Development of collectivity beyond N=50 in the Ge and Se isotopes

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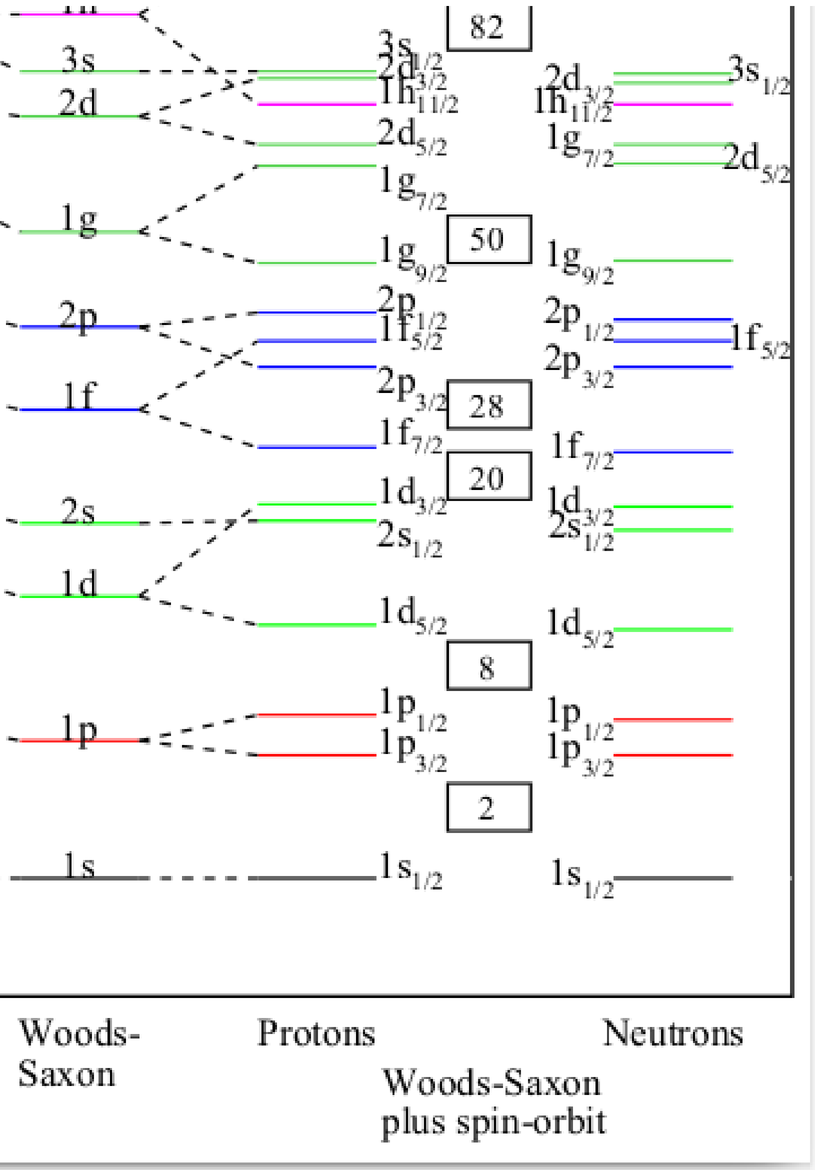
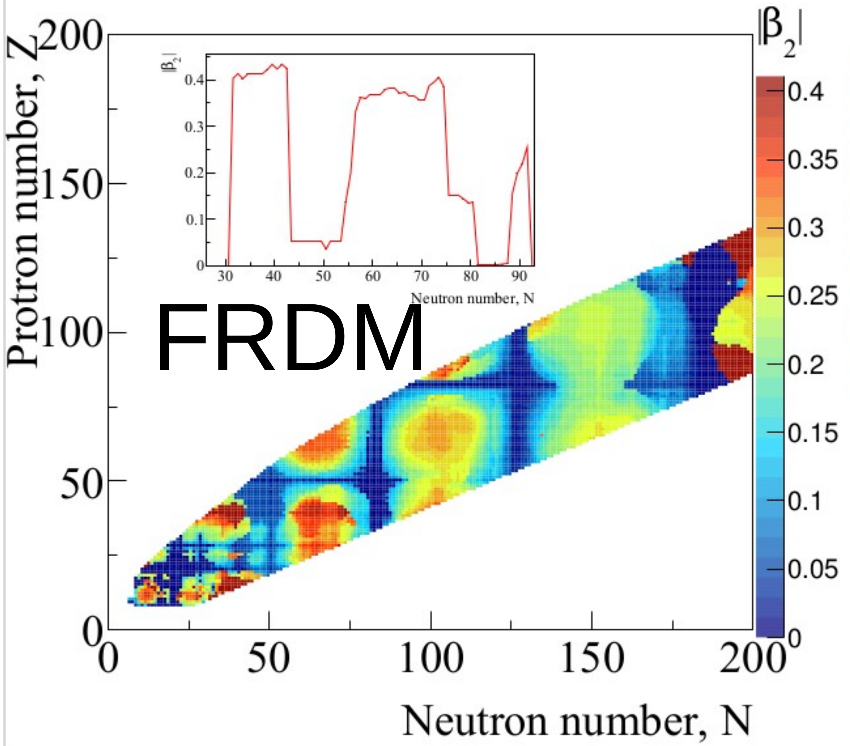
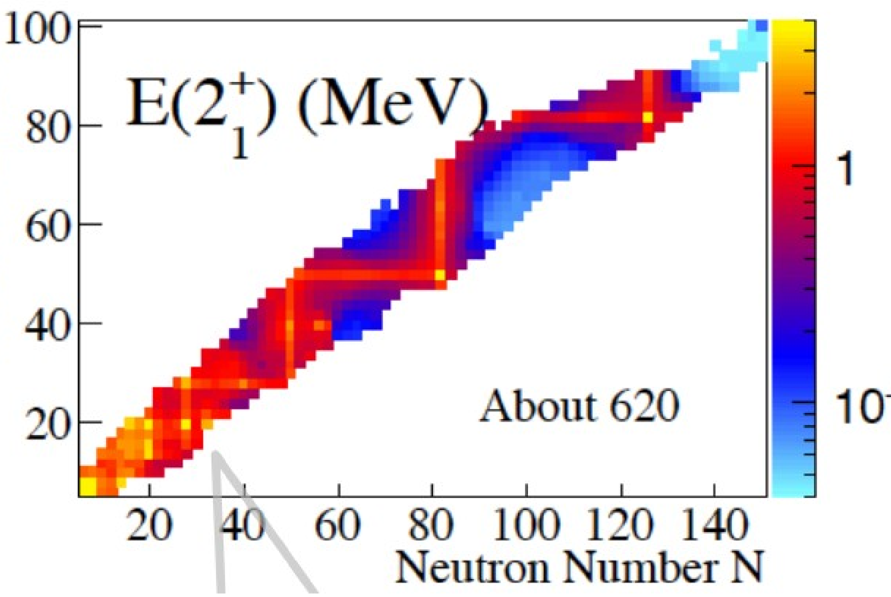
Shells to shapes



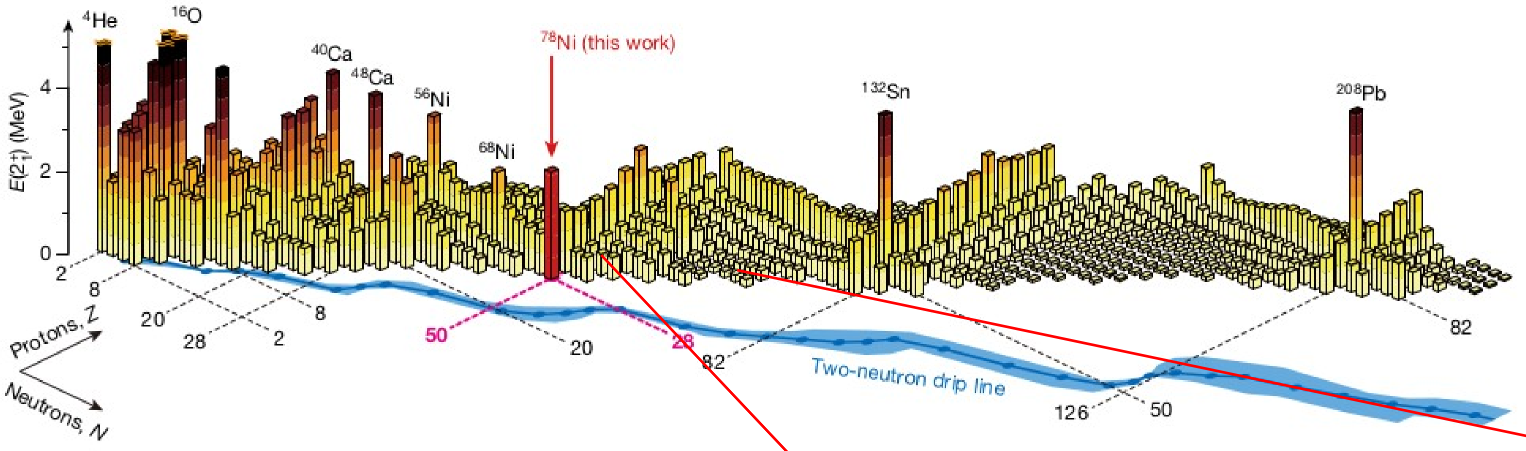


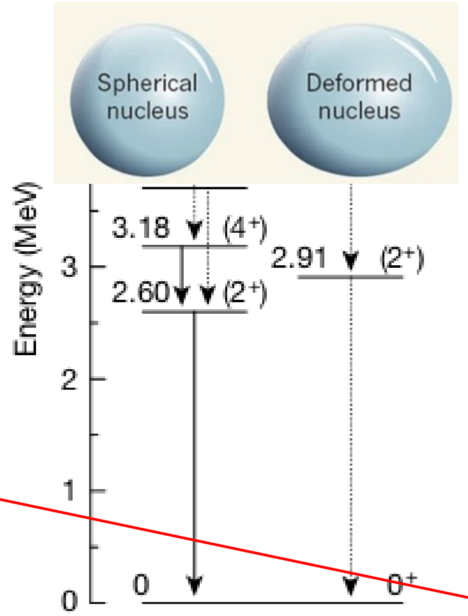


- “Typical magic numbers”
  - Associated with “spherical” shell closures/enhanced stability
- First indication is $E(2^+_1)$

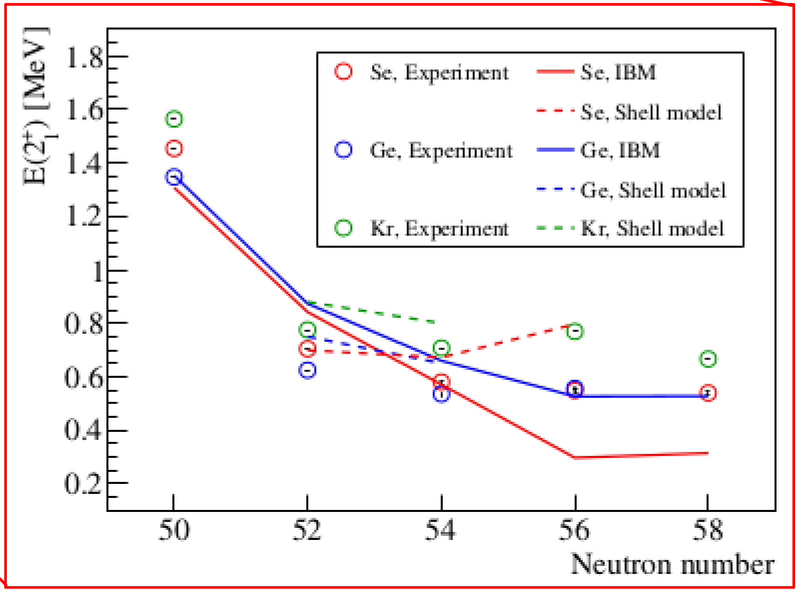
Departure from magicity

R. Taniuchui et al, Nature **569**, 53 (2019).





- Large E(2^{+}_{1}) energies, low B(E2) values
- ^{78}Ni most recently measured
  - Competing structures: spherical/deformed…
  - How are these manifest deeper into mid-shell?



Departure from magicity

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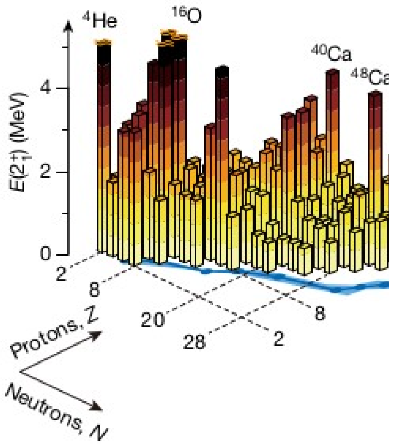
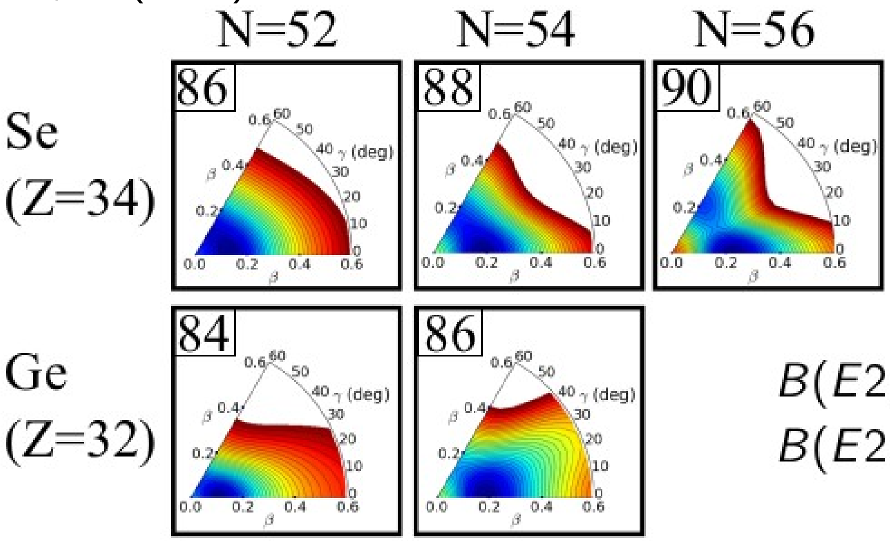
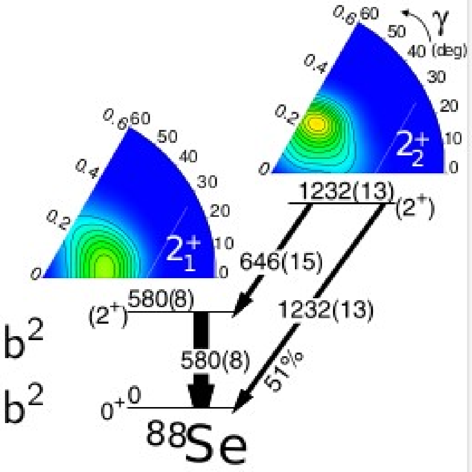
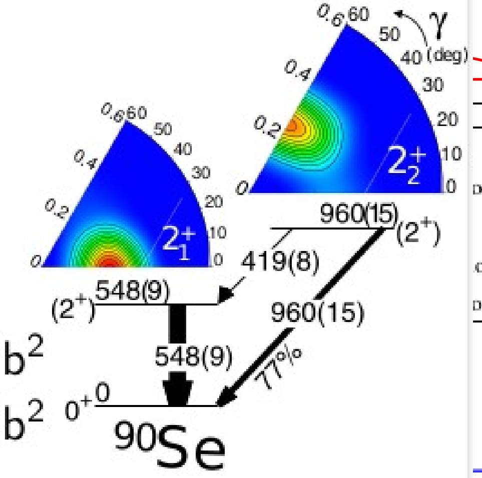






