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Configuration mixing investigation in Ge isotopes through *E0* strength measurements

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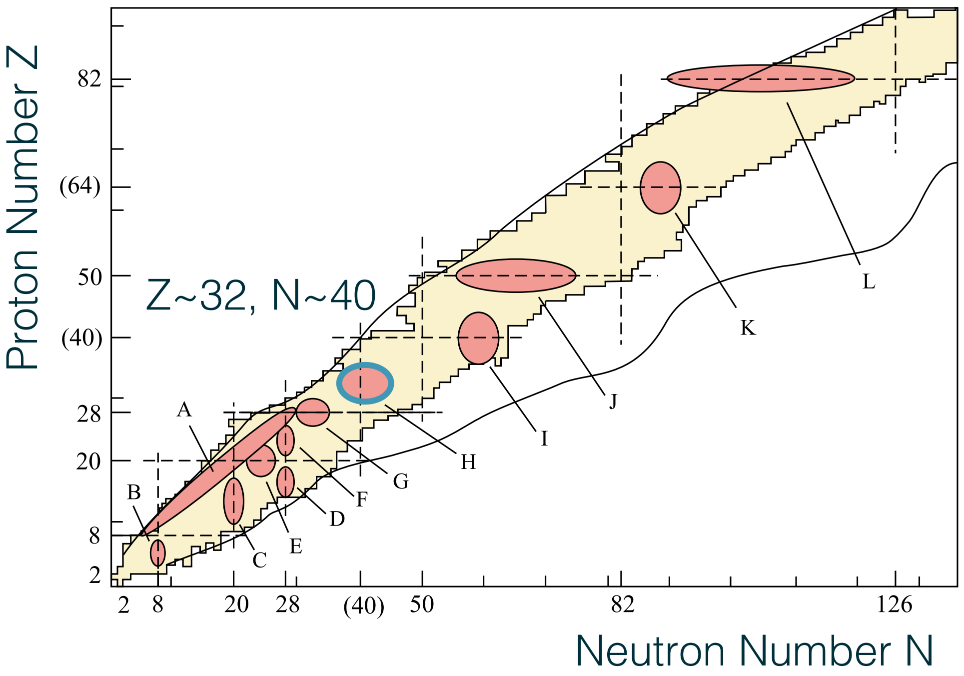
Nuclear Structure 2022 – 16th June 2022

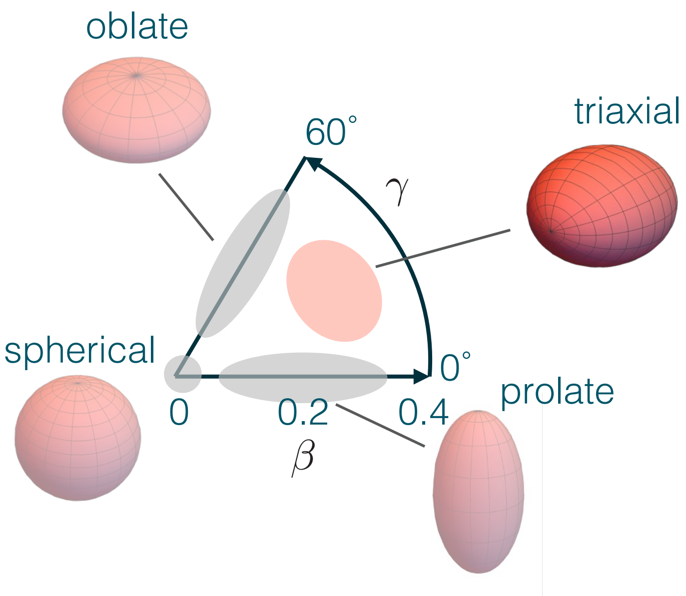
Outline

- Motivation
  Shape Coexistence in Nuclei
- Experimental Details
  The GRIFFIN Spectrometer at TRIUMF
- Analysis Techniques
  γ-Ray and Electron Spectroscopy
- Results
  E0 Strength Measurements
- Summary

Shape Coexistence in the Nuclear Landscape



➤ Heyde and Wood, Rev. of Mod. Phys. 83, 1467 (2011)



