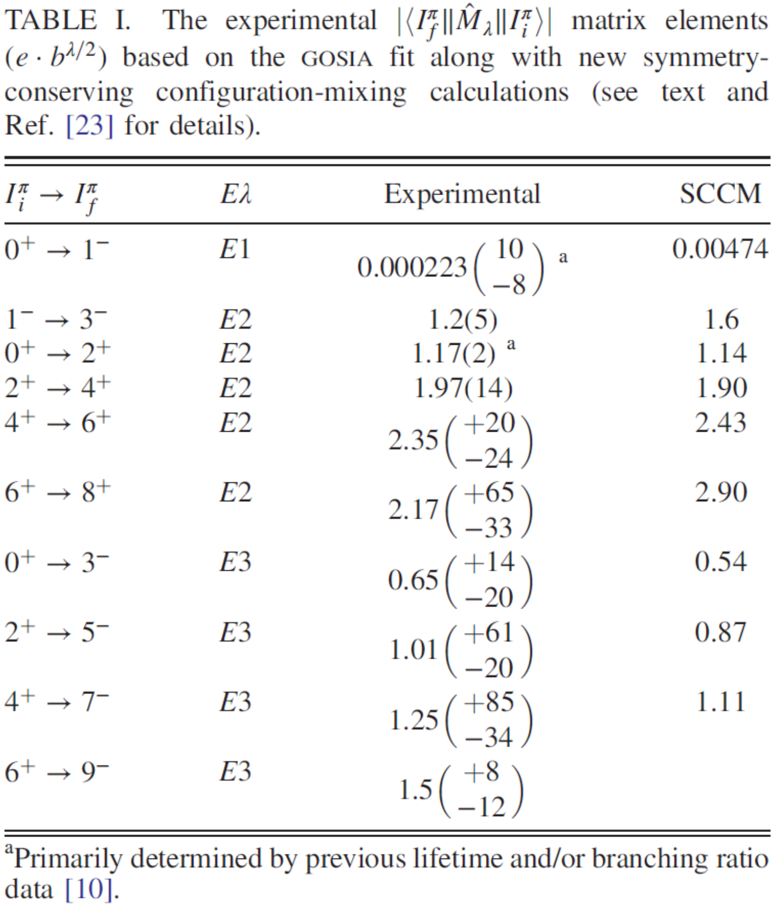


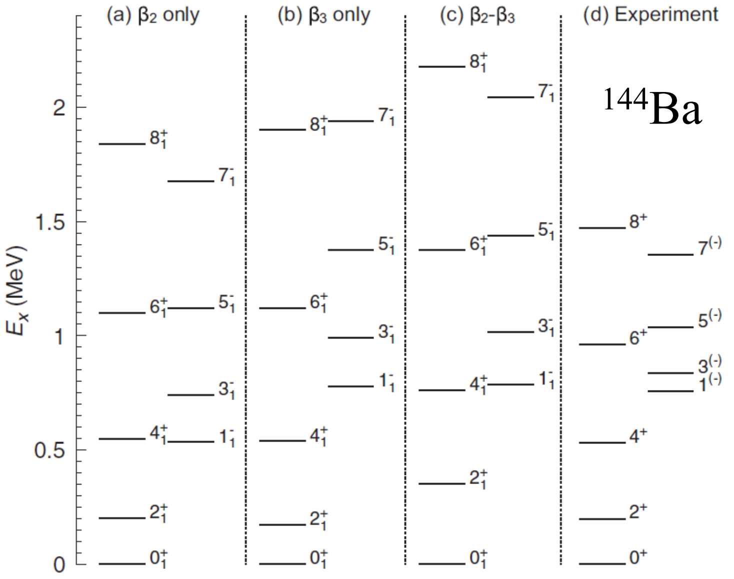
TABLE I. The experimental $|\langle I_f^\pi \| \hat{M}_\lambda \| I_i^\pi \rangle|$ matrix elements ($e \cdot b^{\lambda/2}$) based on the GOSIA fit along with new symmetry-conserving configuration-mixing calculations (see text and Ref. [23] for details).

$I_i^\pi \to I_f^\pi$	$E\lambda$	Experimental	SCCM
$0^+ \to 1^-$	$E1$	$0.000223\binom{10}{-8}$ [a]	0.00474
$1^- \to 3^-$	$E2$	1.2(5)	1.6
$0^+ \to 2^+$	$E2$	1.17(2) [a]	1.14
$2^+ \to 4^+$	$E2$	1.97(14)	1.90
$4^+ \to 6^+$	$E2$	$2.35\binom{+20}{-24}$	2.43
$6^+ \to 8^+$	$E2$	$2.17\binom{+65}{-33}$	2.90
$0^+ \to 3^-$	$E3$	$0.65\binom{+14}{-20}$	0.54
$2^+ \to 5^-$	$E3$	$1.01\binom{+61}{-20}$	0.87
$4^+ \to 7^-$	$E3$	$1.25\binom{+85}{-34}$	1.11
$6^+ \to 9^-$	$E3$	$1.5\binom{+8}{-12}$	

[a] Primarily determined by previous lifetime and/or branching ratio data [10].

$$B(E3; 3_1^- \to 0_1^+) = 48^{+25}_{-34}\ \text{W.u. for } ^{144}\text{Ba}$$
$$B(E3; 3_1^- \to 0_1^+) = 48^{+21}_{-29}\ \text{W.u. for } ^{146}\text{Ba}$$

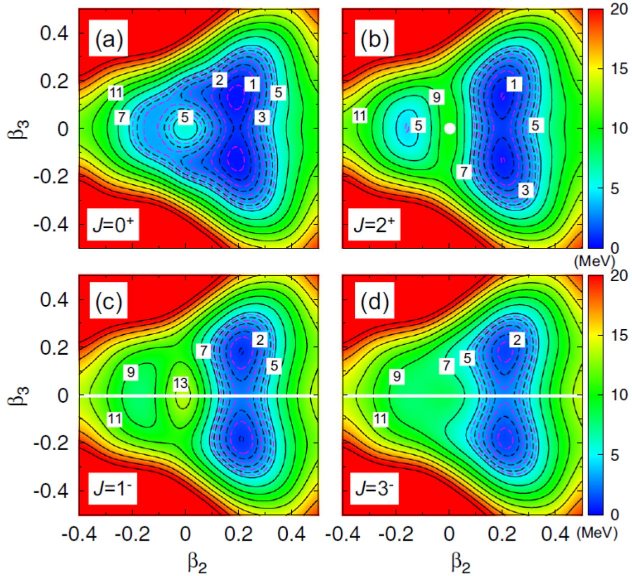
[B. Bucher *et al.*, PRL **116**, 112503 (2016) & PRL **118**, 152504 (2017)]



[SCCM: R.N. Bernard *et al.*, PRC **93**, 061302(R) (2016)]

^{144,146}Ba – What we know from ANL experiments

Beyond mean field level



“It is important to point out that a fully quantitative agreement with the experimental data cannot be expected within the present framework because neither triaxial (*K* mixing) nor time-reversal symmetry breaking (cranking) intrinsic wave functions are considered. As a consequence, the ground state is better explored variationally than the excited states and gains more correlation energy producing the stretching of the spectrum. Including triaxial cranking intrinsic states would thus produce a compression of the calculated spectrum, and a better quantitative agreement with the experiments.”

$$B(E3;3_1^- \rightarrow 0_1^+) = 48^{+25}_{-34}\ \text{W.u. for } ^{144}\text{Ba}$$
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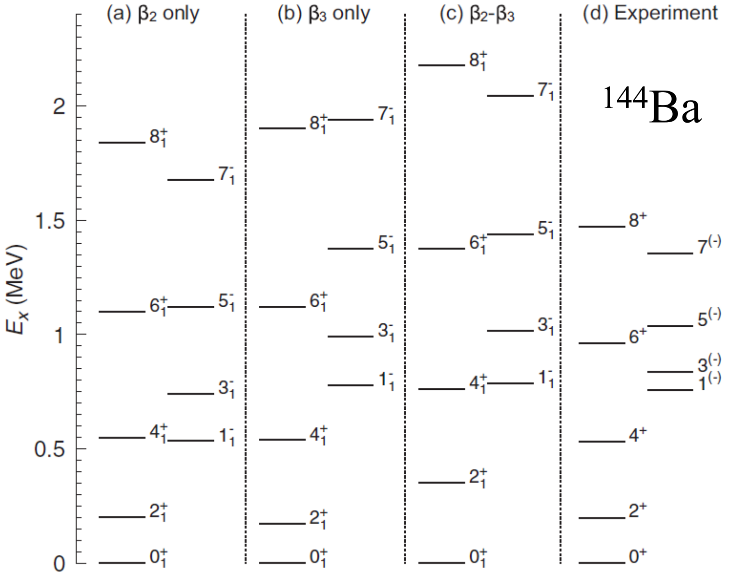
[B. Bucher *et al.*, PRL **116**, 112503 (2016) & PRL **118**, 152504 (2017)]



[SCCM: R.N. Bernard *et al.*, PRC **93**, 061302(R) (2016)]