$B(E2; 2^+_1) \uparrow = 0.284\ e^2b^2$

$B(E2; 2^+_2) \uparrow = 0.006\ e^2b^2$



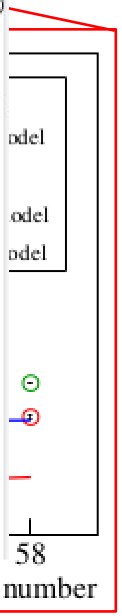
$B(E2; 2^+_1) \uparrow = 0.193\ e^2b^2$

$B(E2; 2^+_2) \uparrow = 0.052\ e^2b^2$

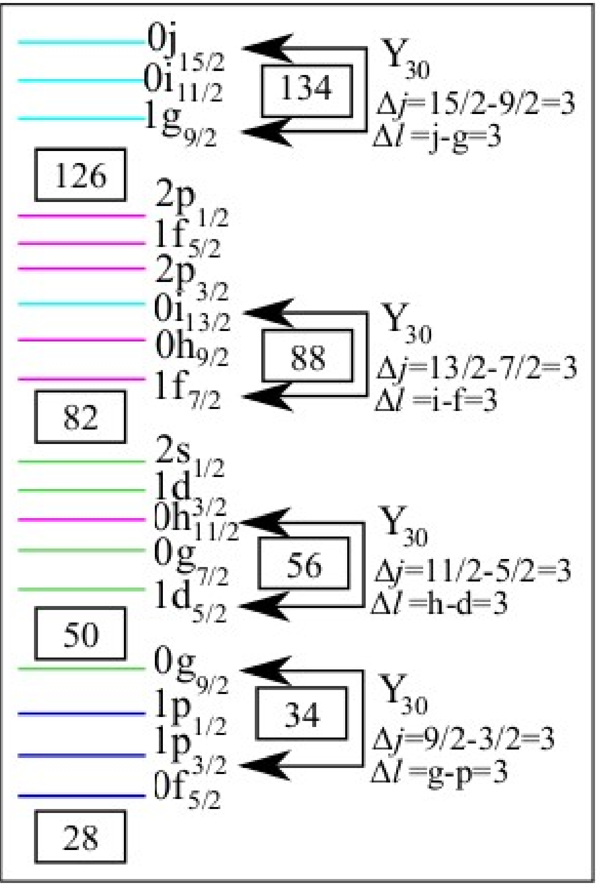
- Large E(2^+_1)
- ^{78}Ni most re
  - Competinc spherical/c
  - How are th mid-shell?

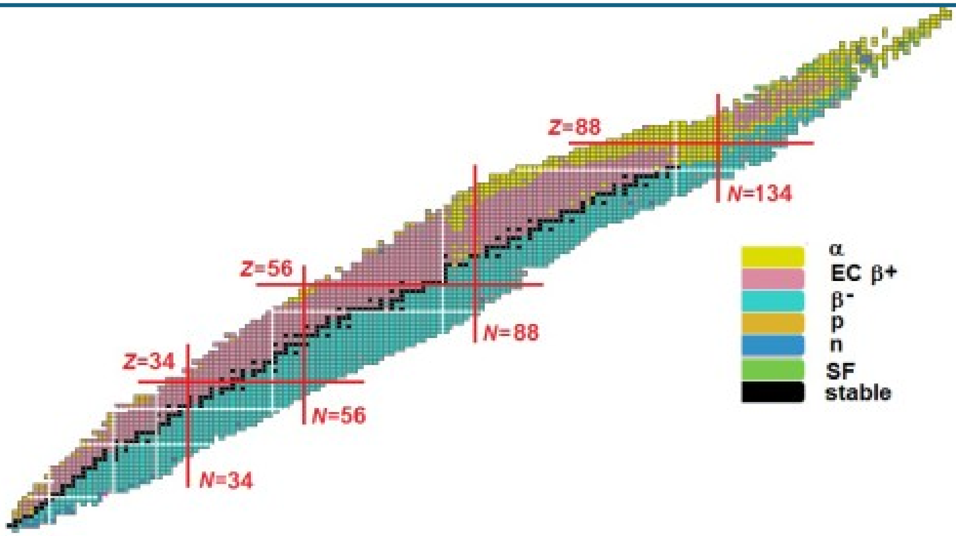
- Shell model, SCCM *and* mean-field predict:
  - → Triaxiality in ^{86}Ge
  - → Prolate & oblate minima in ^{90}Se
- Enhacement of $B(E2; 2^+_2)$ in ^{90}Se
  - → Strong test of models

K. Nomura *et al*, Phys. Rev. C **95**, 064310 (2017).
K. Sieja *et al*, Phys. Rev. C **88**, 034327 (2013).
S. Chen *et al*, Phys. Rev. C **95**, 041302(R) (2017).
K. Sieja, Private communication (2019).

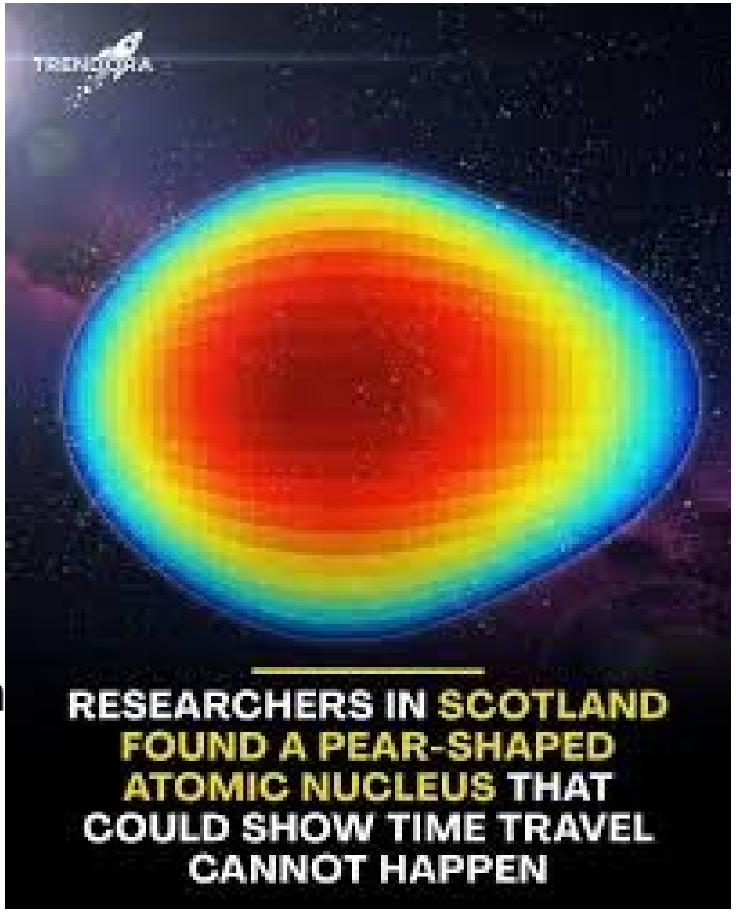


Octupole collectivity at N=56 and Z=34





- ISOLDE, CERN: $Z \approx 88$ & $N \approx 134$
  - $\rightarrow {}^{220}_{86}\mathrm{Rn}_{134} \Rightarrow$ Vibrational β_3 mode
  - $\rightarrow {}^{224}_{88}\mathrm{Ra}_{136} \Rightarrow$ *Static* β_3 deformation
- ATLAS, ANL: $Z \approx 56$ & $N \approx 88$
  - $\rightarrow {}^{144}_{56}\mathrm{Ba}_{88} \Rightarrow$ larger β_3 than any prediction
- RIBF, RIKEN: $Z \approx 34$ & $N \approx 56$
  - $\rightarrow$ The final frontier...?



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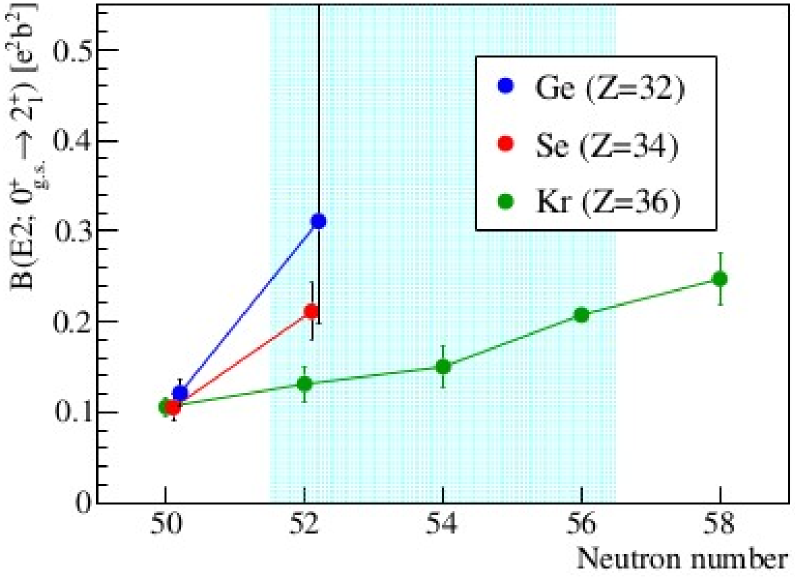
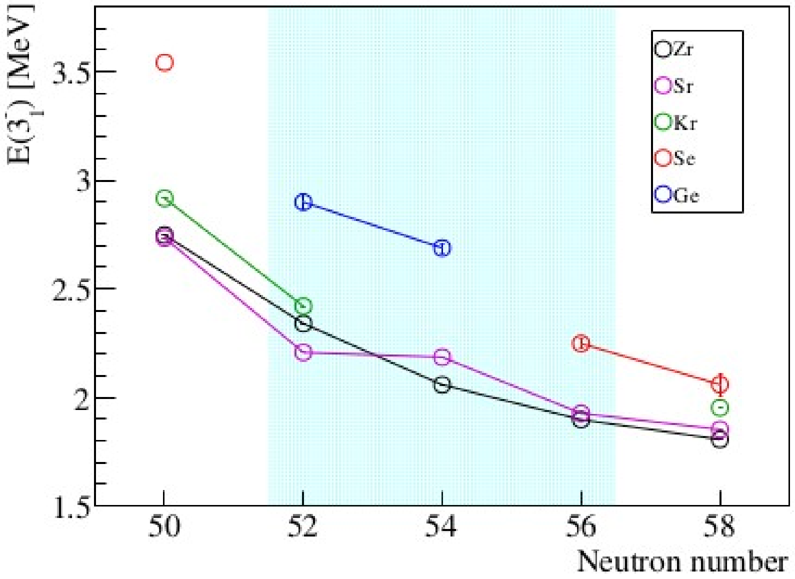
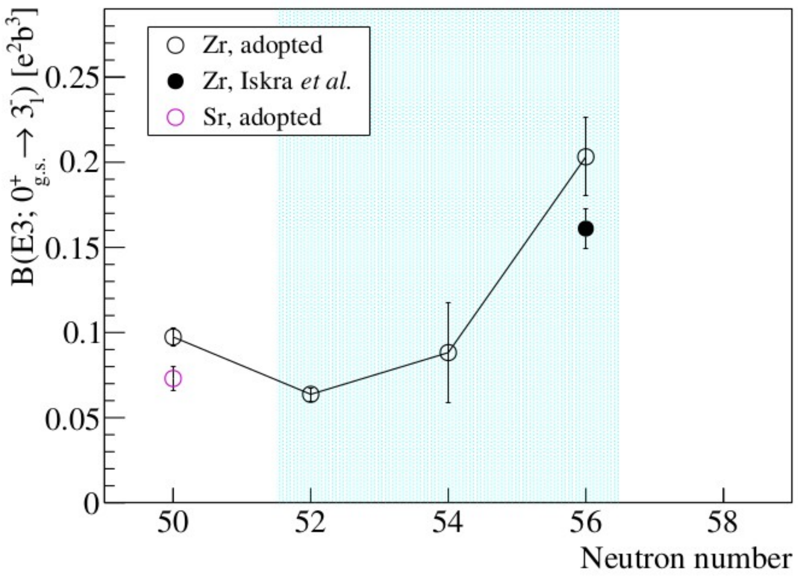
Measurement objectives







	^{84}Ge	^{86}Ge	^{86}Se	^{88}Se	^{90}Se
$E(2_1^+)$	✓	✓	✓	✓	✓
$B(E2;0^+_{g.s.} \to 2_1^+)$	(✓)●	●	✓●	●	●
$E(2_2^+)$	✓	✓	✓	✓	✓
$B(E2;0^+_{g.s.} \to 2_2^+)$	▲	▲	▲	▲	▲
$E(3_1^-)$	✚	✚	●	●	✚
$B(E3)$	✗	✗	◆	◆	◆

✓ = Measured
(✓) = Measured with large uncertainty
✚ = Measured but not published
● = Easily measurable, well controlled model-dependence
▲ = Potential for measurement/limit
◆ = Measurement model dependent
✗ = Not yet feasible