- ➤ ^{76}Ge – Toh *et al.*, PRC 87, 041304(R) (2013)
  - ➤ ^{72}Ge – Ayangeakaa *et al.*, PLB 754 (2016)
  - ➤ ^{76}Ge – Ayangeakaa *et al.*, PRL 123 (2019)
  - ➤ ^{78}Ge – Forney *et al.*, PRL 120 (2018)
- ➤ ^{66}Zn – Rocchini *et al.*, PRC 103, 014311 (2021)
- ➤ ^{68}Zn – Koizumi *et al.*, Nucl. Phys. A730, 46 (2004)

Shape Coexistence along the Ge Chain

Motivation

Experimental Details

Analysis Techniques

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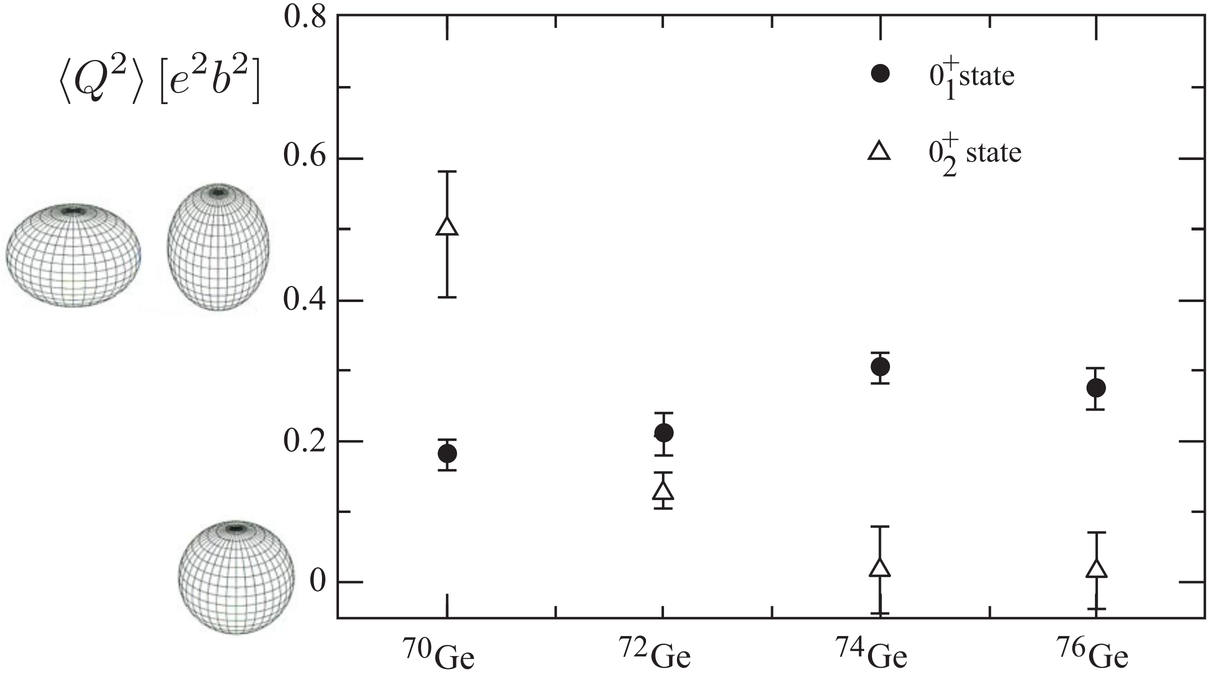
Summary

Electric quadrupole moment

Radial deviation from sphericity

$$\langle Q^2 \rangle \propto \beta^2$$



- ➤ Figure from Sugawara *et al.*, Eur. Phys. J. A 16, 409–414 (2003)
- ➤ Coulex data from Sugawara *et al.,* Eur. Phys. J. A 16, 409–414 (2003), Kotliński *et al.,* Nucl. Phys. A 519, 646–658 (1990), Toh *et al.,* Eur. Phys. J. A 9, 353–356 (2000), Toh *et al.,* J. Phys. G: Nucl. Part. Phys. 27, 1475 (2001)