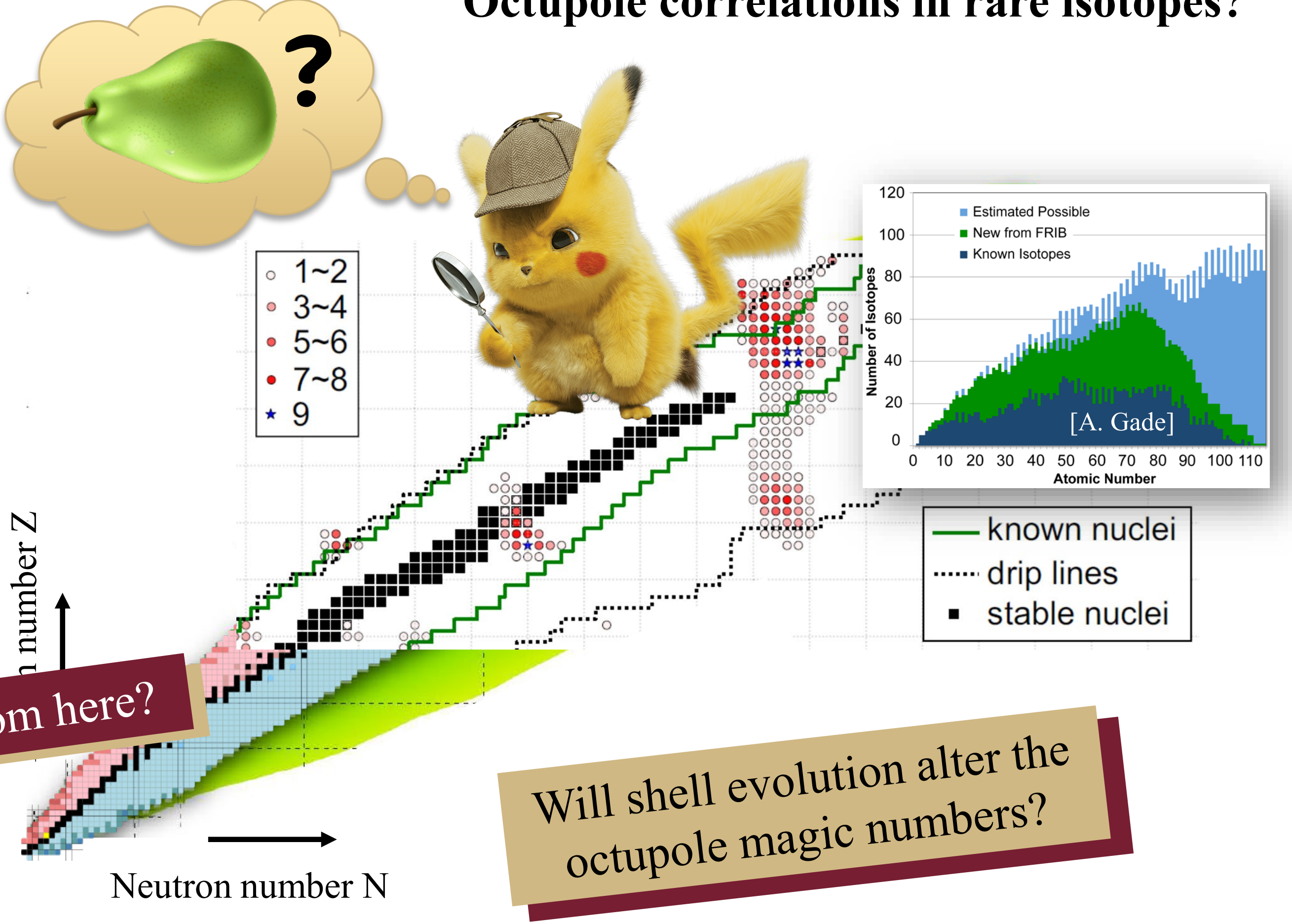
An open question?

Octupole correlations in rare isotopes?

HOT TOPIC

10 years ago and

where from here?



[A. Gade]

Will shell evolution alter the octupole magic numbers?

FLORIDA STATE
UNIVERSITY

Back-up

FLORIDA STATE
UNIVERSITY

Octupole (NSCL)

Acknowledgments

Thank you very much to the GRETINA project management and team at LBNL.

M. Spieker, S. Baker, A.L. Conley, D. Houlihan, B. Kelly, P.D. Cottle, and K.W. Kemper

L.A. Riley

S. Agbemava, D. Bazin, S. Biswas, P.J. Farris, A. Gade, T. Ginter, S. Giraud, J. Li, W. Nazarewicz, S. Noji, J. Pereira, M. Smith, D. Weisshaar, and R.G.T. Zegers

K. Nomura

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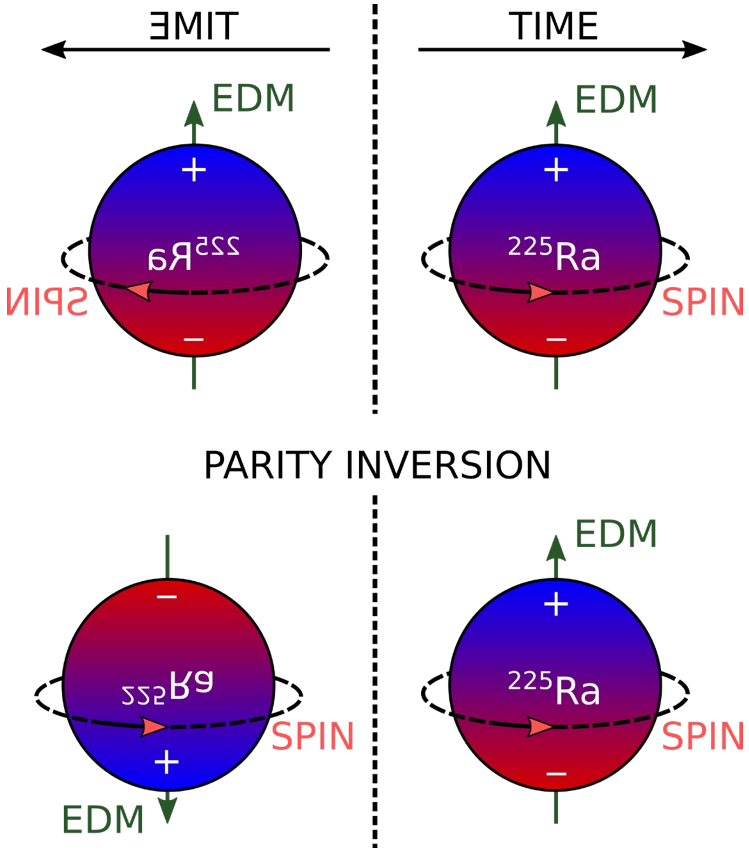
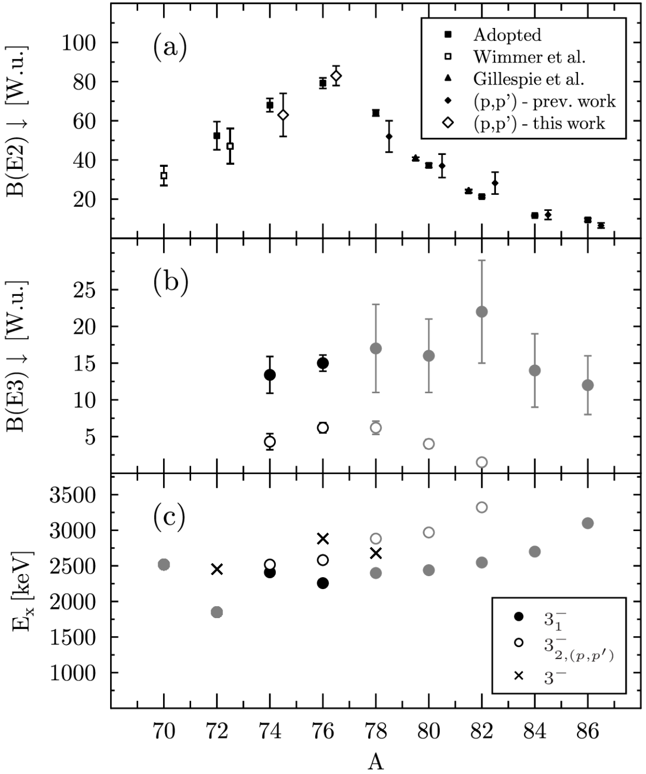
Electric Dipole Moment (EDM)



Systematics in the Kr isotopes with $N \leq 50$

- **Direct observable:** (p,p') cross sections.
- (p,p') cross sections allow model-dependent determination of deformation parameters β_λ.
  $\rightarrow B(E\lambda; 0_1^+ \rightarrow J_f^\pi)$ can be calculated.