A. Korgul *et al*, Phys. Rev. C **88**,044330 (2013). K. Miernik *et al*, Phys. Rev. Lett. **111**, 132502 (2013).
E. F.Jones *et al*, Phys. Rev. C **73**, 017301 (2006). S. Chen *et al*, Phys. Rev. C **95**, 041302(R) (2017).
C. Delafosse *et al*, Phys. Rev. Lett. **121**, 192502 (2018). B. Elman *et al*, Phys. Rev. C **96**, 044332 (2017).
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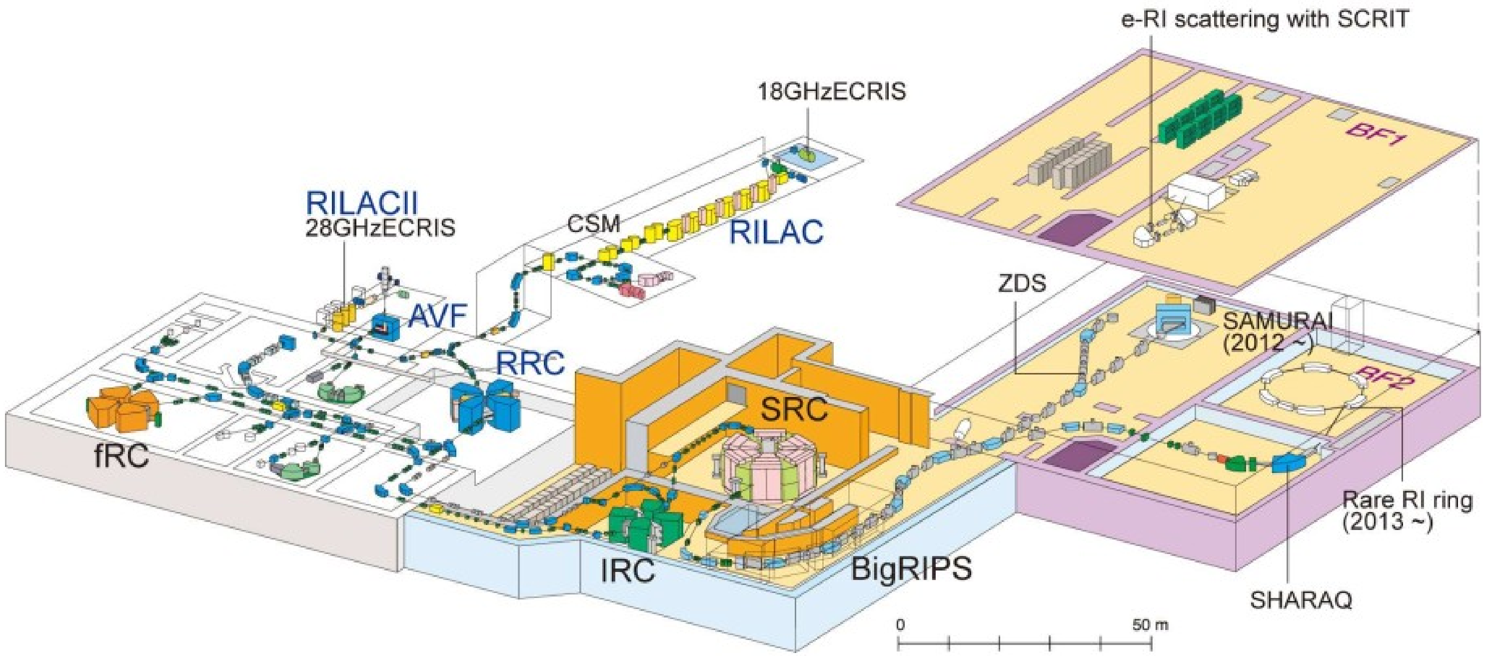
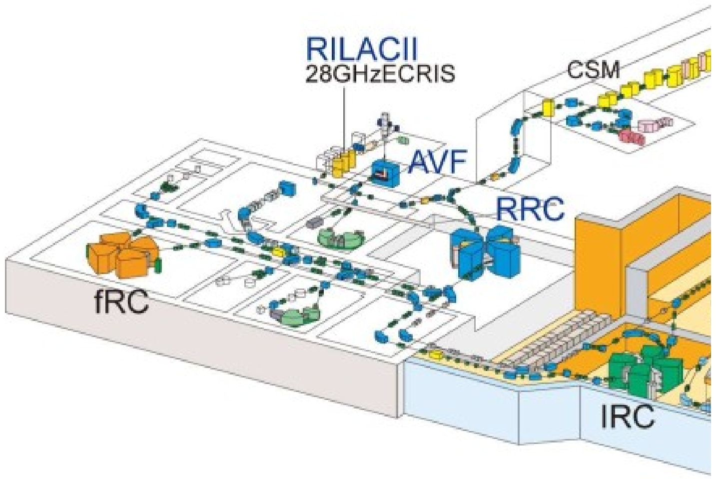
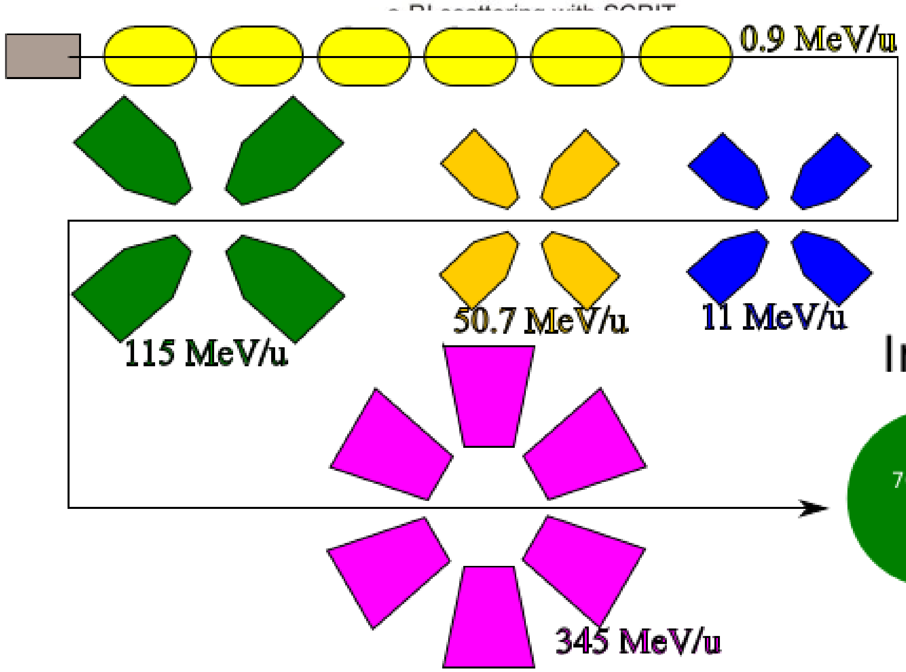
Radioactive Isotope Beam Factory



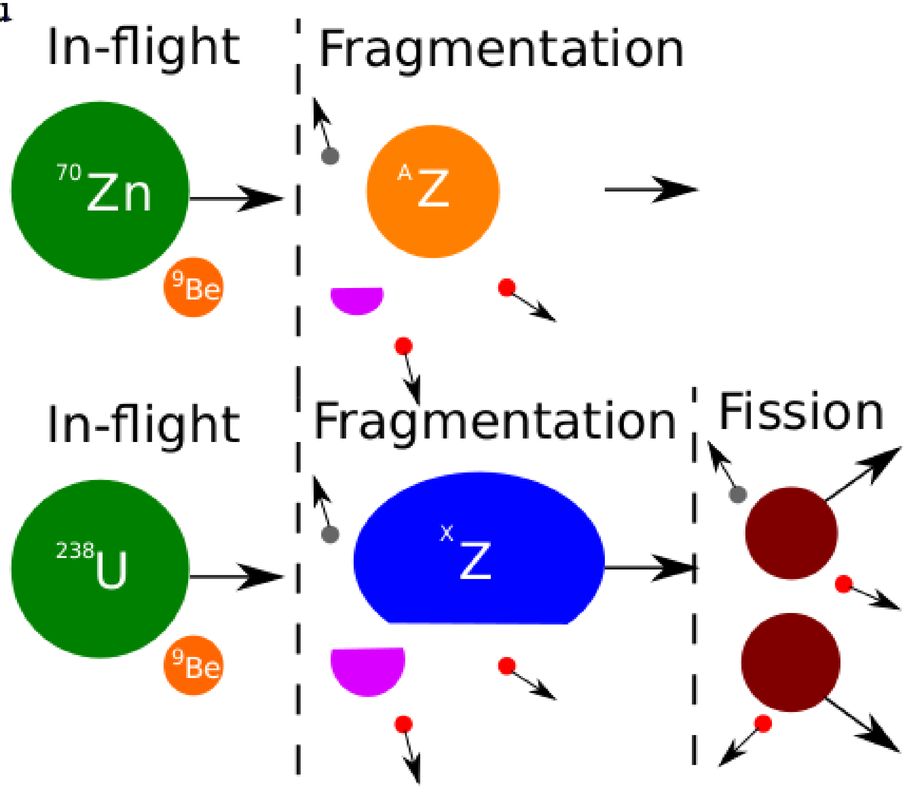
- Radioctive Isotope Beam Factory
  - →**Heavy** ion accelerator complex
  - →At RIKEN HQ, close to Tokyo
- "Old facility" since 1986
  - →RILAC/AVF→RRC→RIPS
  - →∼60–100 MeV/*u*
- "New facility" since 2007
  - →3 new cyclotrons
  - →Several spectrometers
  - →→fRC→IRC→SRC→BigRIPS
  - →345 MeV/u
  - →Heavy primary beams, ^{238}U!

Radioactive Isotope Beam Factory





- ▶ Target: (Typically)
  - →^{9}Be, 3–20 mm
- ▶ Beam:
  - →345 MeV/u, $\beta = 0.68$



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  - →**Heavy** ion accelerator comple
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- ▶ “Old facility” since 1986
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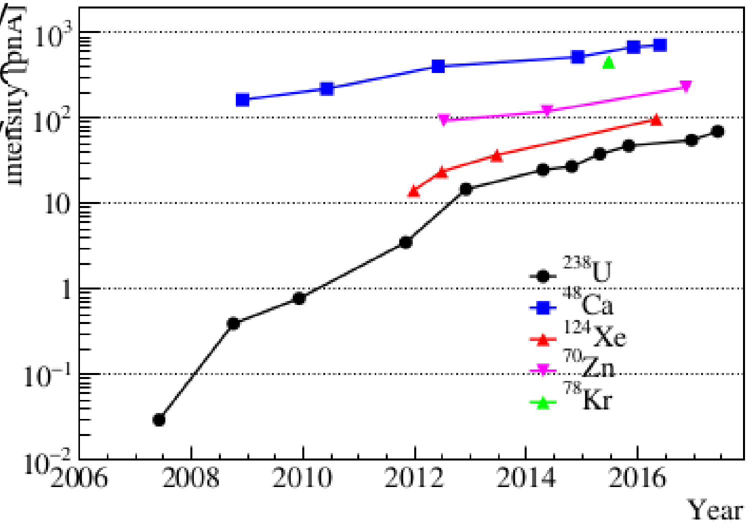
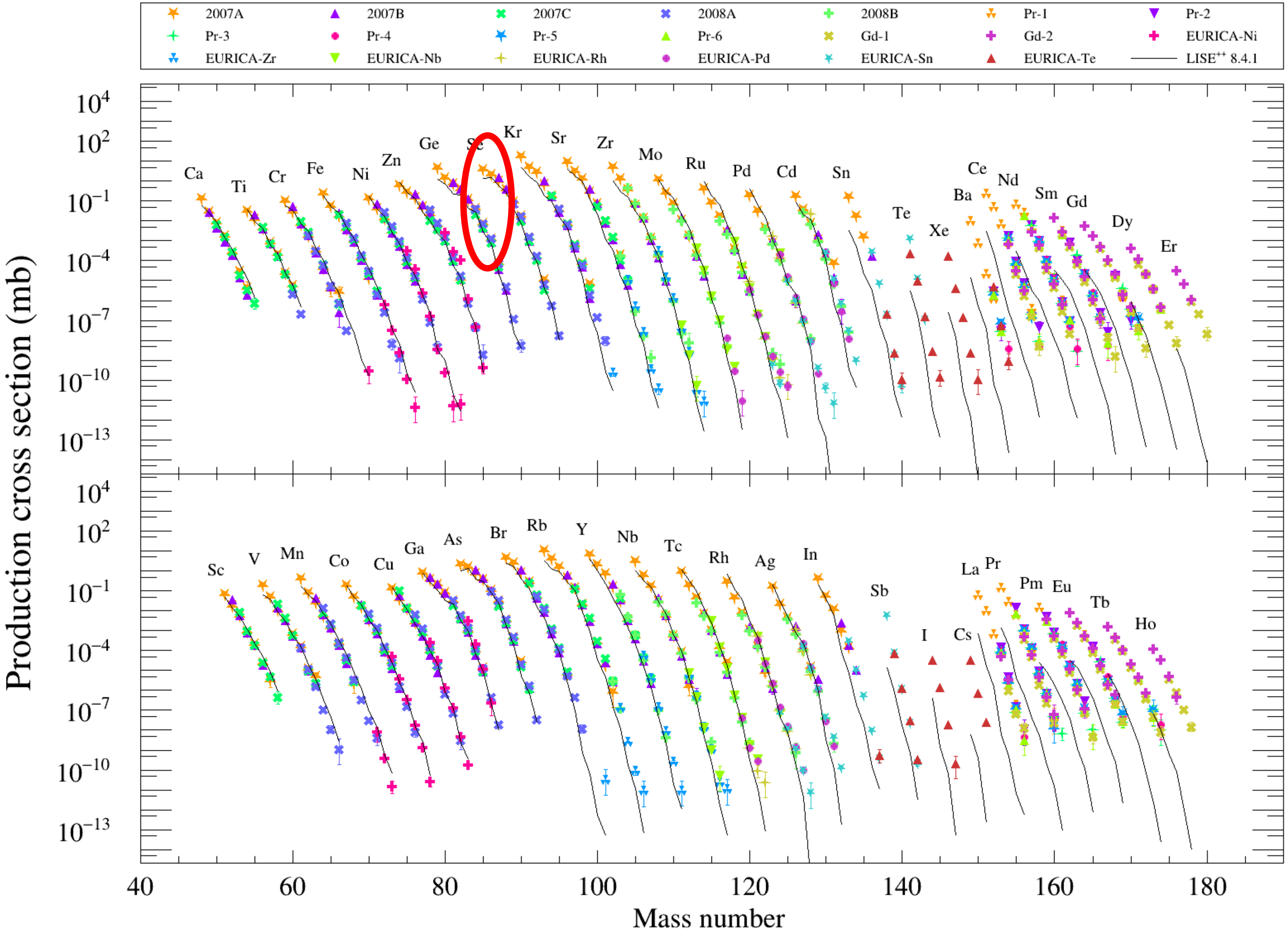