Configuration Mixing and *E0* Strengths

Motivation

Experimental Details

Analysis Techniques

Results

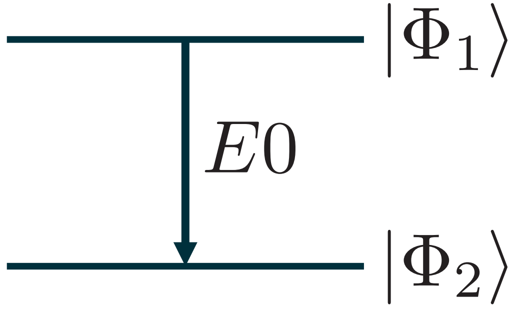
Summary

In a two-state mixing scenario

$$\Phi_1 = \alpha\Psi_1 + \beta\Psi_2$$

$$\Phi_2 = -\beta\Psi_1 + \alpha\Psi_2$$

the *E0* transition strength can be related to the degree of mixing:

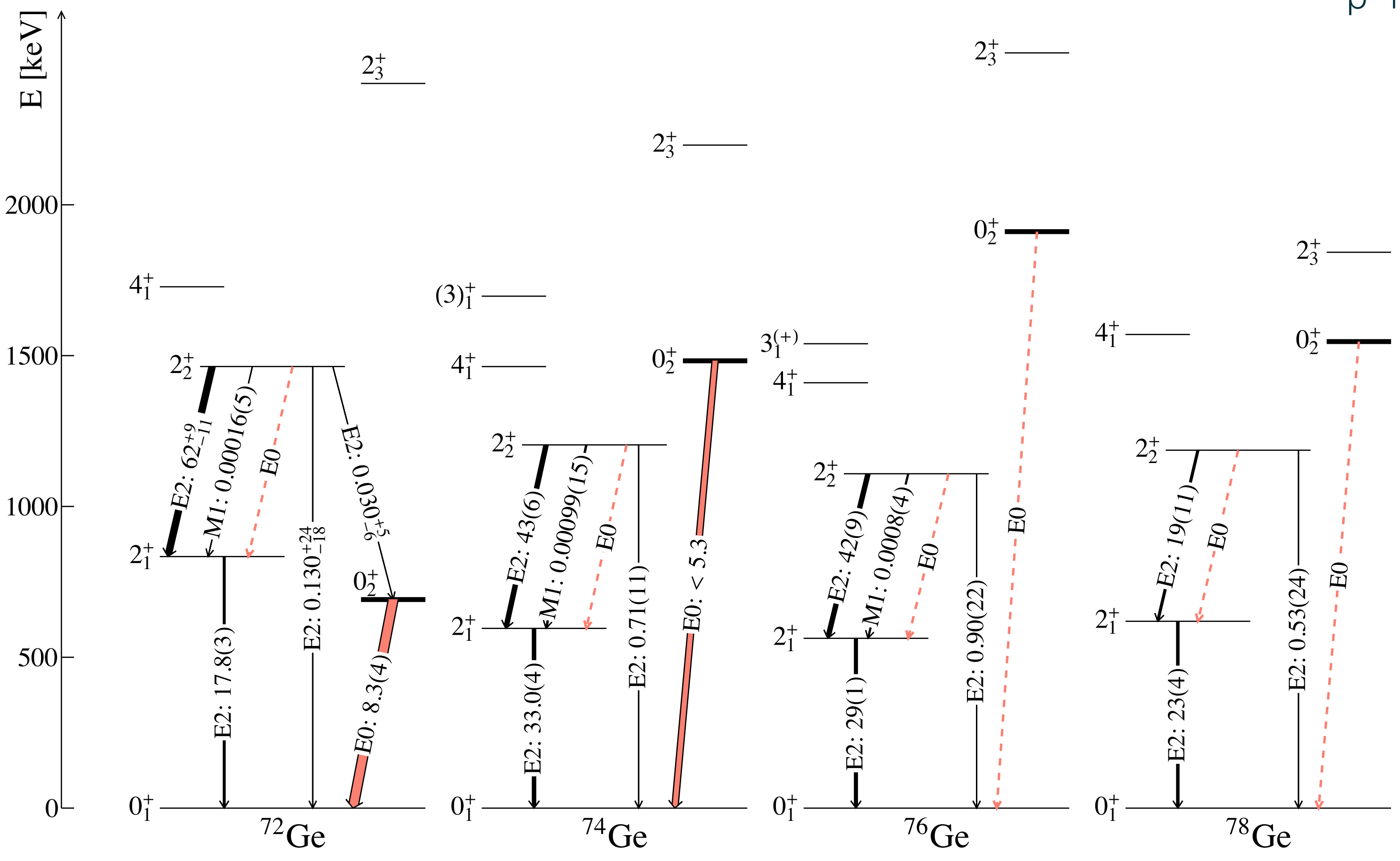


$$\rho^2(E0) \simeq \alpha^2\beta^2(\Delta\langle r^2\rangle)^2$$

E0 Strength Measurements in Ge Isotopes

$$\rho^2(E0) \simeq \alpha^2\beta^2(\Delta\langle r^2\rangle)^2$$

B(*M1*) and B(*E2*) in W.u.
ρ² in milliunits



- ➤ Nuclear Data Sheets 111, 1 (2010)
- ➤ Nuclear Data Sheets 107, 1923 (2006)
- ➤ Nuclear Data Sheets 74, 63 (1995)