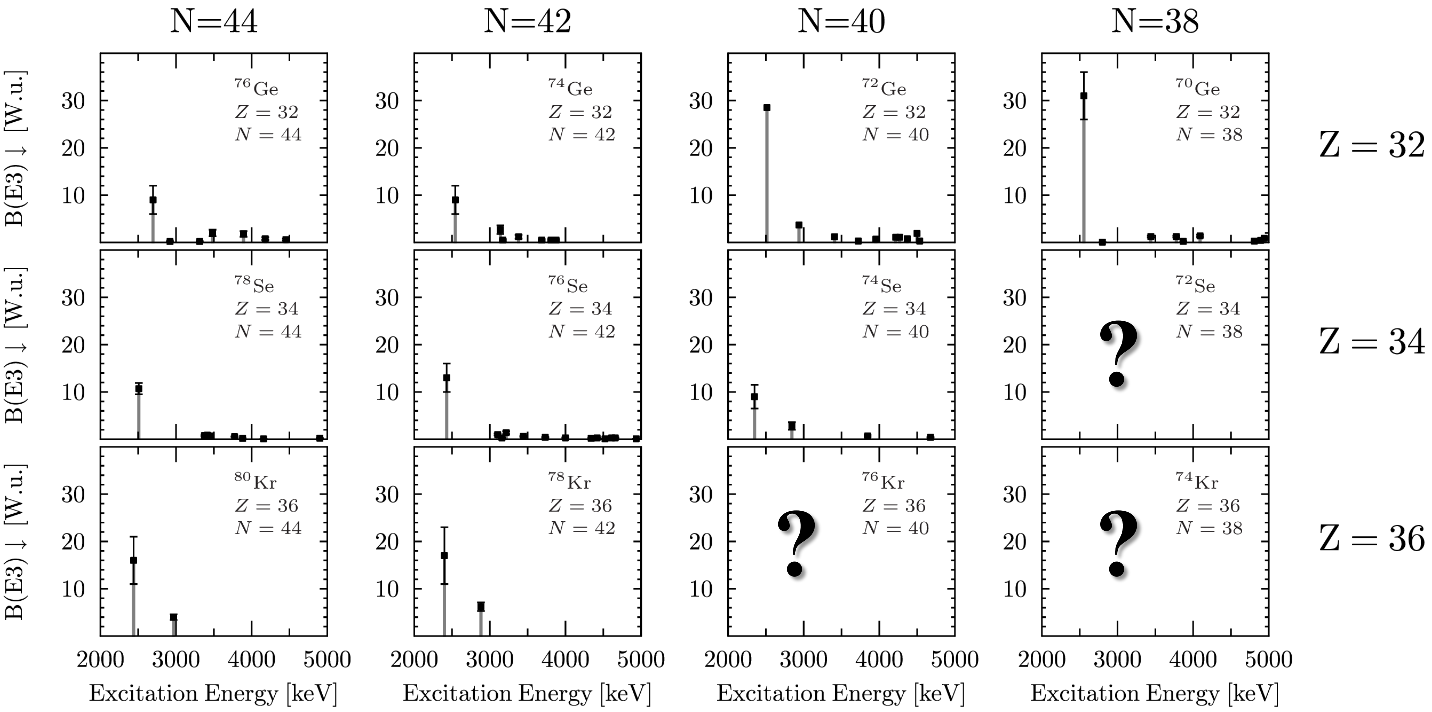
[MS *et al.*, PRC **106**, 054305 (2022)] and other data from: [Wimmer *et al.*, EPJA **56**, 159 (2020); Wimmer *et al.*, PRL **126**, 072501 (2021); Pritychenko *et al.*, Nuclear Data Sheets **120**, 112 (2014); Gillespie *et al.*, PRC **104**, 044313 (2021); Matsuki *et al.*, PLB **113**, 21 (1982)]

Disclaimer

Results:

- Excellent agreement of $B(E2; 2_1^+ \rightarrow 0_1^+)$ to values determined with other probes.
- $B(E3; 3_1^- \rightarrow 0_1^+)$ strengths fit well into systematics.
- $B\left(E3; 3_{2,(p,p')}^- \rightarrow 0_1^+\right)$ strengths, even though assigned tentatively in ^{74,76}Kr, show that strength remains fragmented.
  $\rightarrow$ Fragmentation appears nontrivial as 2nd 3^- is not necessarily 2nd strongest fragment.

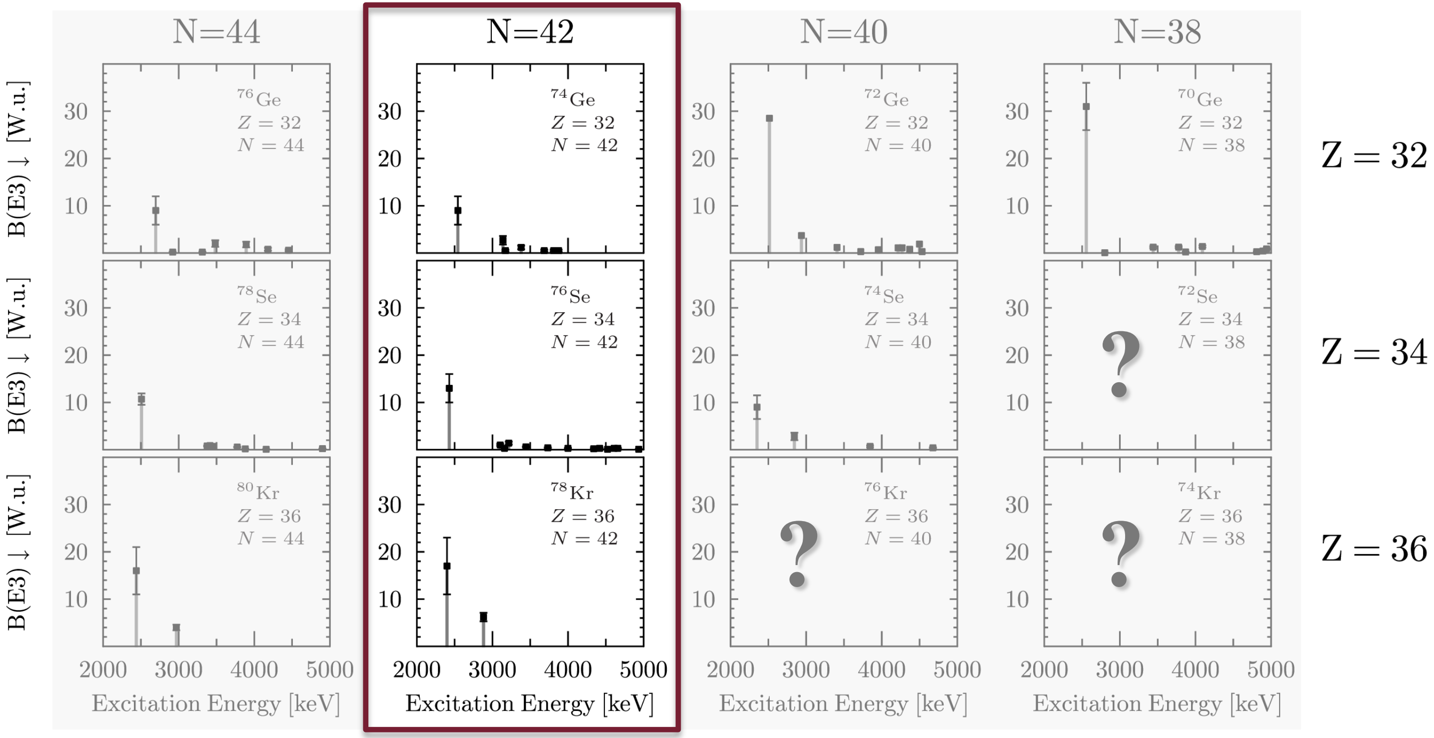
B(E3) systematics in Ge-Kr mass region



$B(E3; 3^-_{\mathrm{LEOS}} \rightarrow 0^+_1)$ strength is fragmented in Ge-Kr mass region.

[Rosier *et al.*, NPA **453**, 389 (1986); Schürmann *et al.*, NPA **475**, 361 (1987); Ogino, PRC **33**, 71 (1986); Matsuki *et al.*, PLB **113**, 21 (1982)]

B(E3) systematics in Ge-Kr mass region

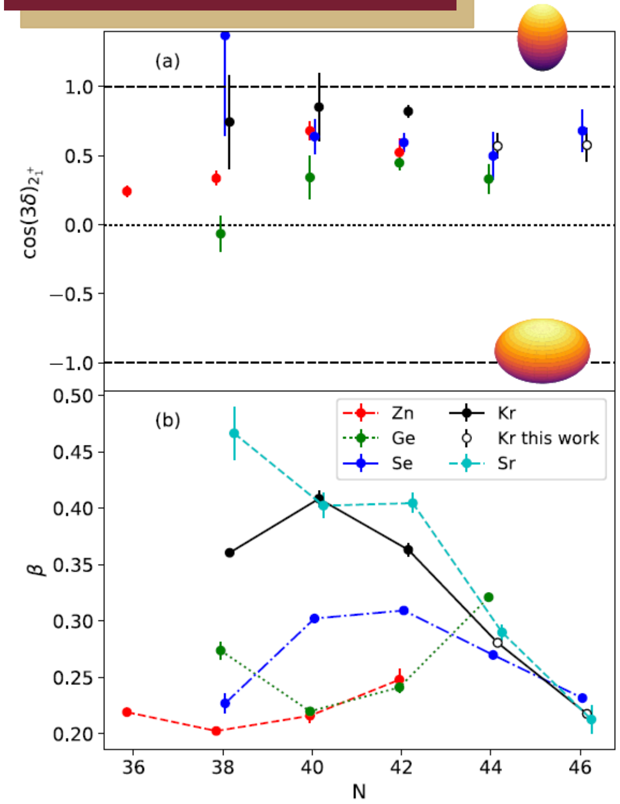


Strength fragmentation different but most of the strength in $B(E3; 3_1^- \rightarrow 0_1^+)$.