Radioactive Isotope Beam Factory



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- Beam:
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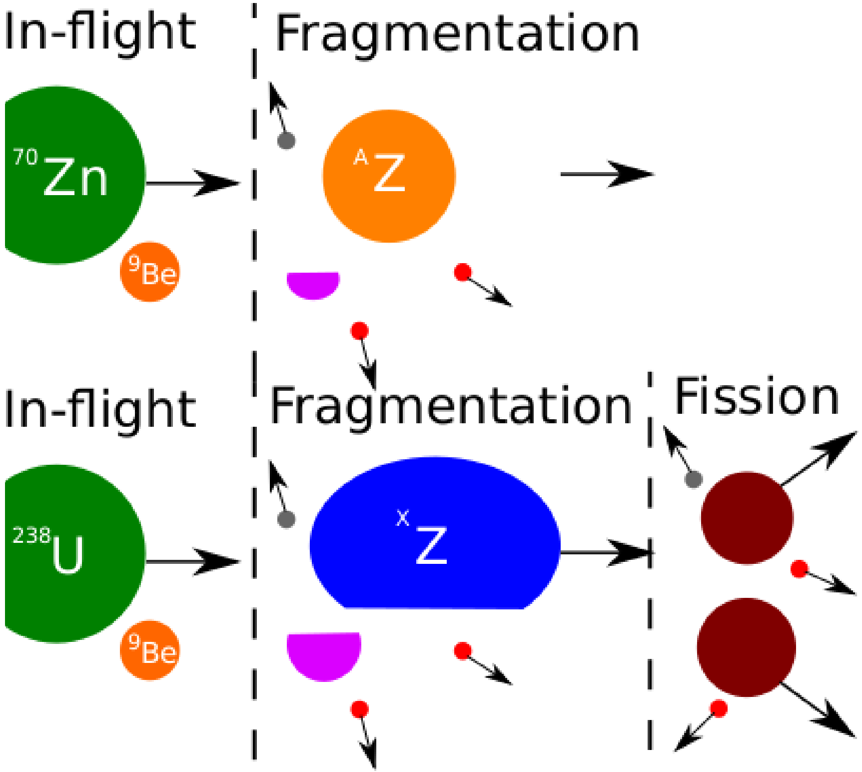
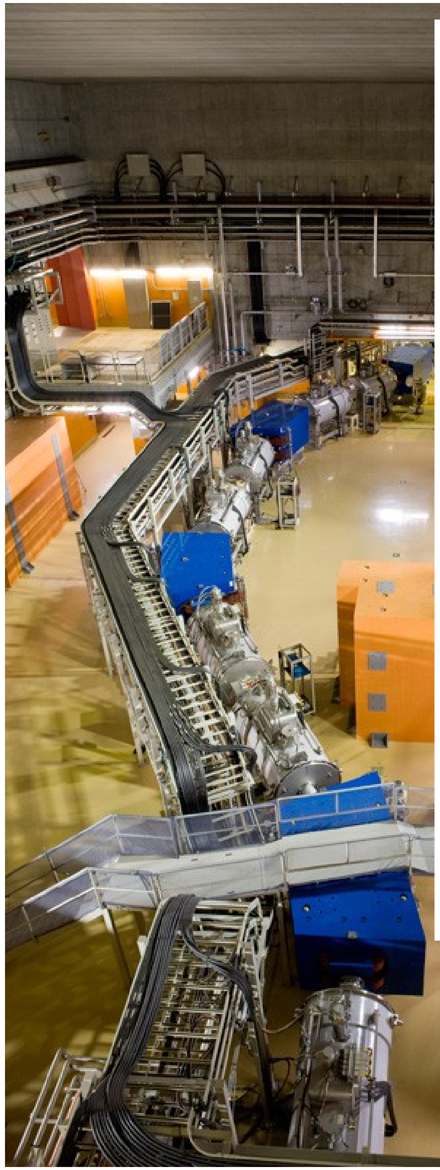
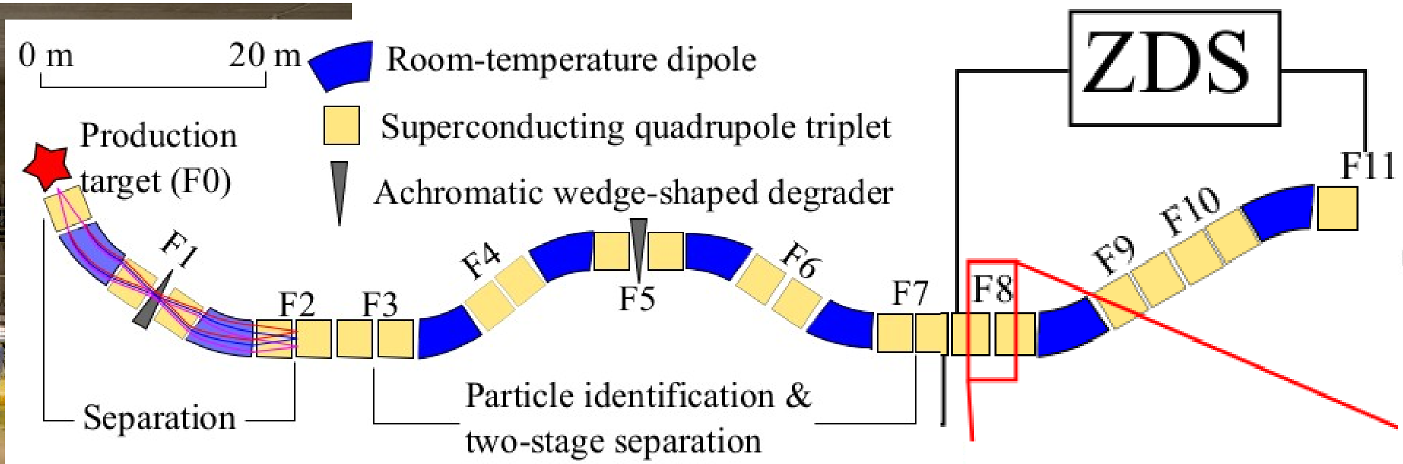
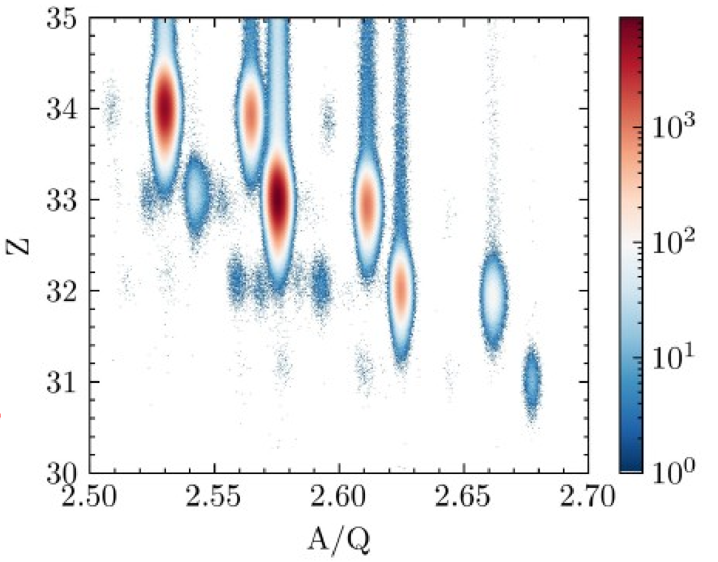


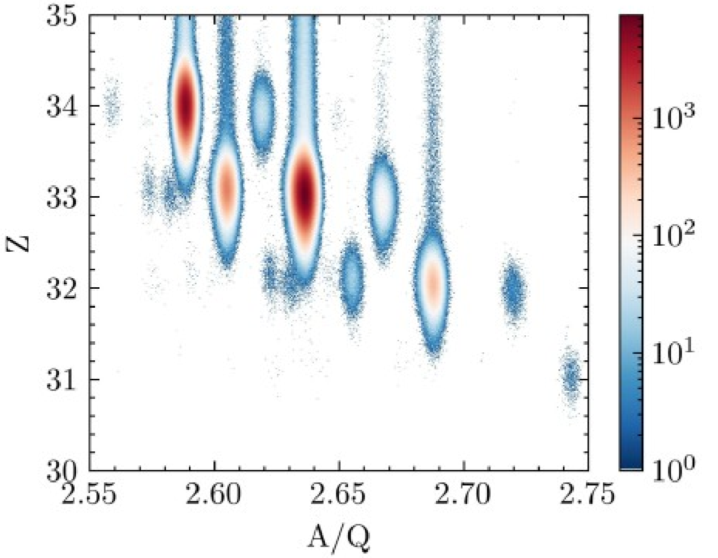
RI Beam settings



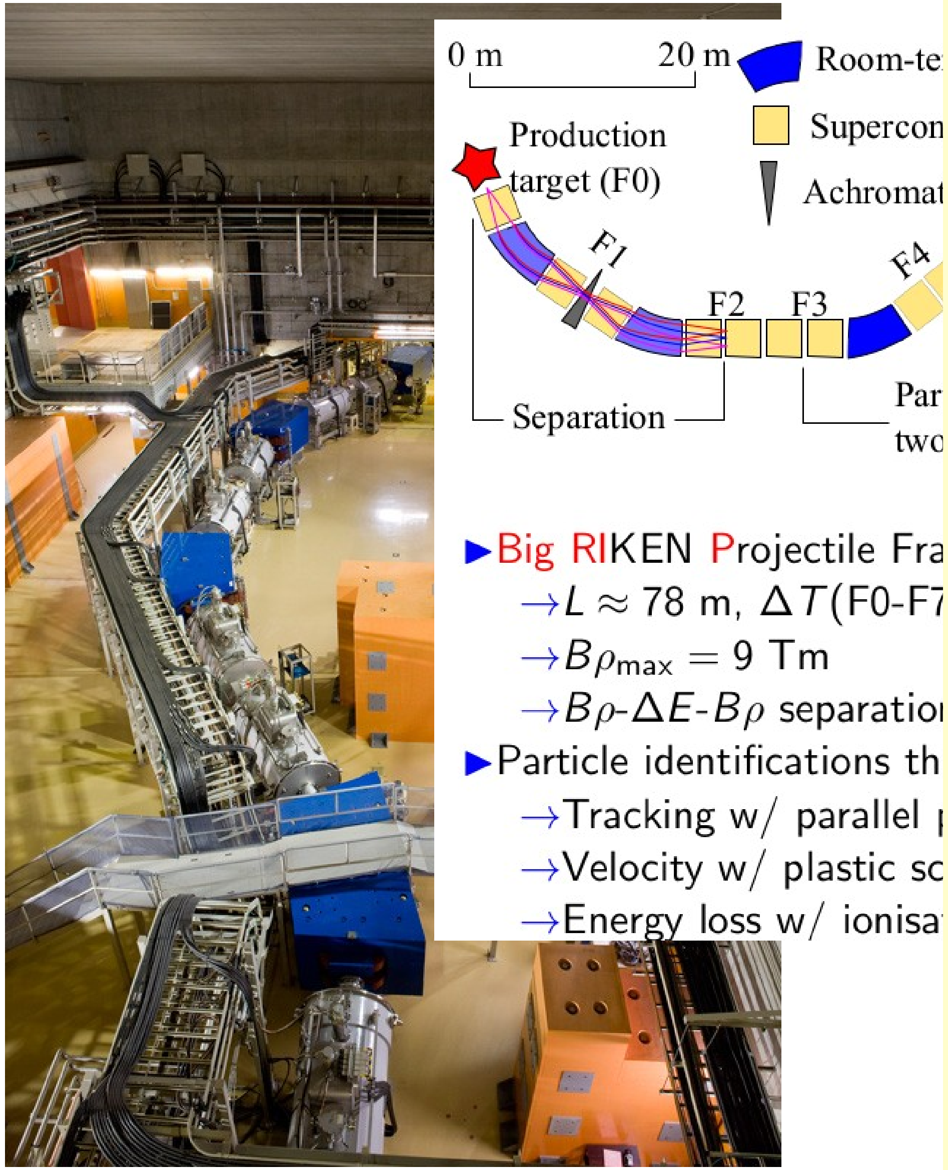


- ▶ Big RIKEN Projectile Fragment Separator
  - → $L \approx 78$ m, ΔT(F0-F7) ≈ 400 ns
  - → $B\rho_{max} = 9$ Tm
  - → $B\rho$-ΔE-$B\rho$ separation
- ▶ Particle identifications through:
  - → Tracking w/ parallel plate avalanche chambers
  - → Velocity w/ plastic scintillators
  - → Energy loss w/ ionisation chambers





RI Beam settings



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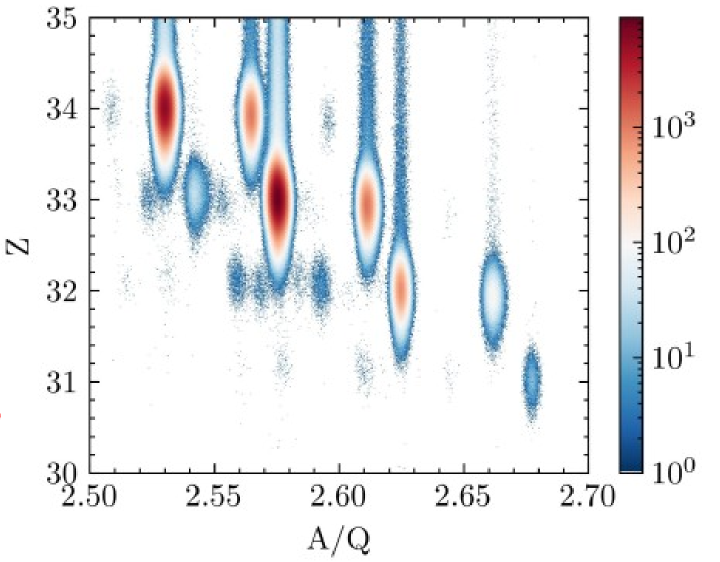
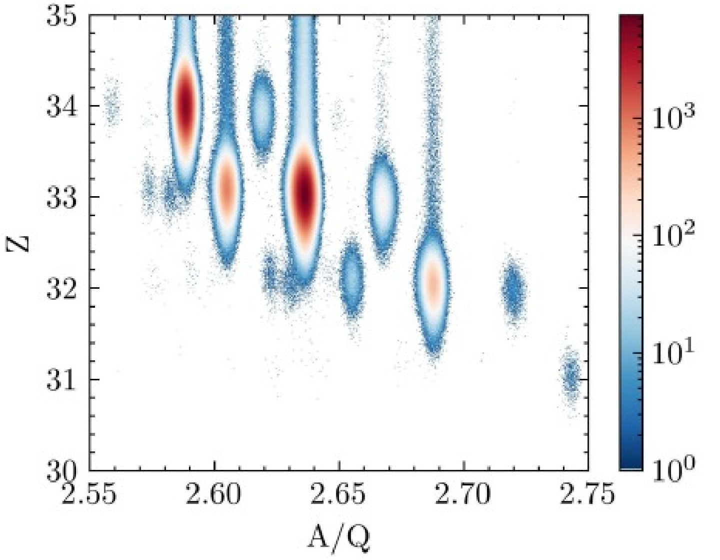
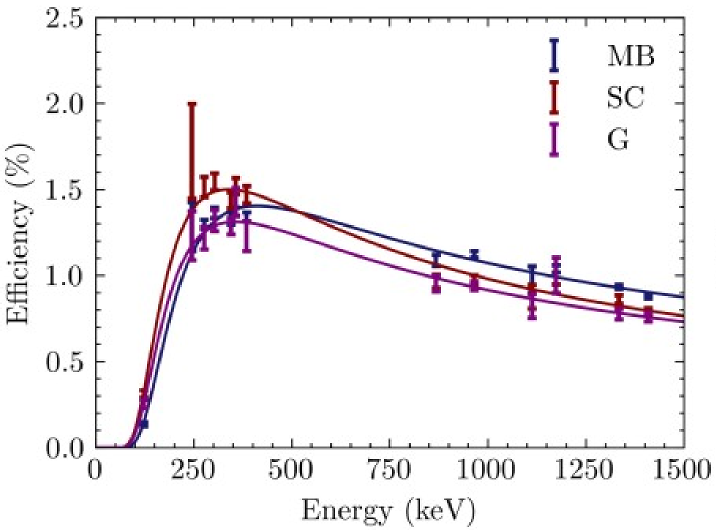


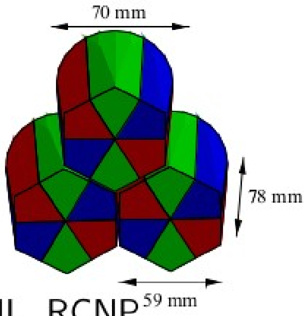


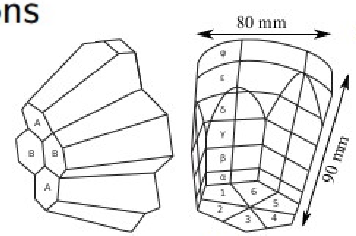
HiCARI

- High Resolution Cluster Array at RIBF
  - →"HIKARI" = 光 means "light"
    Wako-shi = 和光市
- Mixed array of segmented HPGe detectors
  - →Full tracking, clovers, Miniball
    - –From many countries/institutions

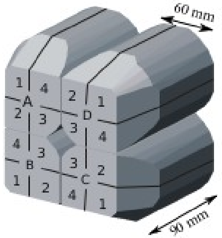


- Miniball: KU Leuven/U. of K oln
  - →6-fold segmentation
  - →Triplet crystal arrangement
  - →6×in the array

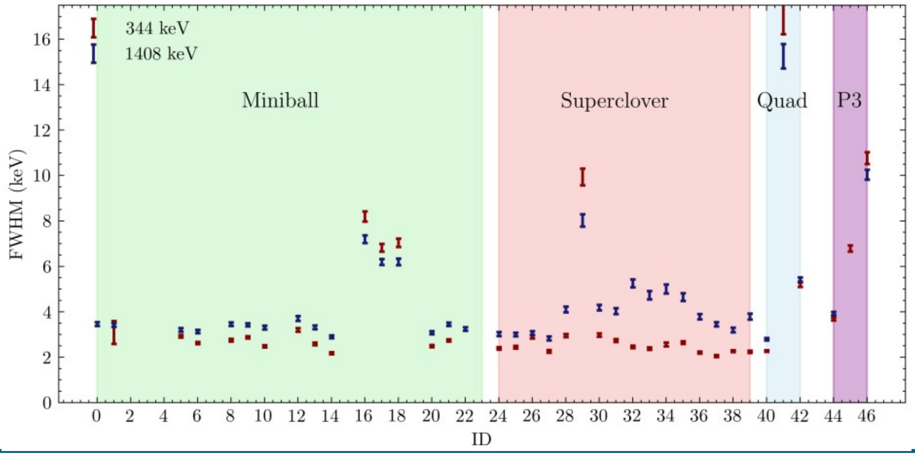




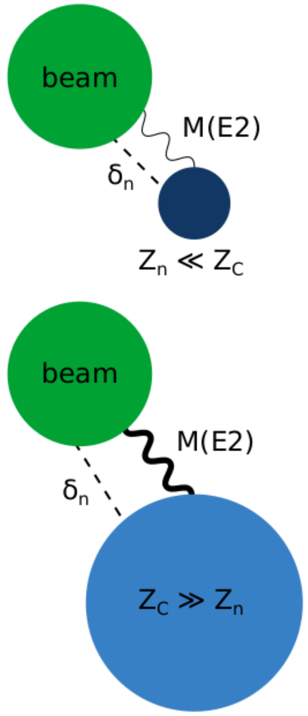
- Tracking detectors: LBNL, RCNP
  - →36-fold segmentation
  - →1×GRETINA triplet prototype (P3)
  - →1×GRETINA quad-type (QUAD)
- Clovers: IMP Lanzhou
  - →4 crystals/detector
  - →4-fold segmentation
  - →4× in the array



P. Doornenbal, PhD Thesis (2007).
P. Fallon *et al*, Annu. Rev. Part. Sci. **66**, 321 (2016).
N.-T. Zhang *et al*, Chin. Phys. Lett. **29**, 042901 (2012).

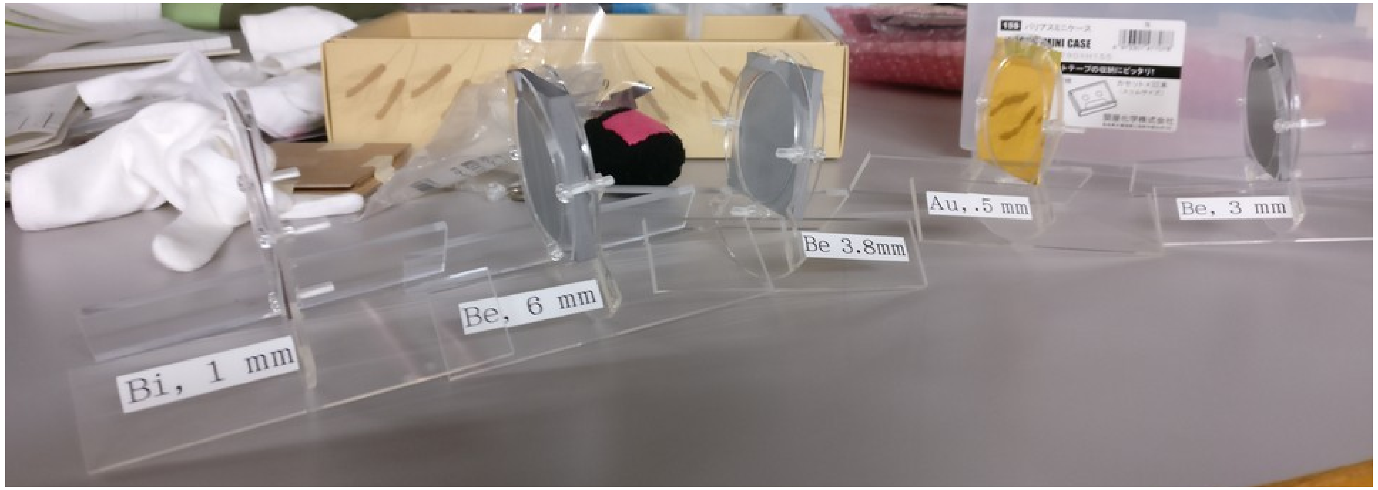


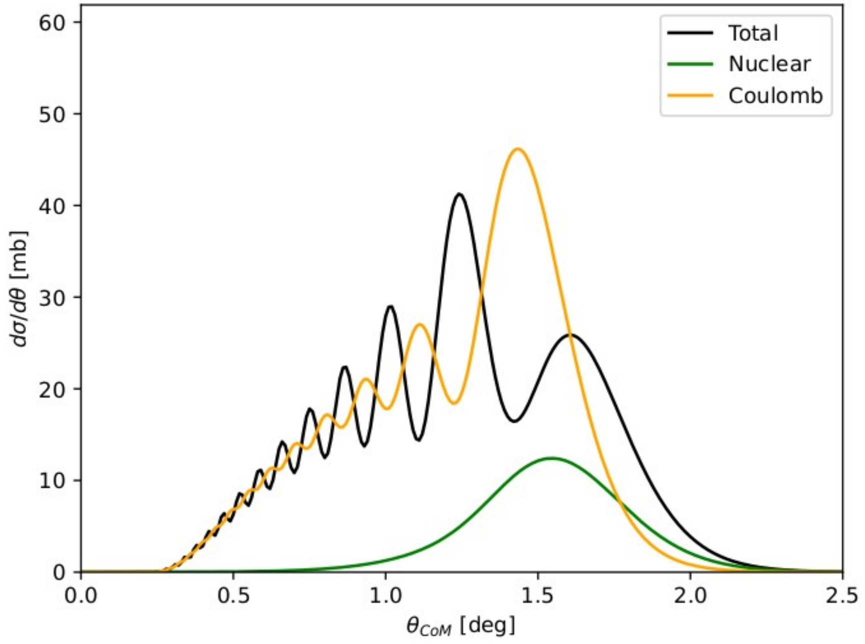
Coulomb excitation at 100s of MeV/u

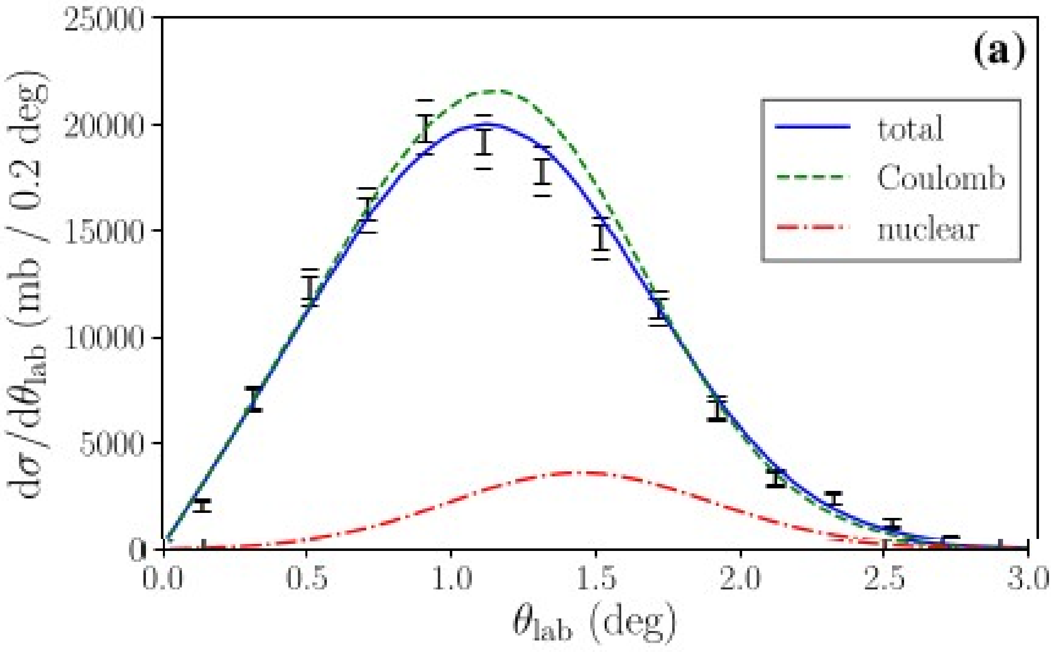


- determine nuclear deformation length δ_n from data on light target (Be or C)
  limiting electro-magnetic excitation
- analyze using a guess for $M(E2)$ (0 or theoretical value)
- use this δ_n value in the analysis of the scattering on high-Z target (Au, Pb, Bi, etc)
- obtain $M(E2)$
- $\rightarrow$ repeat
- convergence reached after two iterations
- compare to assumption $\delta_n = \delta_C$