[Rosier *et al.*, NPA **453**, 389 (1986); Schürmann *et al.*, NPA **475**, 361 (1987); Ogino, PRC **33**, 71 (1986); Matsuki *et al.*, PLB **113**, 21 (1982)]

Prolate-oblate shape transition and triaxiality in Ge-Kr mass region

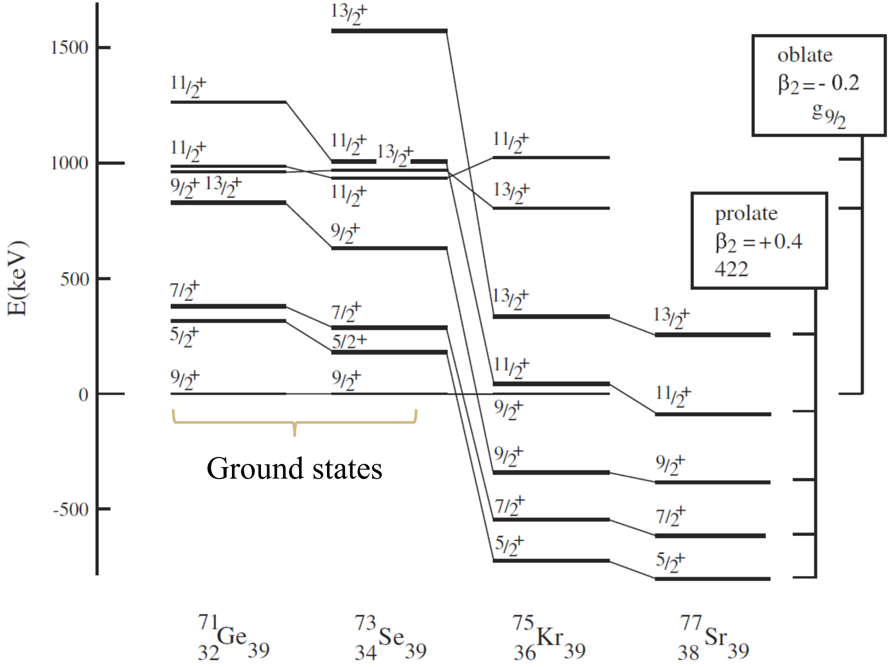
From safe CoulEx



[Gillespie *et al.*, PRC **104**, 044313 (2021)]

Shape transition in N = 39 isotones

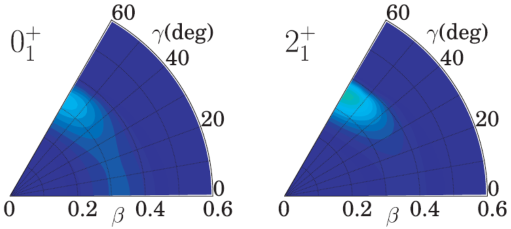
Pairing delays shape transition in even-A isotopes?



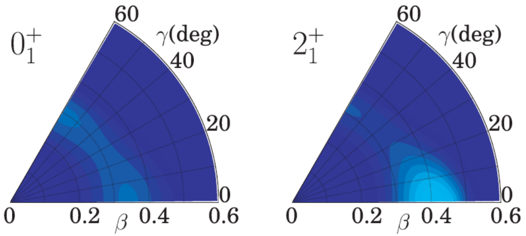
[Heyde and Wood, RMP **83**, 1467 (2011)]

Prolate-oblate shape transition and triaxiality in Ge-Kr mass region

^{70}Se (CHFB+LQRPA)

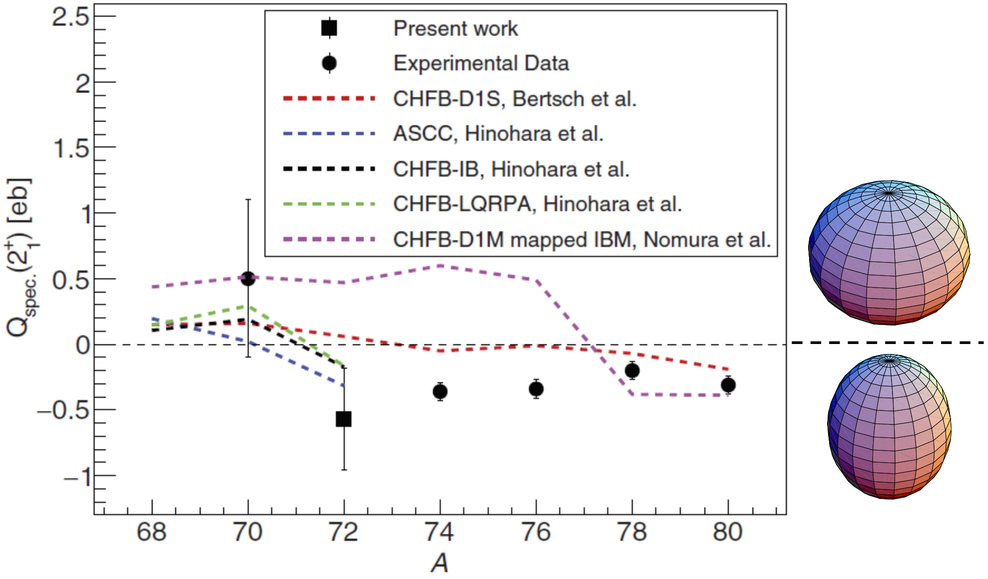


^{72}Se (CHFB+LQRPA)



[N. Hinohara *et al.*, PRC **82**, 064313 (2010)]

Shape transition in Se isotopes
(spectroscopic quadrupole moment)



[J. Henderson *et al.*, PRL **121**, 082502 (2018)]

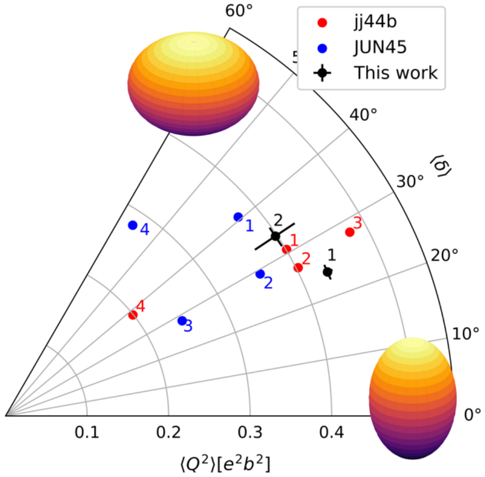
^{72}Se from safe CoulEx @ ReA

Prolate-oblate shape transition and triaxiality in Ge-Kr mass region

^{76}Se from safe CoulEx @ ReA

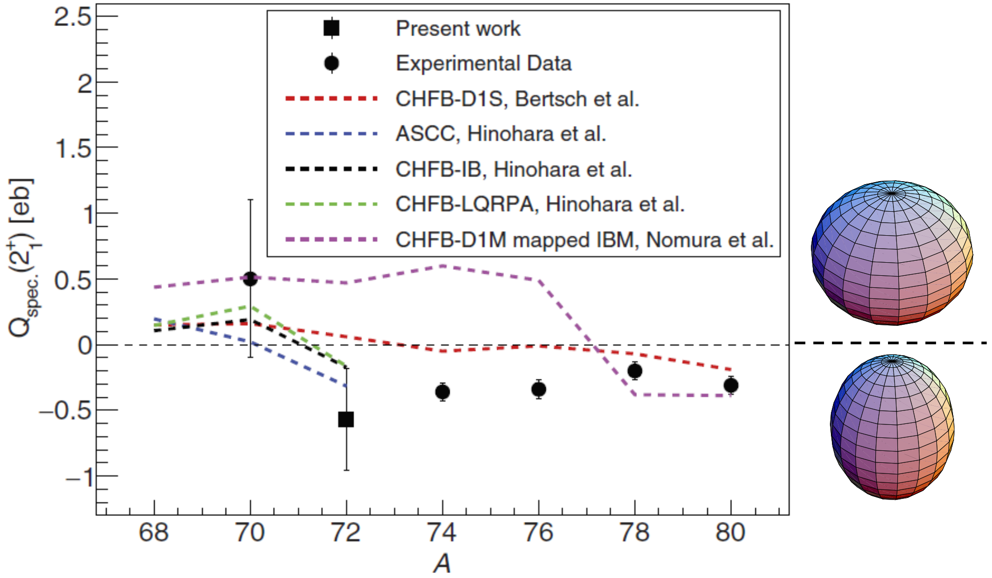
Triaxiality in ^{76}Se

(experiment and shell model)



[J. Henderson, C.Y. Wu, *et al.*, PRC **99**, 054313 (2019)]

Shape transition in Se isotopes
(spectroscopic quadrupole moment)

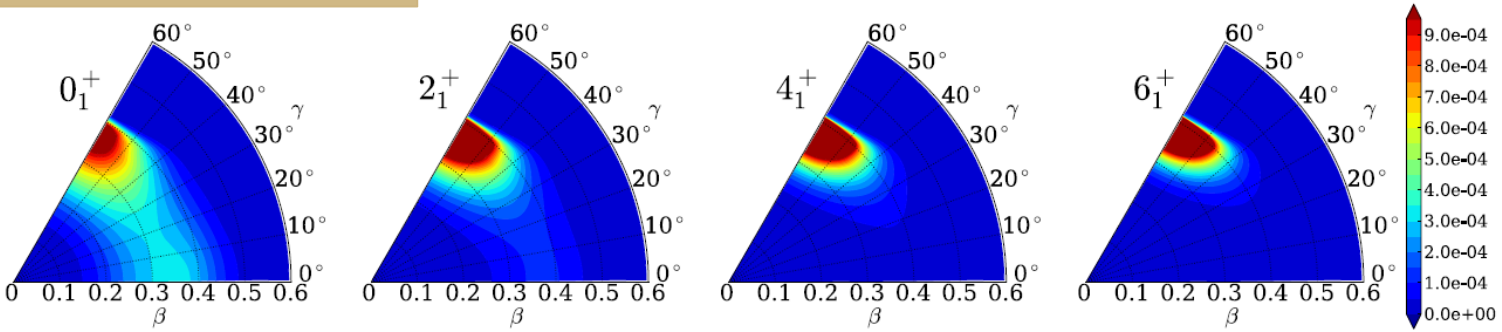


[J. Henderson *et al.*, PRL **121**, 082502 (2018)]