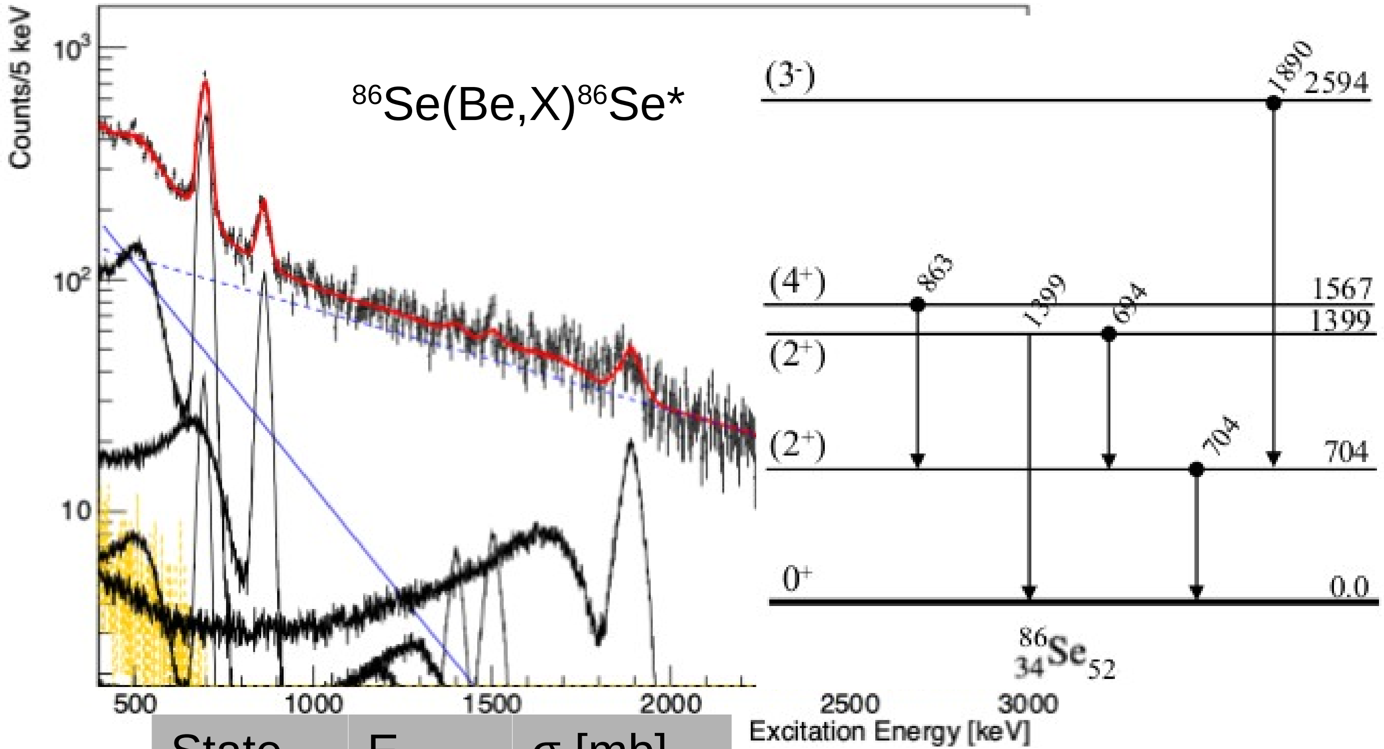
$$M(E2) = \frac{3}{4\pi} ZeR\delta_C$$



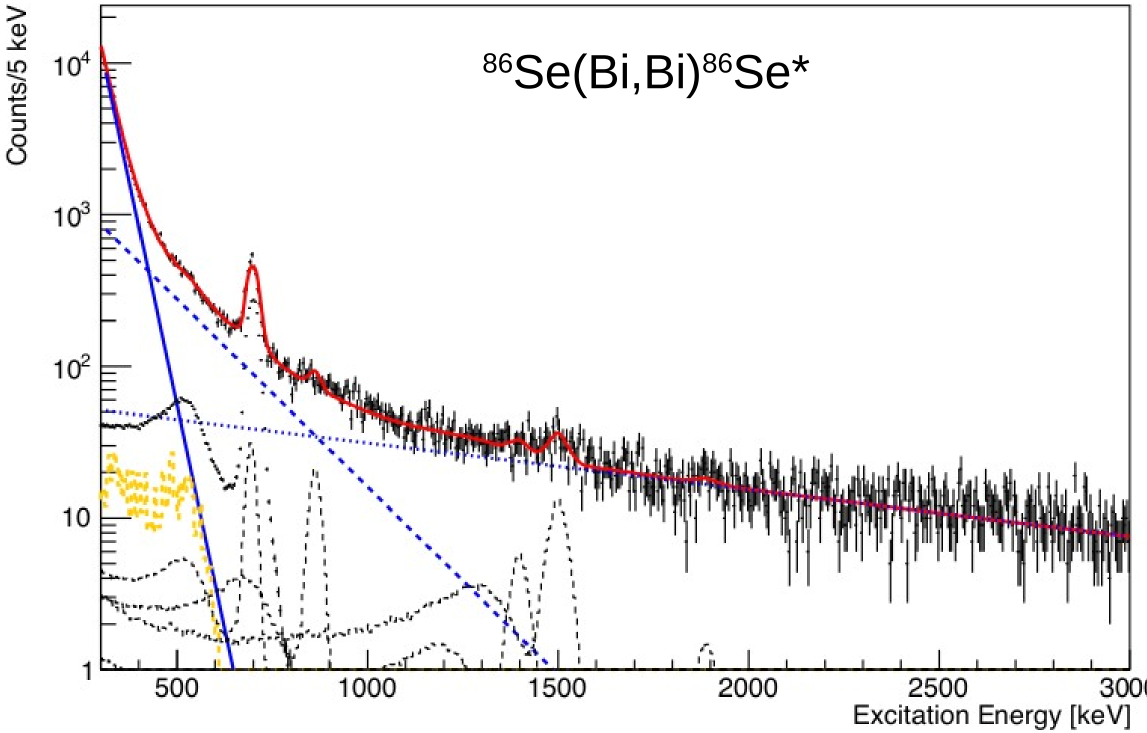




Results: ^{86}Se

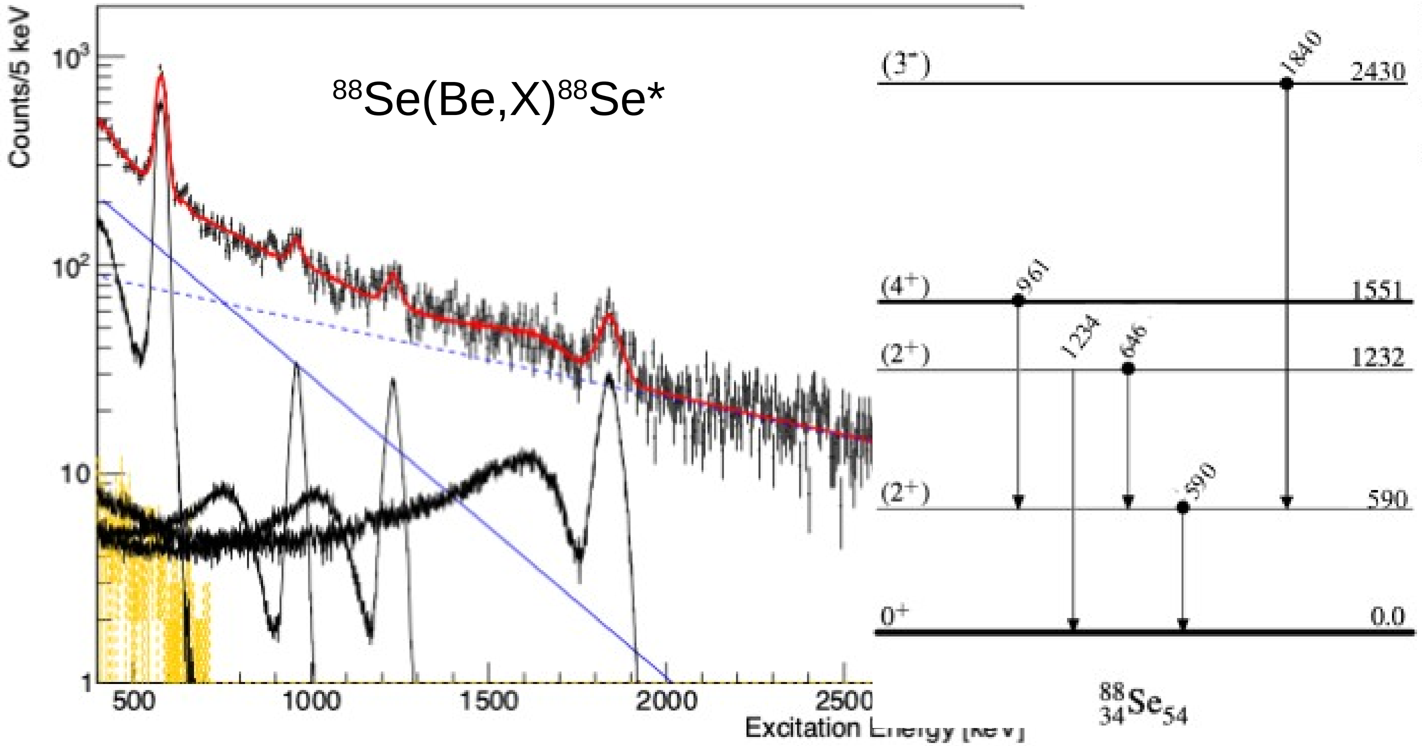


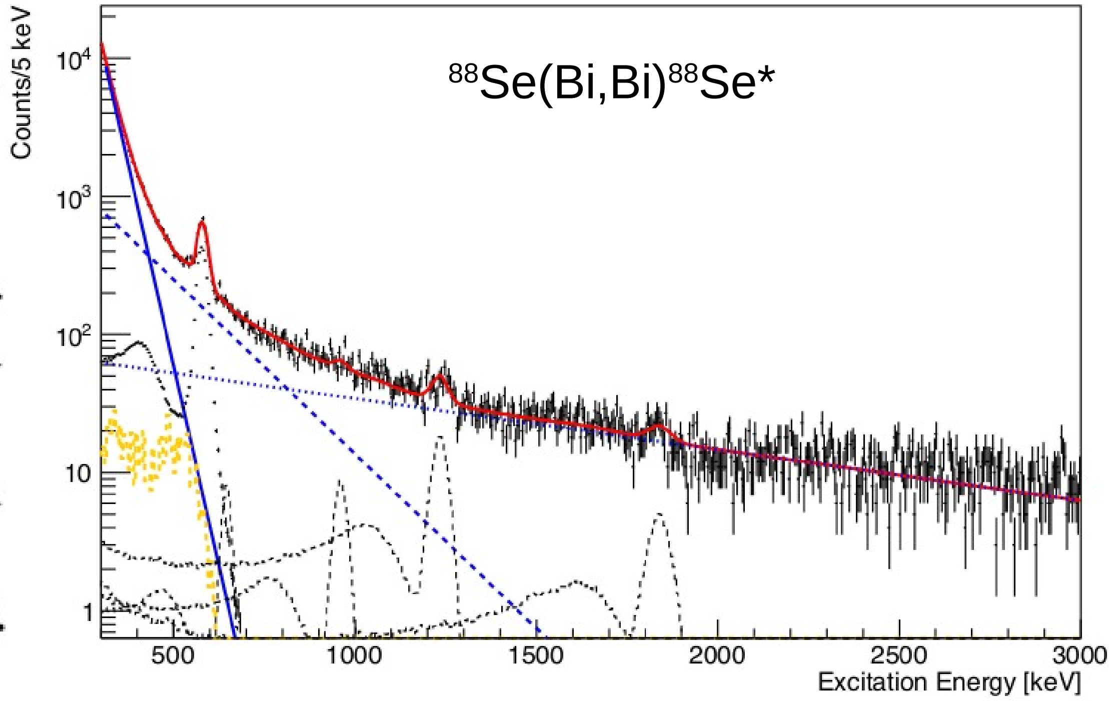
State	E_{level}	σ [mb]
2^+_1	704	13(2)
2^+_2	1399	1.8(8)
2^+_3	2208	1.4(4)
3^-_1	2594	3.8(4)
4^+_1	1567	5.9(4)



State	E_{level}	σ [mb]
2^+_1	704	169(24)
2^+_2	1399	42.5(66)
2^+_3	2208	18.2(3)
3^-_1	2594	4.9(33)

Results: ^{88}Se

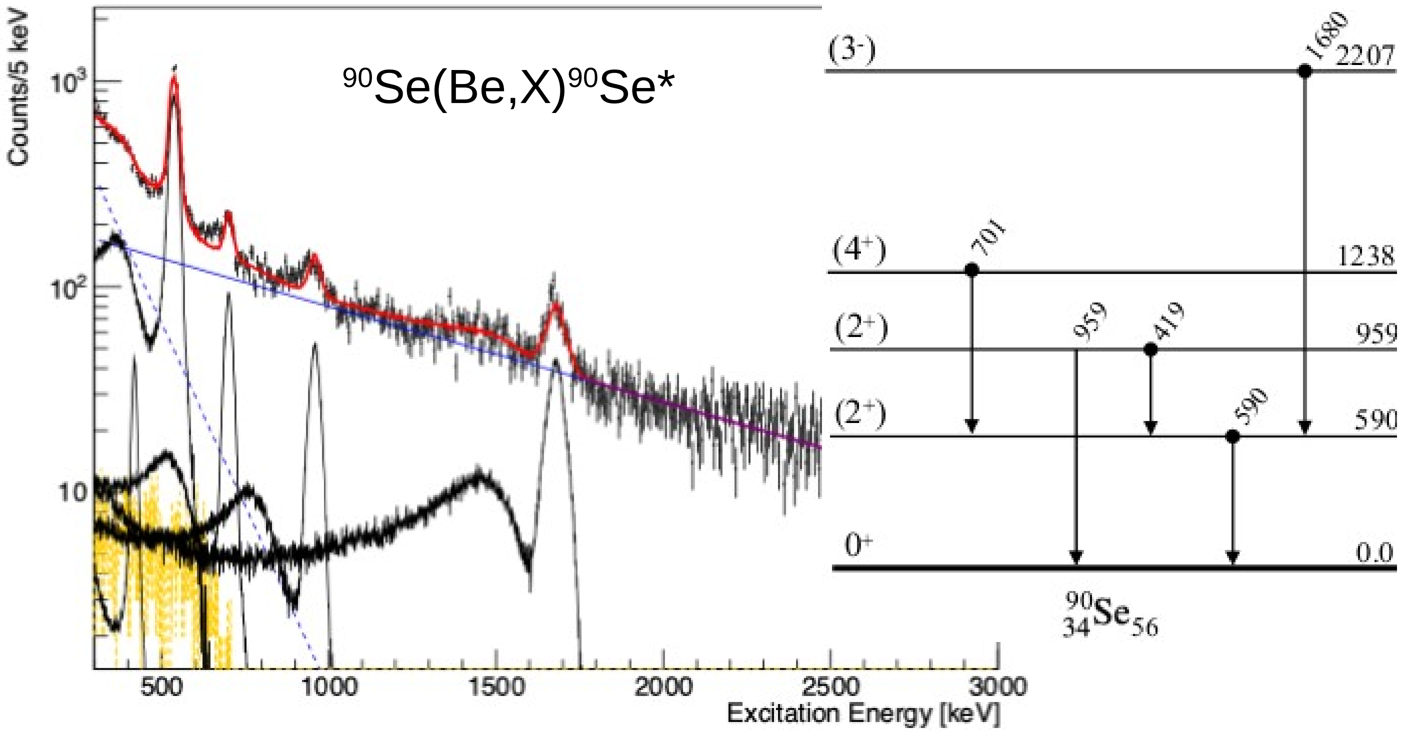


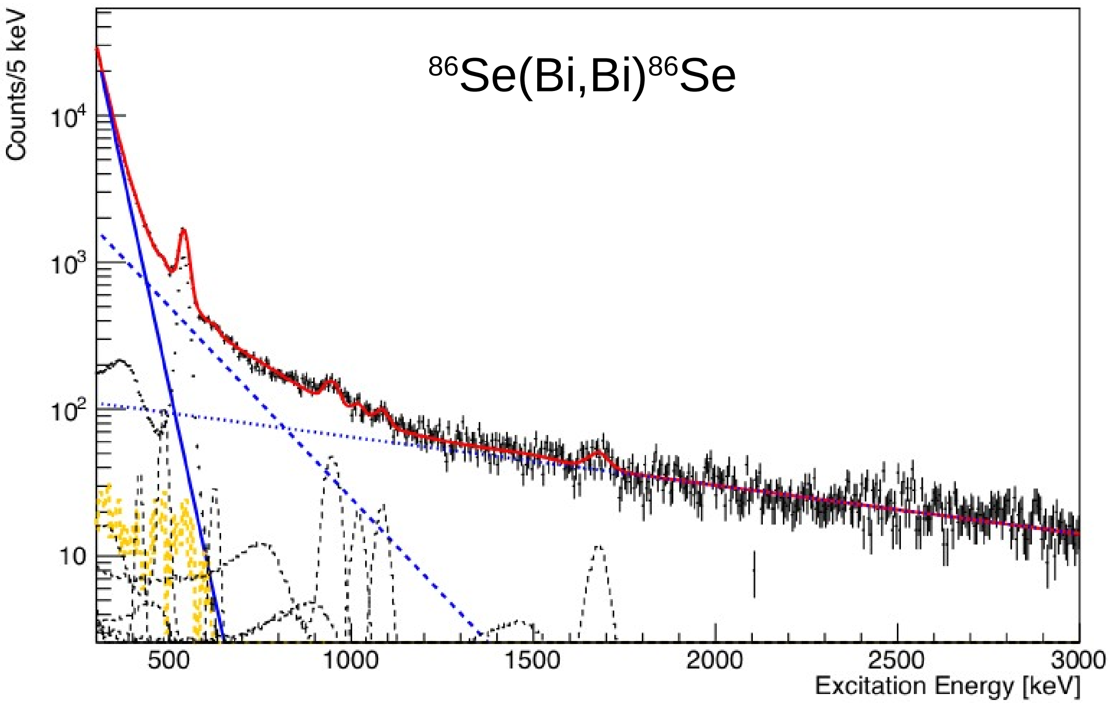


State	E_{level}	σ [mb]
2^+_1	590	17(2)
2^+_2	1232	3.3(4)
3^-_1	1840	5.3(4)
4^+_1	1551	2.1(5)

State	E_{level}	σ [mb]
2^+_1	590	195(28)
2^+_2	1232	30.7(31)
3^-_1	1840	5.6(35)

Results: ^{90}Se

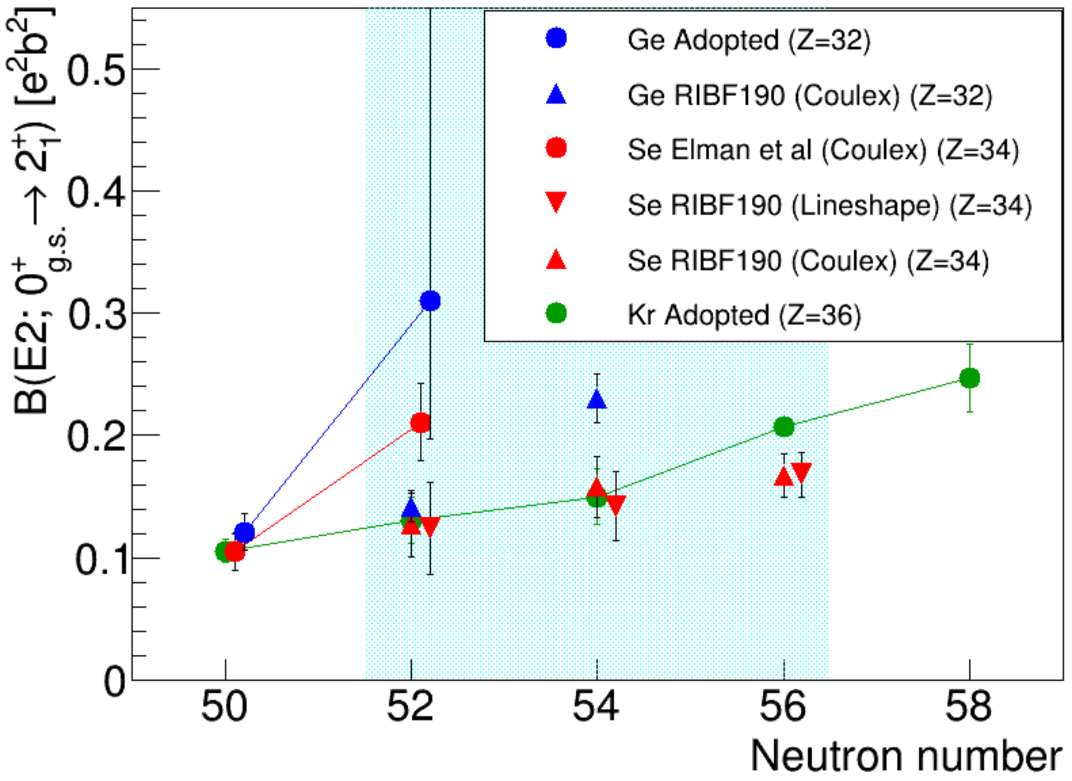


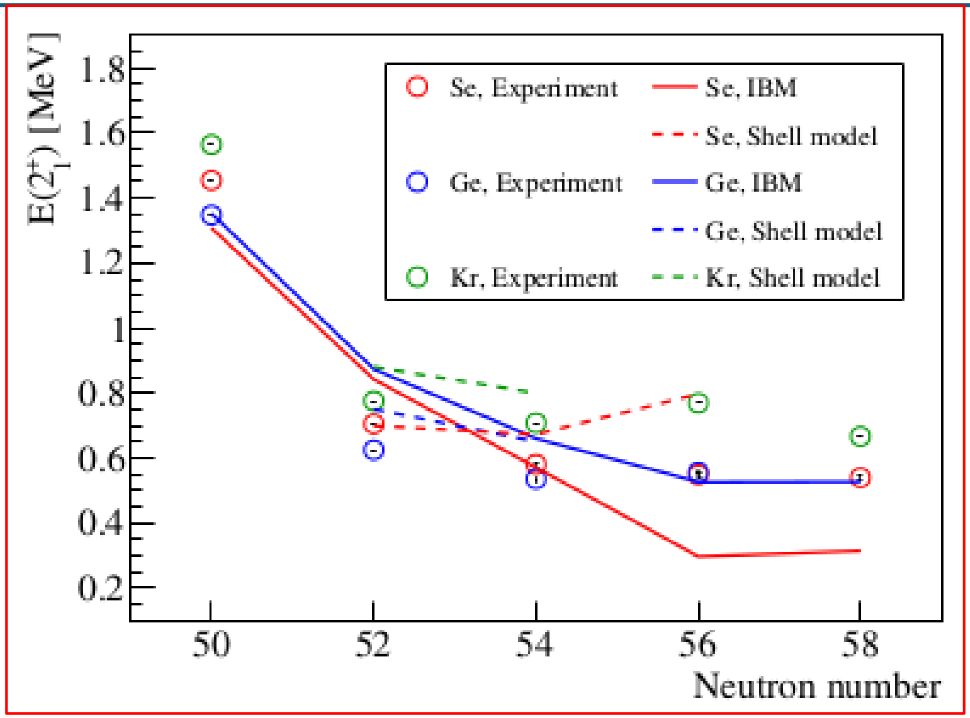


State	E_{level}	σ [mb]
2^+_1	548	17(1)
2^+_2	959	3.4(3)
3^-_1	2207	3.7(3)
4^+_1	1238	2.5(3)

State	E_{level}	σ [mb]
2^+_1	548	196(27)
2^+_2	959	25.2(20)
3^-_1	2207	7.1(23)

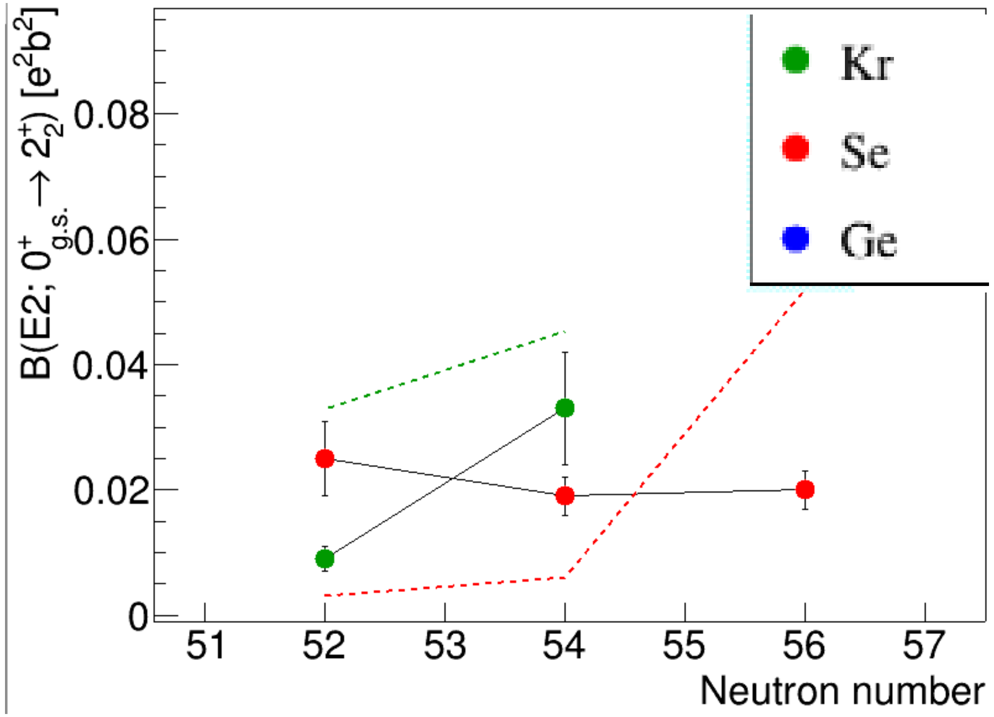
$0_{g.s.}^{+} \rightarrow 2^{+}_{1,2}$ transition probabilities

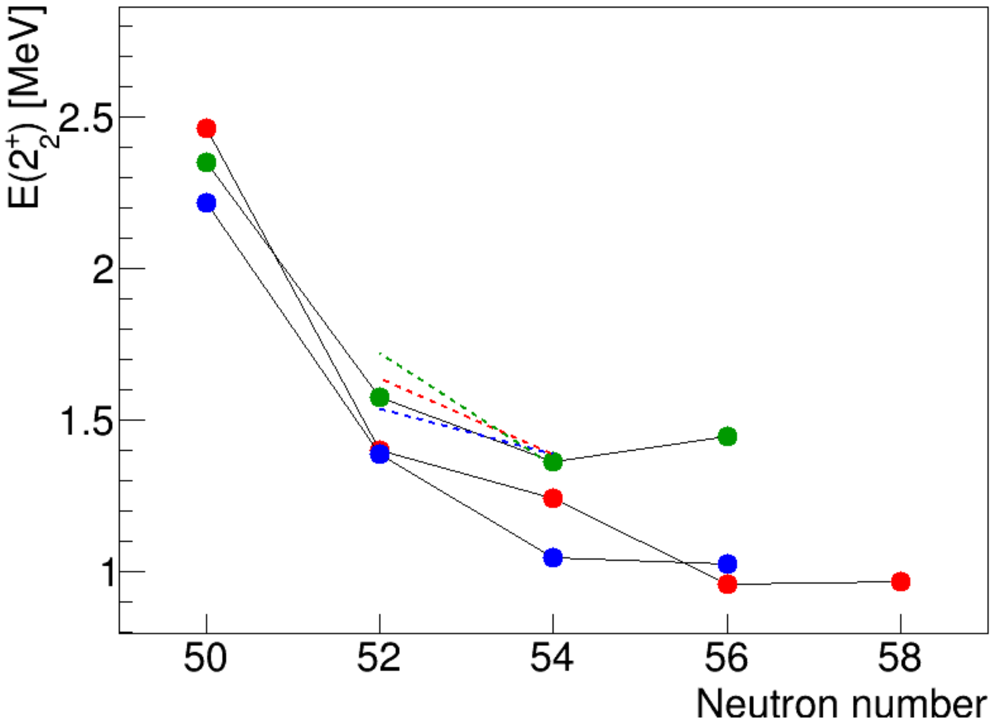




- New values reflect a less abrupt transition to collective behaviours
- B(E2) from lineshape and Coulex cross section are consistent
- In-line with $E(2_+^1)$

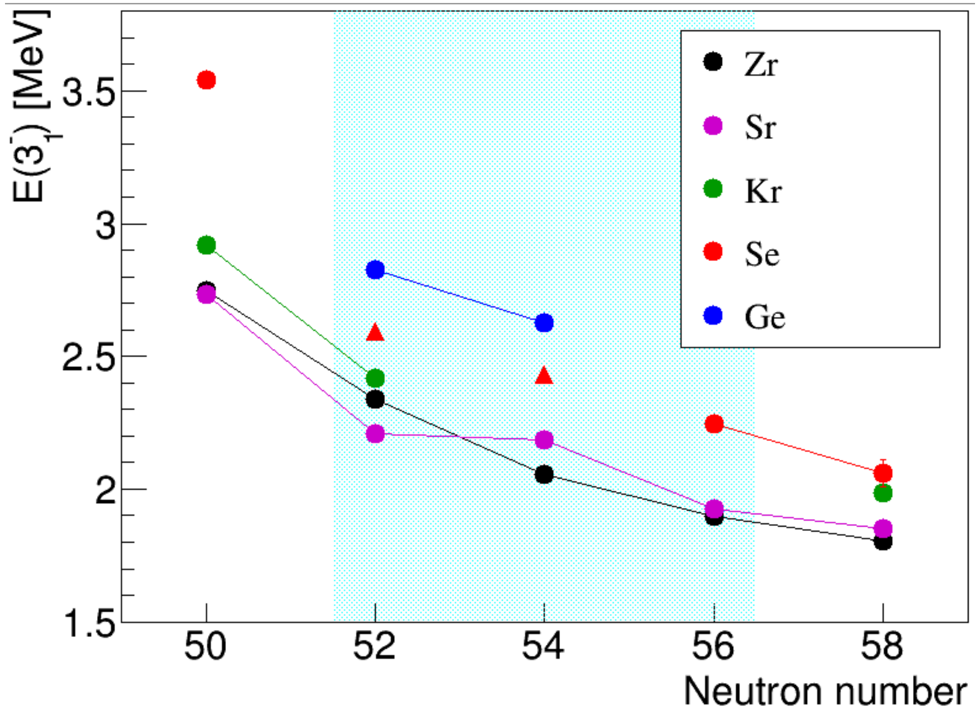
$0_{g.s.}^{+} \rightarrow 2^{+}_{1,2}$ transition probabilities

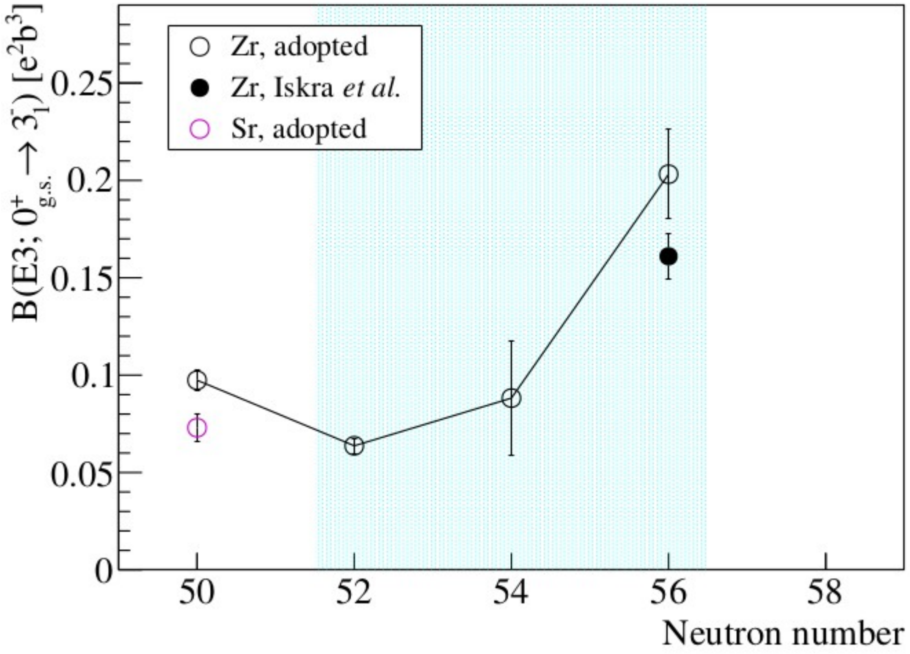




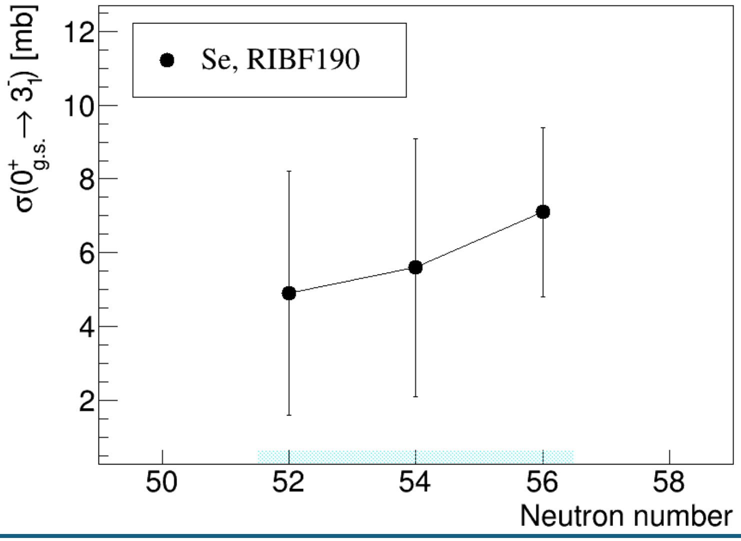
- Limited values for systematics in 2^{+}_{2} B(E2) values
  - Smoother trend in Se than the $E(2^{+}_{2})$
- Shell model which predicts shape co-existence predicts sharp increase at N=56, not seen in data.

3^-_1 state measurements





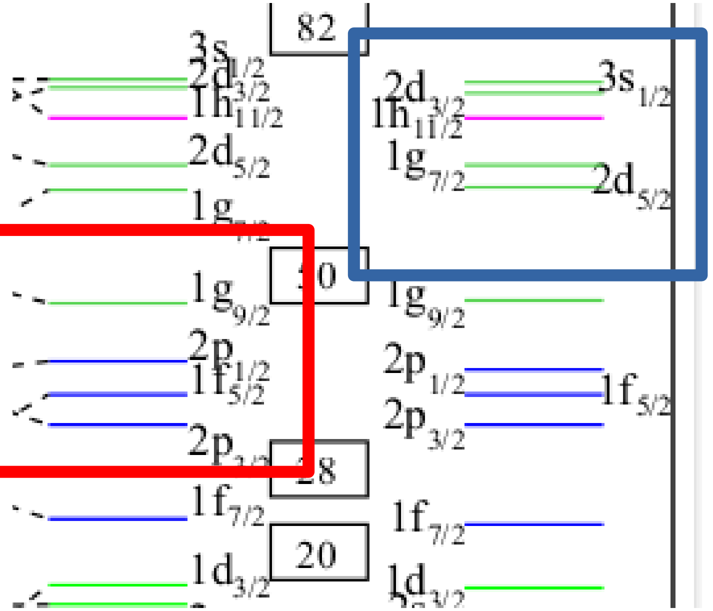
- New E(3^-_1) values complete systematics
  - Quite sharp decrease for Se
- B(E3) still work in progress….
  - Cross sections measured in this work have large uncertainties

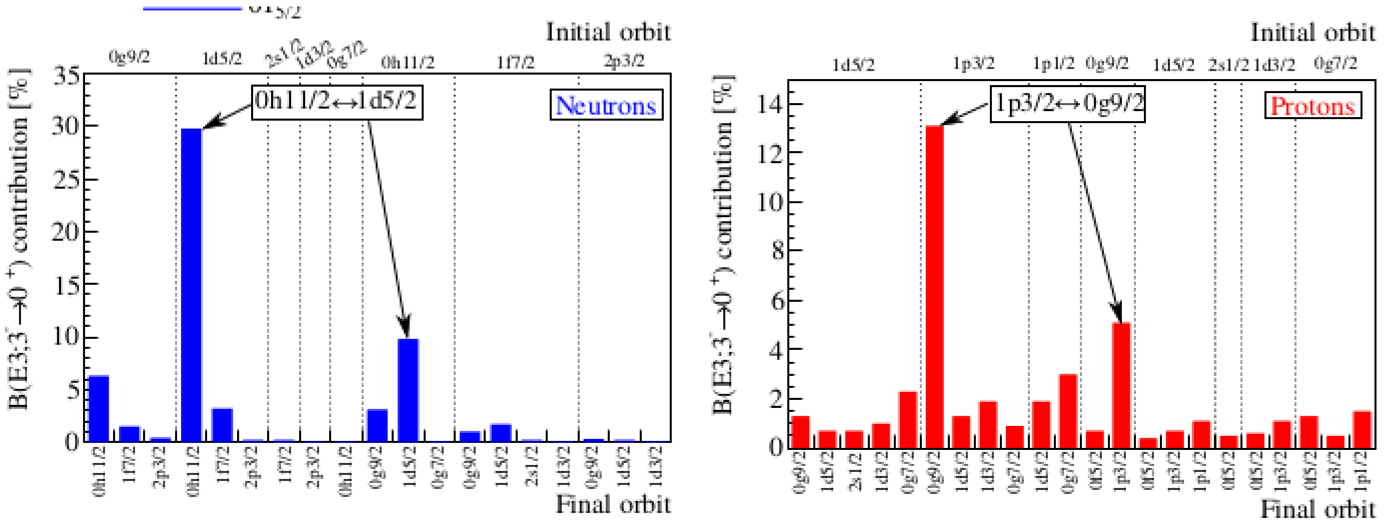


L. W. Iskra et al, Phys. Lett B 88 396 (2019).

Where next?