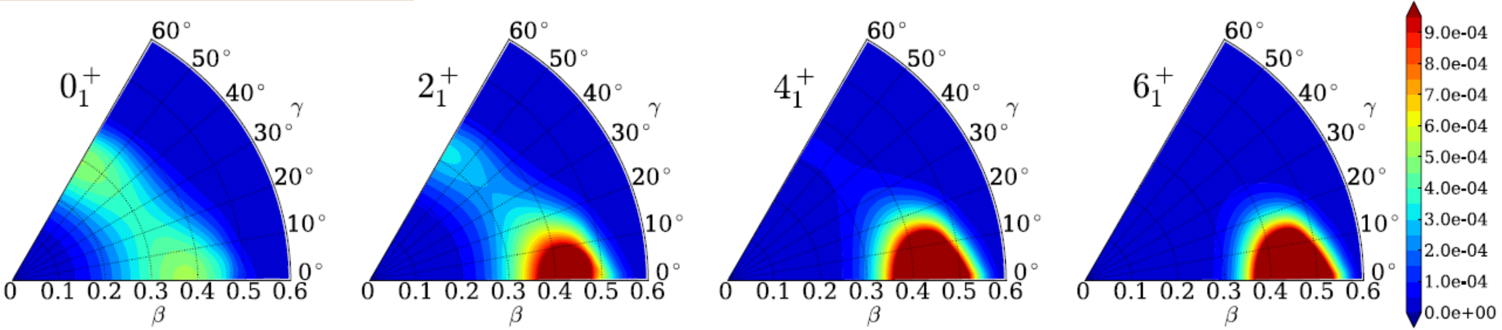
^{72}Se from safe CoulEx @ ReA

Prolate-oblate shape transition and triaxiality in Kr isotopes

^{72}Kr (CHFB+LQRPA)



^{74}Kr (CHFB+LQRPA)

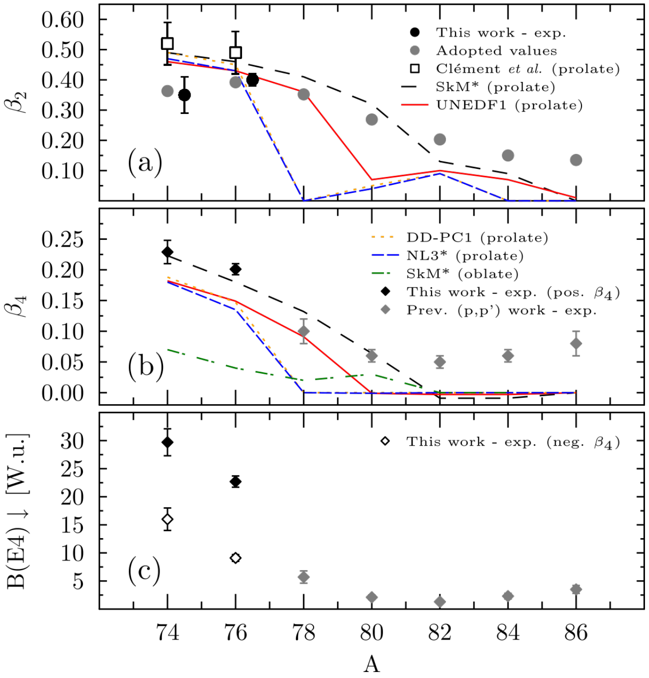


[K. Sato and N. Hinohara, Nuclear Physics A **849**, 53 (2011)]

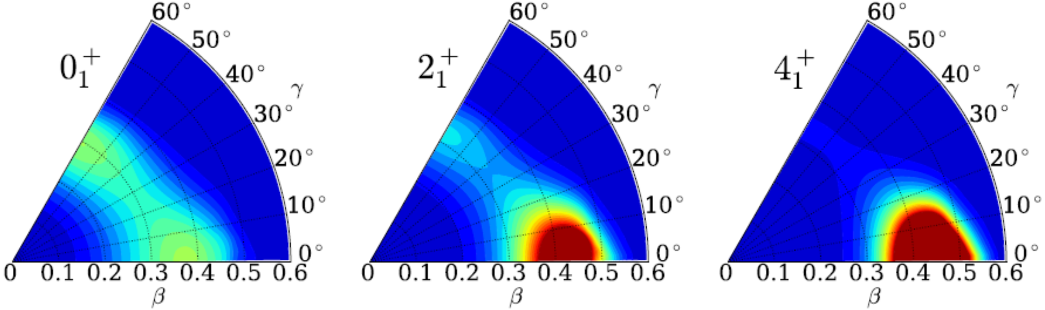
Prolate-oblate shape transition in Kr isotopes

^{74,76}Kr @ NSCL

[In collaboration with S. Agbemava and W. Nazarewicz]



^{74}Kr (CHFB+LQRPA)



[K. Sato and N. Hinohara, Nuclear Physics A **849**, 53 (2011)]

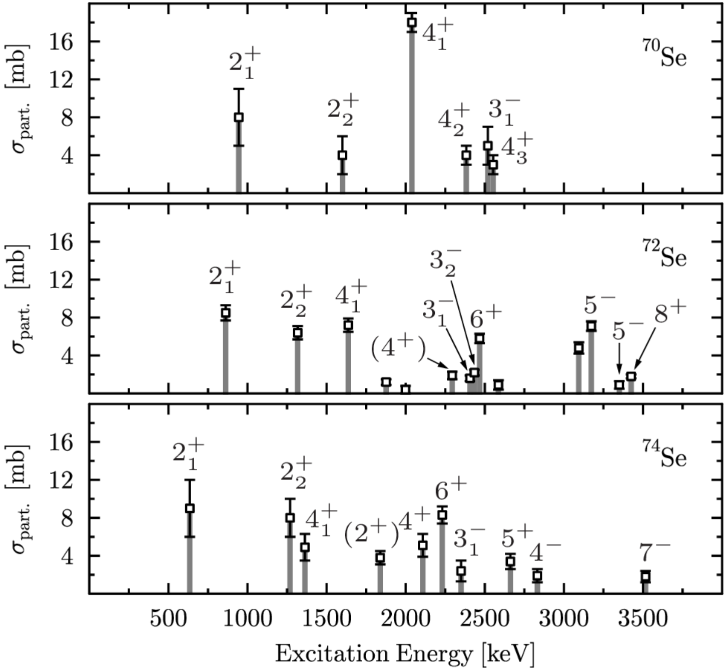
- We were able to determine β_2 and β_4 from our inverse kinematics (p,p') experiments.
- Mixing between oblate and prolate configuration influences $B(E2; 2_1^+ \rightarrow 0_1^+)$ but appears to have only minor influence on $B(E4; 4_1^+ \rightarrow 0_1^+)$ strength. The latter is linked to prolate configuration.

→ In agreement with CHFB+LQRPA predictions?

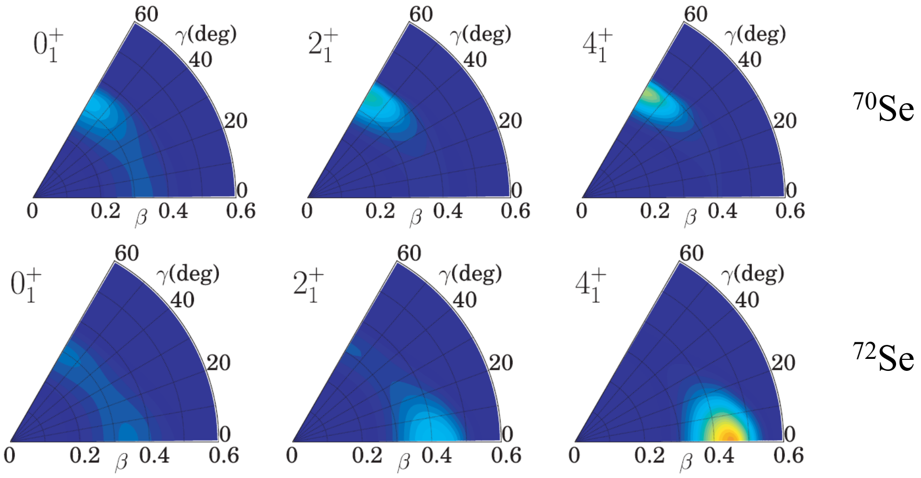
[Data from MS *et al.*, accepted for publication in PLB and E. Clement *et al.*, Phys. Rev. C **75**, 054313 (2007)]

Understanding nuclear structure and octupole collectivity in Ge-Zr mass regions

One-proton knockout reactions



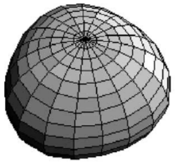
^{70}Se: K. Wimmer *et al.*, PLB **785**, 441 (2018)
^{72,74}Se: MS *et al.*, to be published



[N. Hinohara *et al.*, PRC **82**, 064313 (2010)]

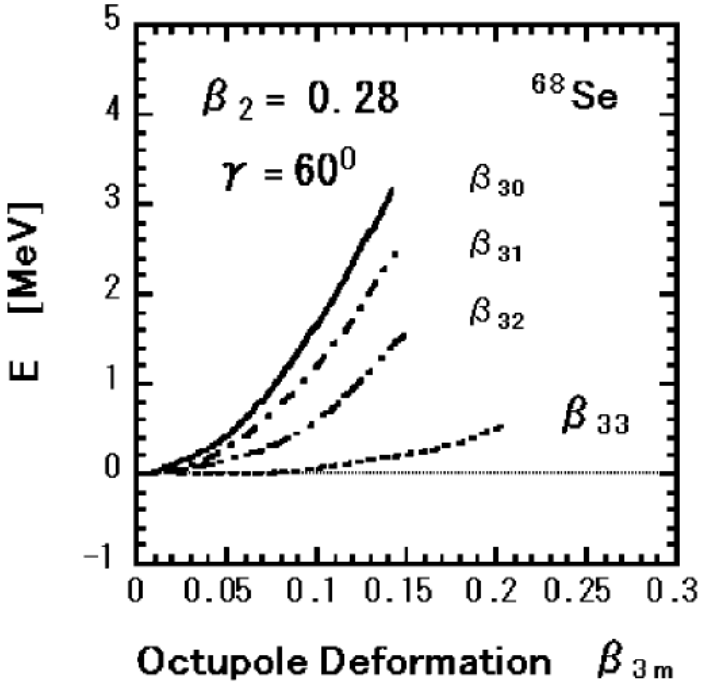
Is sudden increase of the partial (exclusive) cross section for the 4_1^+ state from ^{72}Se to ^{70}Se caused by a structure change?