- Extract B(E3) from cross sections from FRESCO
- Interpretation!
  - Shell model calculations are ongoing: Ni78-II interaction: Shape coexistence/triaxility
    - π ($1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$)
    - ν($2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, $1g_{7/2}$, $1h_{11/2}$)
  - What are the active orbits?
  - Mean field calculations?





K. Sieja *et al*, Phys. Rev. C **88**, 034327 (2013)
L. W. Iskra et al, Phys. Lett B 88 396 (2019).

Thanks to the collaborators

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Consejo Superior de Investigaciones Científicas

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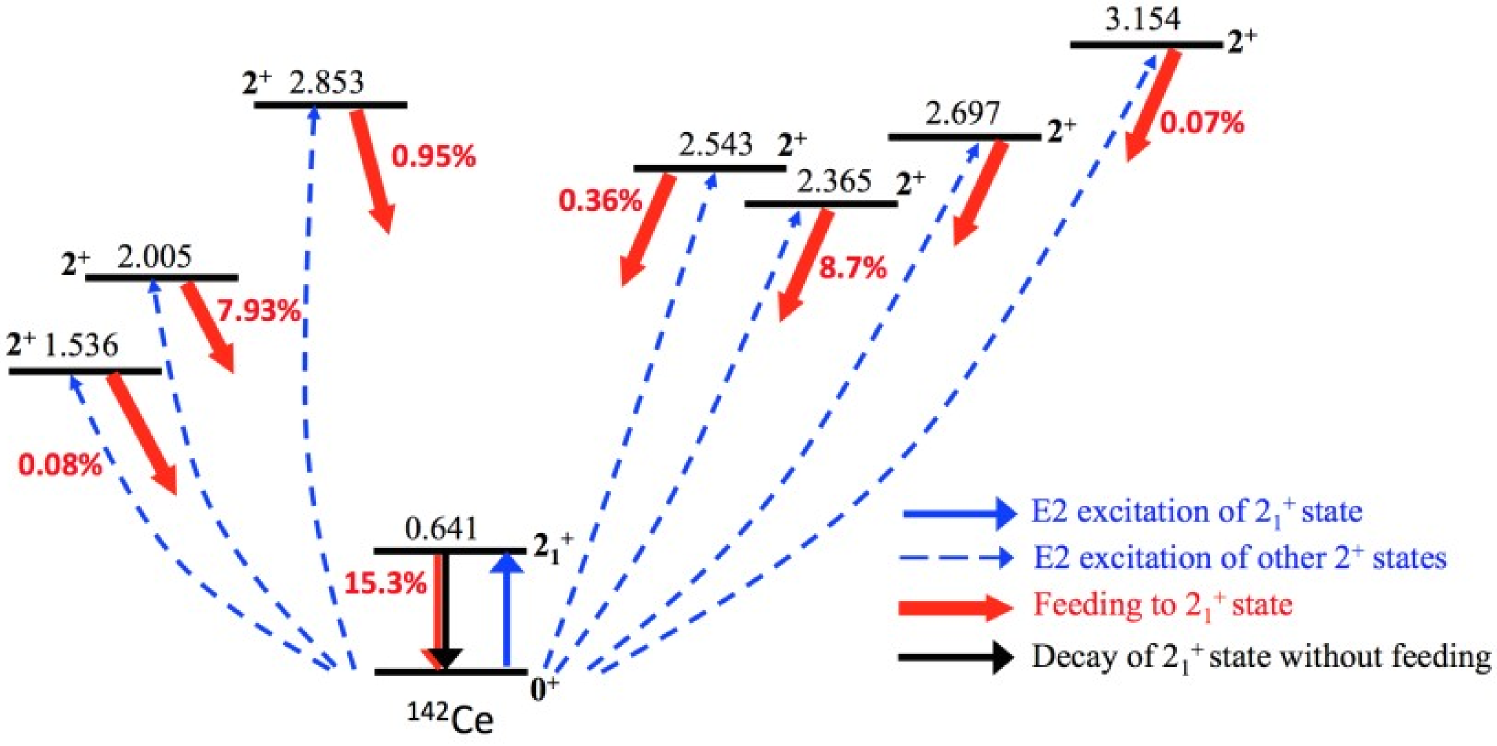
Cross section to transition probability

TABLE I. Measured cross sections, σ, and transition strengths, $B(E2)$, for all isotopes studied in this work, as well as transition strengths from the shell-model calculation described in Sec. IV are shown. The uncertainty includes both statistical uncertainties and systematic contributions from varying the background model, as well as a 5.4% uncertainty from the efficiency determination.

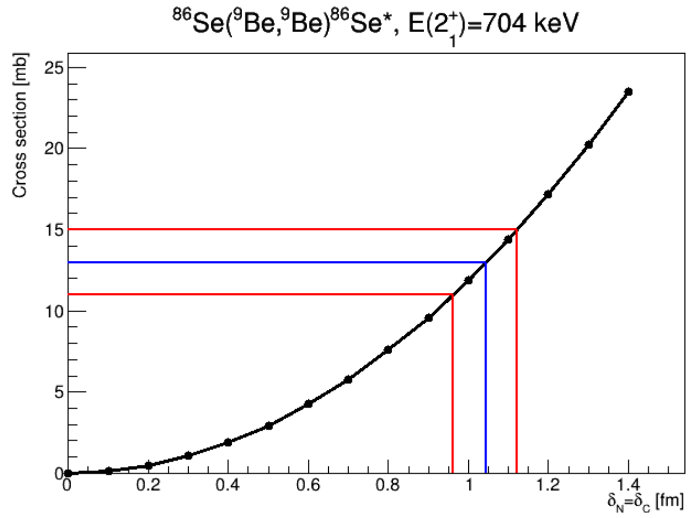
				$B(E2; J_i \rightarrow J_f)$ (e^2 fm^4)	
^{A}Z	J_i	J_f	σ (mb)	Measured	Shell model
^{88}Kr	0_1^+	2_1^+	210(30)	1310(190)	1450
	0_1^+	2_2^+	14(3)	90(20)	80
	2_2^+	2_1^+		$\leqslant$ 2010(450)	440
	0_1^+	2_3^+	50(8)	320(50)	450
	2_3^+	2_1^+		$\leqslant$ 71[a]	69
	0_1^+	(2_4^+)	11(3)	70(20)	170
^{90}Kr	0_1^+	2_1^+	180(30)	1500(230)	1740
	0_1^+	2_2^+	40(10)	330(90)	580
	2_2^+	2_1^+		360(110)	280
	0_1^+	(2_3^+)	17(13)	150(110)	230
^{86}Se	0_1^+	2_1^+	230(30)	2110(320)[b]	1910
	0_1^+	2_2^+			150
	0_1^+	2_3^+			340

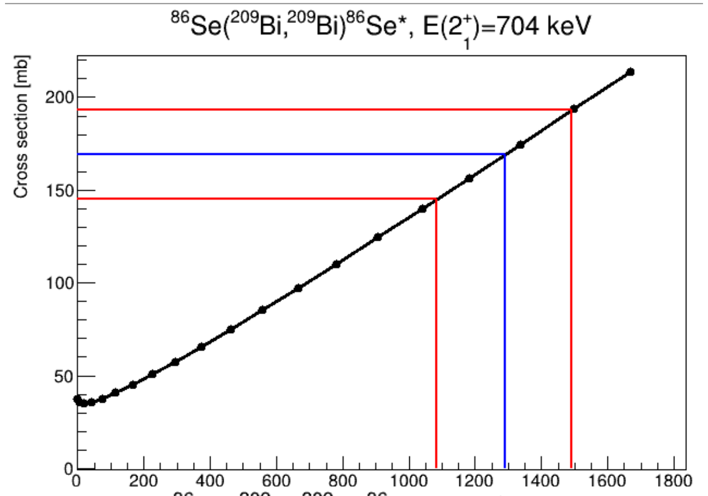
[a]The corresponding $B(M1; 2_3^+ \rightarrow 2_1^+) = 0.46(8)\mu_N^2$ strength was extracted using the multipole mixing ratio from Ref. [32] and compares well to our shell-model prediction of $0.51\mu_N^2$ obtained with standard orbital and spin nucleon g factors.

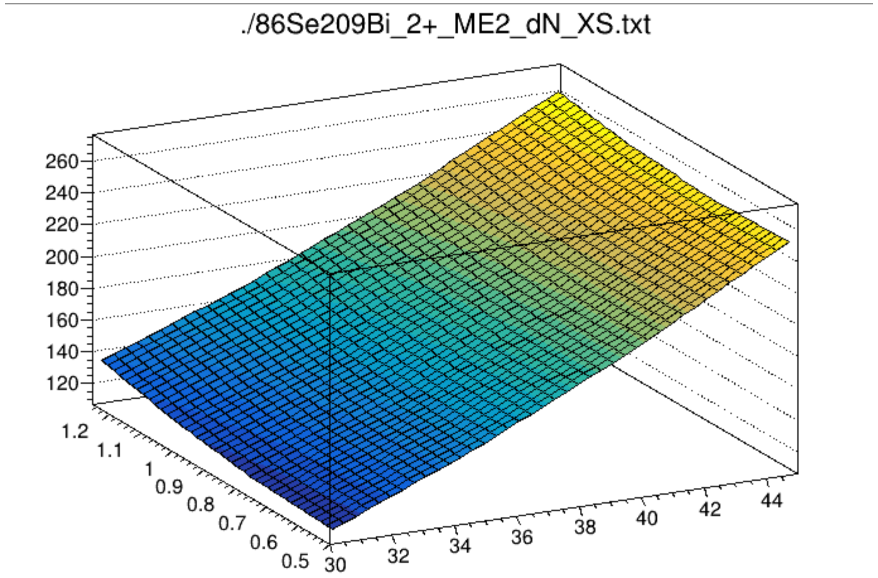
[b]See Sec. III C for discussion of possible unobserved feeding contributions.

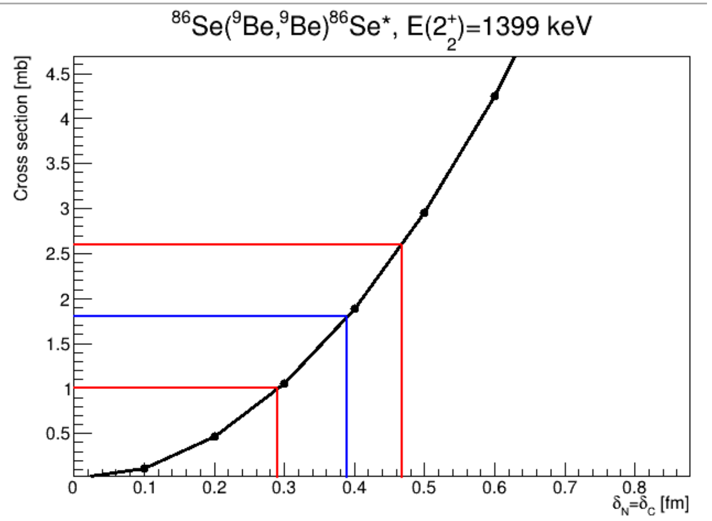


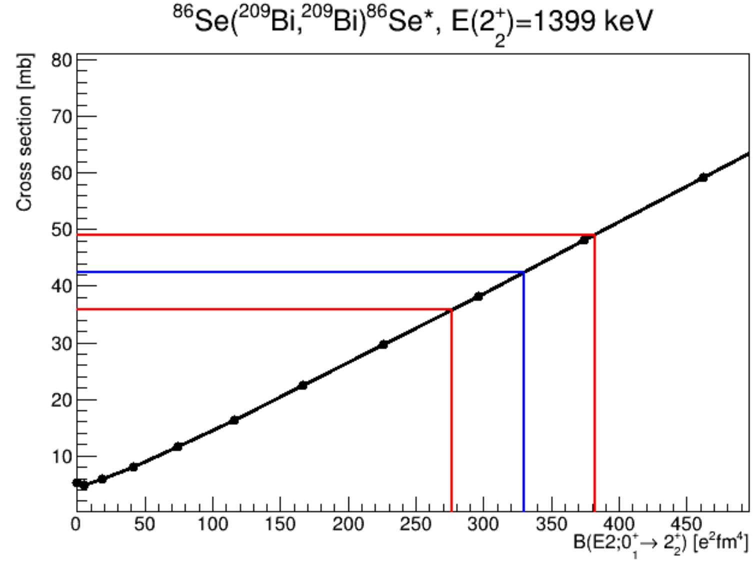
Cross section to transition probability

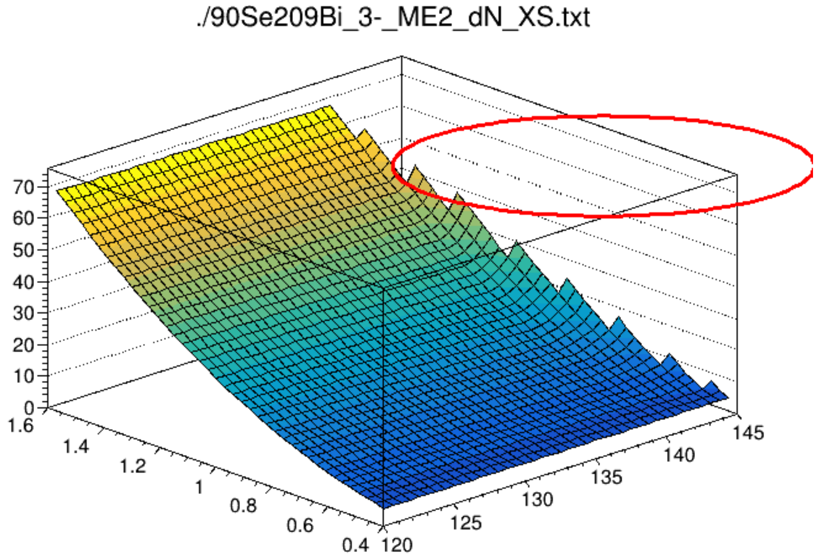












Realising the potential of HISPEC

- Rigorous implementation and commissioning of AGATA
  - Build confidence of abilities and **results**
  - Commitment to **timely** 4pi
  - Reliable analysis procedures for online and offline:
    - What is the **final** word in tracking algorithms? (Is there a **final** word?)
- Realistic physics cases

- **Coulomb excitation**
  - Large body of work at ~150 MeV/u (RIBF) s
    importance of Coulomb-nuclear interferenc
    - How about at higher energies? How can t
      exploited for Coulomb multipolarimetry?
    - **Incoming/outoing tracking capabilities**
    - **Light and heavy target**
  - Use safe Coulex results as anchor points