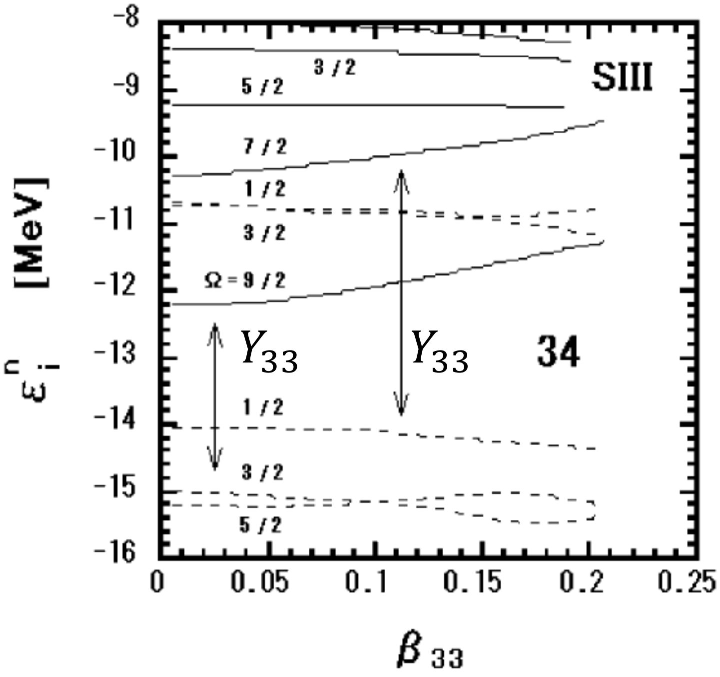
Triangular octupole coupling Y_{33} in ^{68}Se



Triangular octupole shape superimposed on oblate-deformed ground state

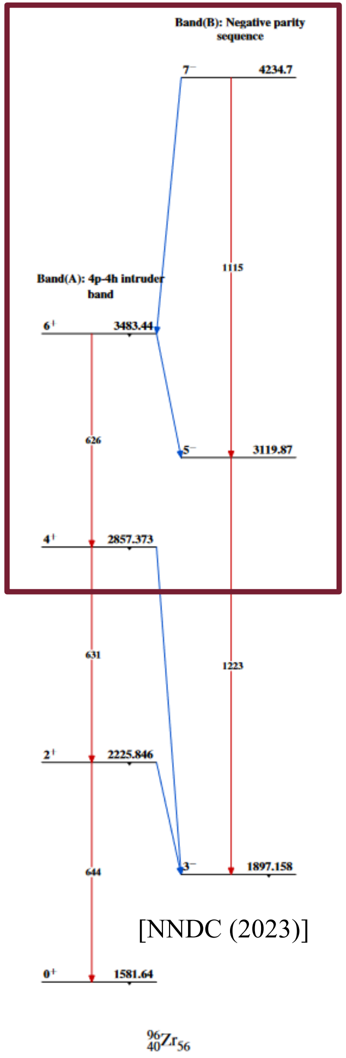
Qualitatively similar results obtained with three different Skyrme interactions.





[Yamagami *et al.*, NPA **693**, 579 (2001)]

Any alternating-parity bands?

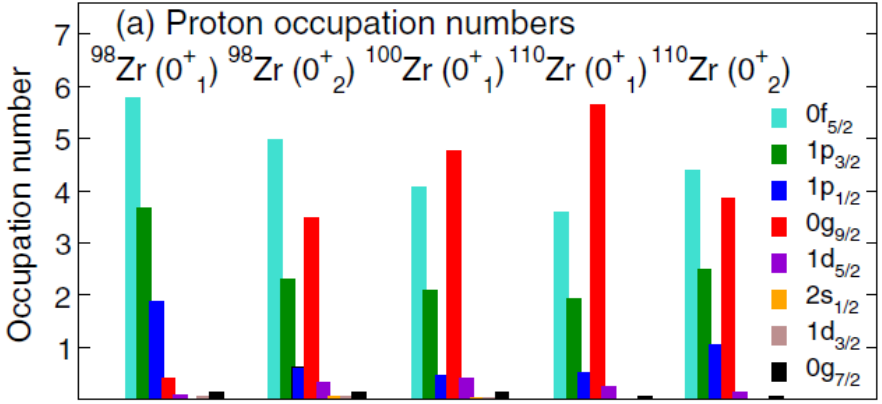


[NNDC (2023)]

If octupole deformed, should we not observe an alternating-parity band?

→ Intruder structure forms alternating-parity sequence with the negative-parity states in ^{96}Zr!

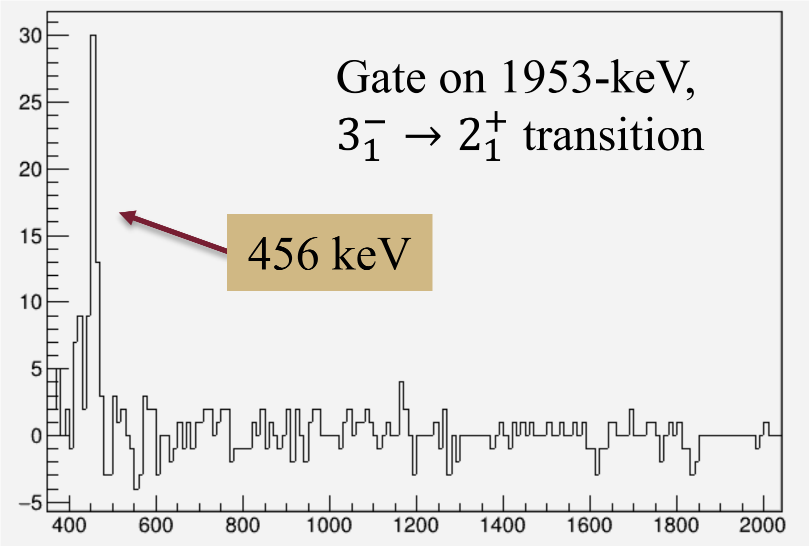
Why could this be interesting?



[T. Togashi, Y. Tsunoda, T. Otsuka, N. Shimizu, Phys. Rev. Lett. **117**, 172502 (2016)]

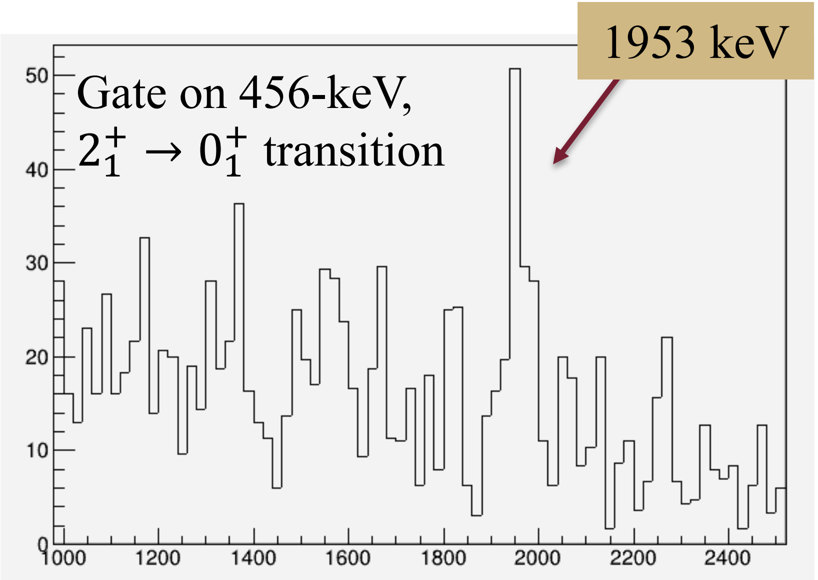
→ Intruder structure becomes ground state of ^{100}Zr. Intruder structure is “dominated” by proton $1g_{9/2}$.

Placing the 3_1^- in ^{74}Kr



Gate on 1953-keV, $3_1^- \rightarrow 2_1^+$ transition

456 keV



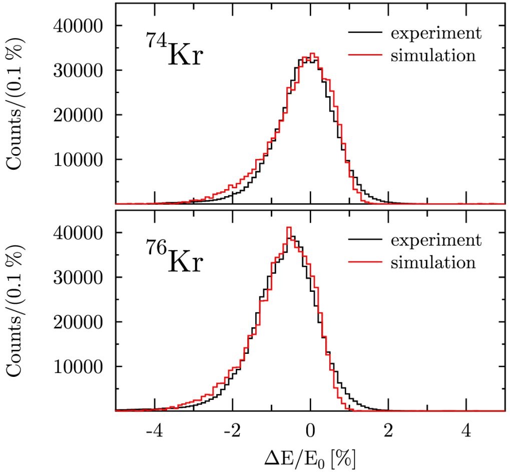
Gate on 456-keV, $2_1^+ \rightarrow 0_1^+$ transition

1953 keV

No add-back

Determining the target thickness

Kapton windows of LH_2 cell



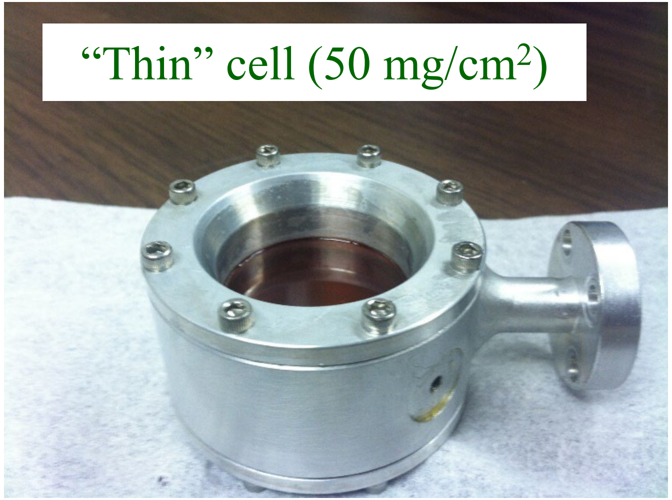
- Pressure difference between Kapton windows cause them to bulge outwards.
- Effect is quantified by simulating the kinetic-energy distribution of the beam.
  → Kinetic-energy distribution of incoming beam through empty cell is used as input.

→ Very good agreement between experimentally measured and simulated distribution for both ^{74,76}Kr.

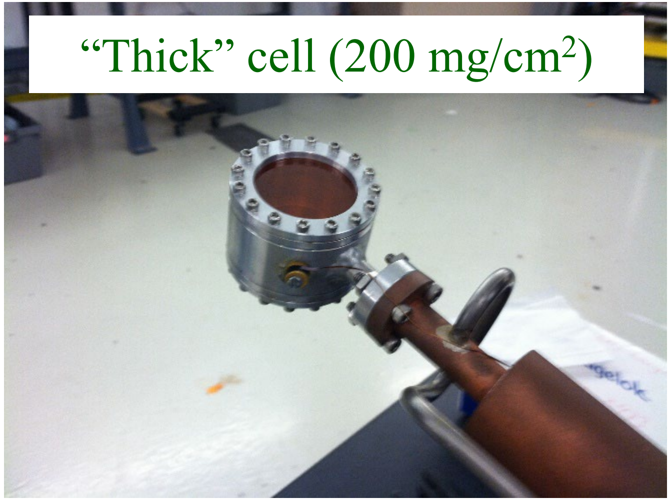
Target thickness: 69(3) mg/cm^2

[MS *et al.*, to be published]

LH_2 target cells



“Thin” cell (50 mg/cm^2)



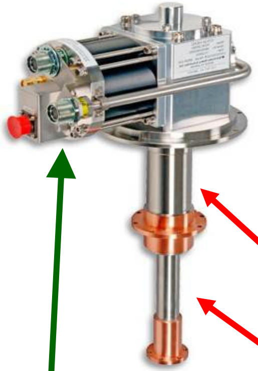
“Thick” cell (200 mg/cm^2)

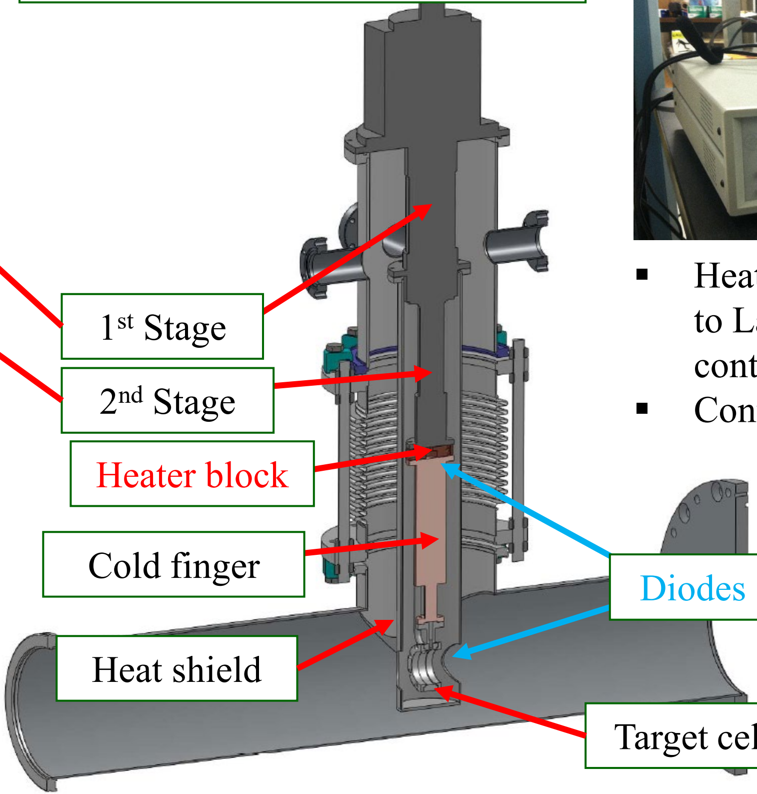
- Aluminum cell
- Different assemblies (50-200 mg/cm^2)
- 125-mm Kapton foils (<2% C contaminant)
- 3-4 ∅ cm
- Future: 400 mg/cm^2 @ HRS?

Courtesy of J. Pereira, L.A. Riley

The refrigerator system

Sumitomo RDK-205D Cryocooler





1st Stage

2nd Stage

Heater block

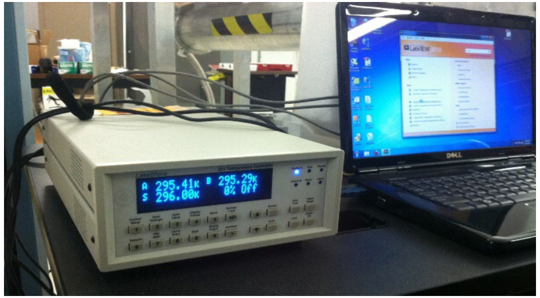
Cold finger

Heat shield

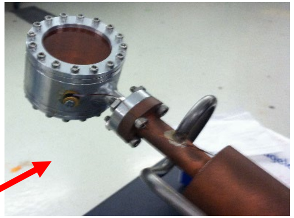
Diodes

Target cell

Sumitomo CKW21 compressor



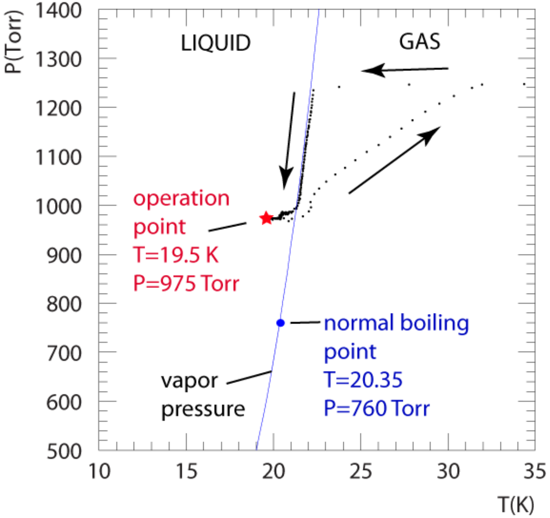
- Heat block + diodes connected to Lakeshore 331S temperature controller
- Controlled via PC

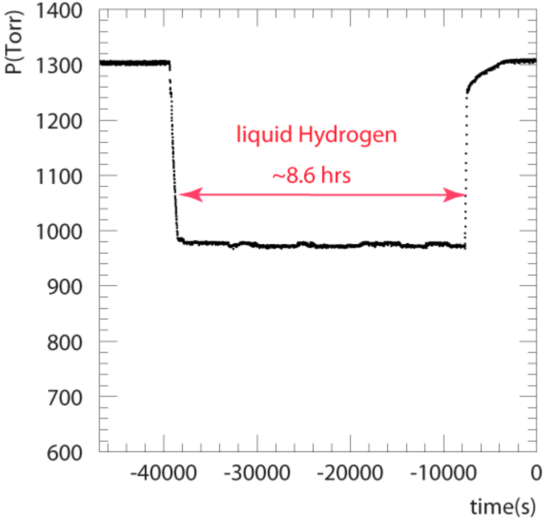


Courtesy of J. Pereira, L.A. Riley

Operation of LH_2 target system

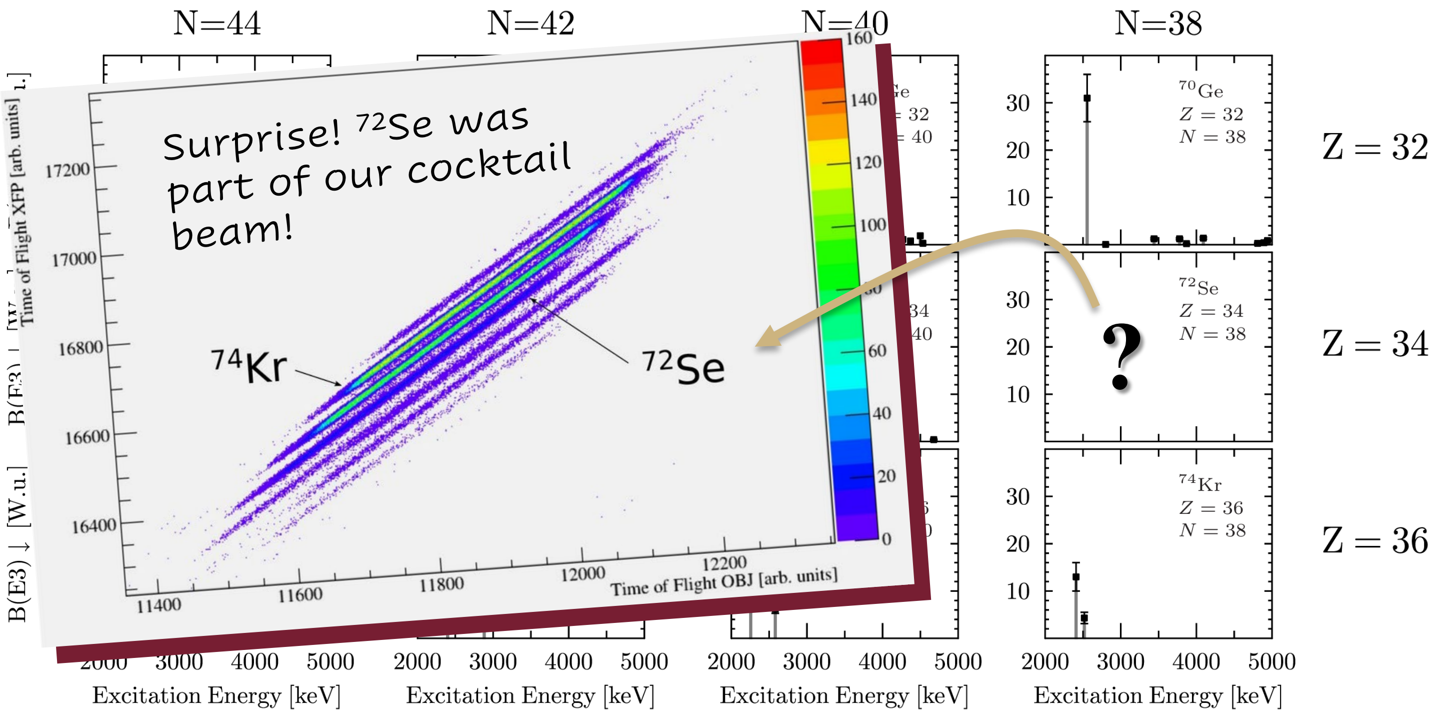
- Evacuating system from air (~2 hours)
- Filling reservoir + target cell (~30 min)
- Cooling-down target cell (~3 hours)
- Remote monitoring of Gas-cell Pressure and Temperature
- Phase diagram: identify liquid stage → **Running conditions**





Courtesy of J. Pereira, L.A. Riley

B(E3) strength distribution in Ge-Kr mass region



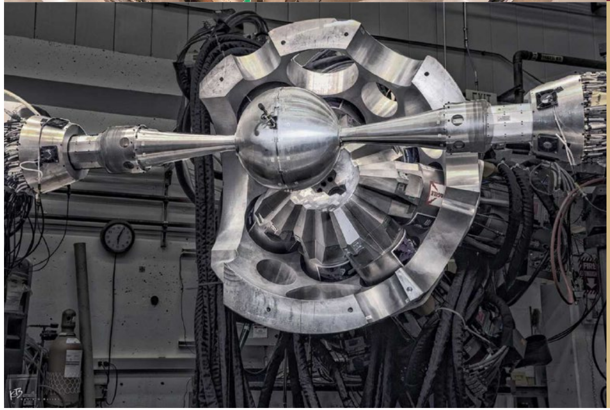
Strength increase not seen in the N = 38 and N = 40 Kr isotopes. So, what is going on?

[Rosier *et al.*, NPA **453**, 389 (1986); Schürmann *et al.*, NPA **475**, 361 (1987); Ogino, PRC **33**, 71 (1986); Matsuki *et al.*, PLB **113**, 21 (1982)]

The state-of-the-art: GRETINA

Gamma-Ray Energy Tracking In-Beam Nuclear Array

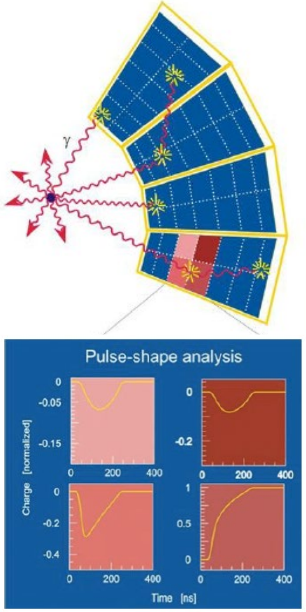
GRETINA@NSCL

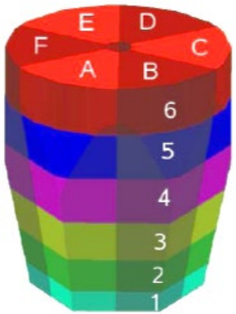


GRETINA@ANL

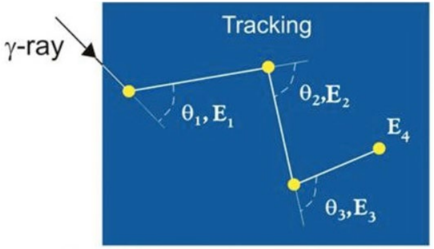
γ-ray tracking

(or why we do not need anti-Compton shields)





36 segments for one HPGe crystal



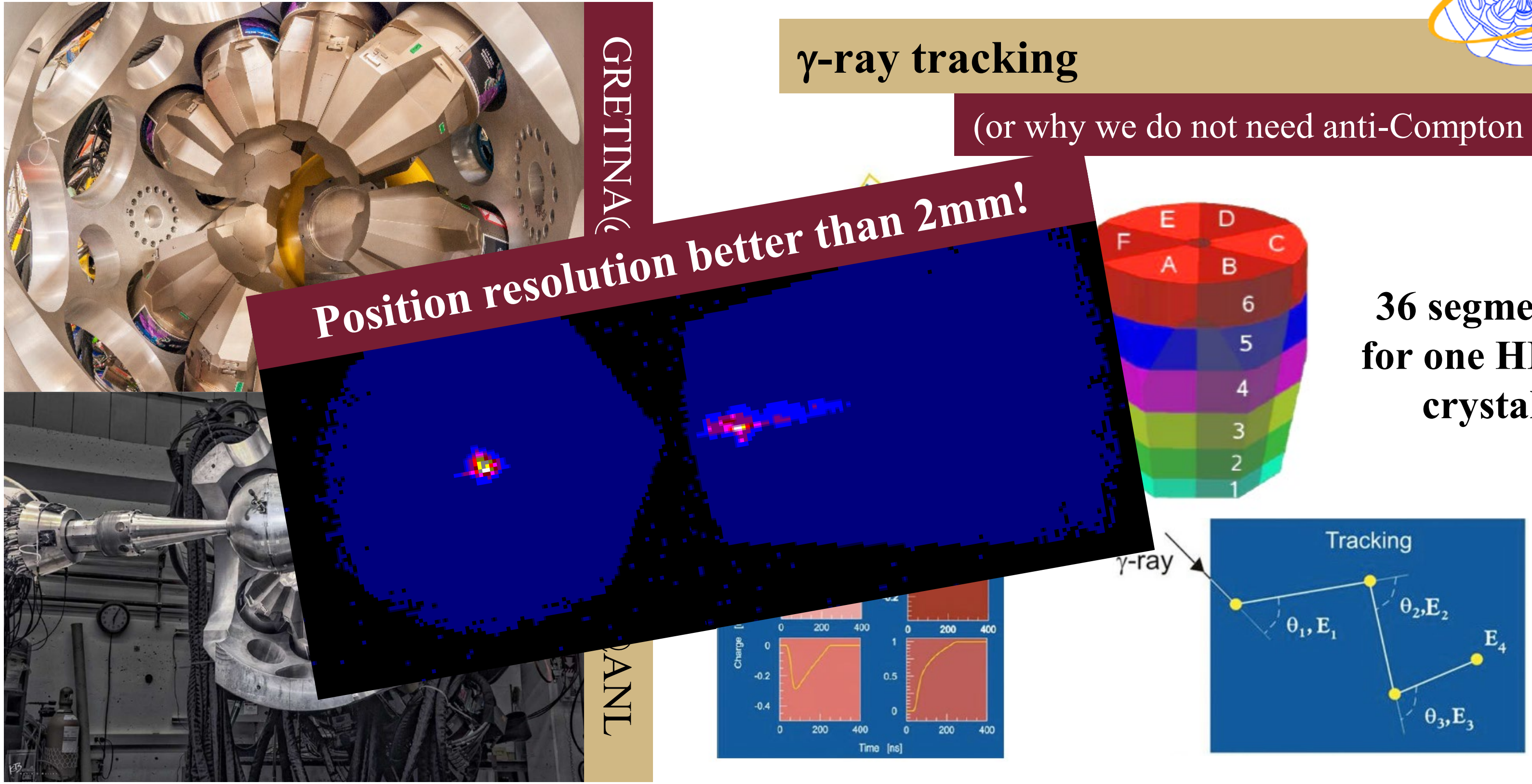
Experiment

The state-of-the-art: GRETINA

Gamma-Ray Energy Tracking In-Beam Nuclear Array

γ-ray tracking

(or why we do not need anti-Compton shields)



Position resolution better than 2mm!

36 segments for one HPGe crystal