- ➤ Nuclear Data Sheets 110, 1917 (2009)
- ➤ Kibédi *et al.*, Prog. Part. Nucl. Phys. 123, 103930 (2022)

β-Decay Experiments @ TRIUMF

Motivation

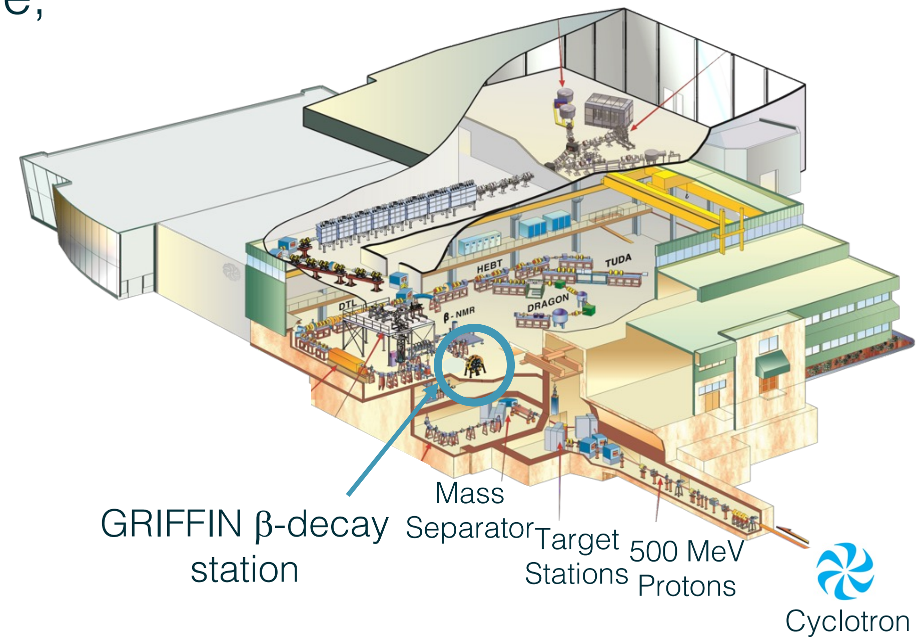
Experimental Details

Analysis Techniques

Results

Summary

- *E0* strength measurements in $^{72,74,76,78}Ge$, populated through β decay.
- Radioactive Ga beams were produced at the ISAC facility @ TRIUMF.
- Two experiments were performed:
  i. ^{72}Ga beam (10^5 pps) in 2017
  ii. $^{72,74,76,78}Ga$ beams (10^4-10^6 pps) in 2019



https://www.triumf.ca/research-program/research-facilities/isac-facilities

The GRIFFIN Decay Spectrometer and its Ancillary Detectors

Motivation

Experimental Details

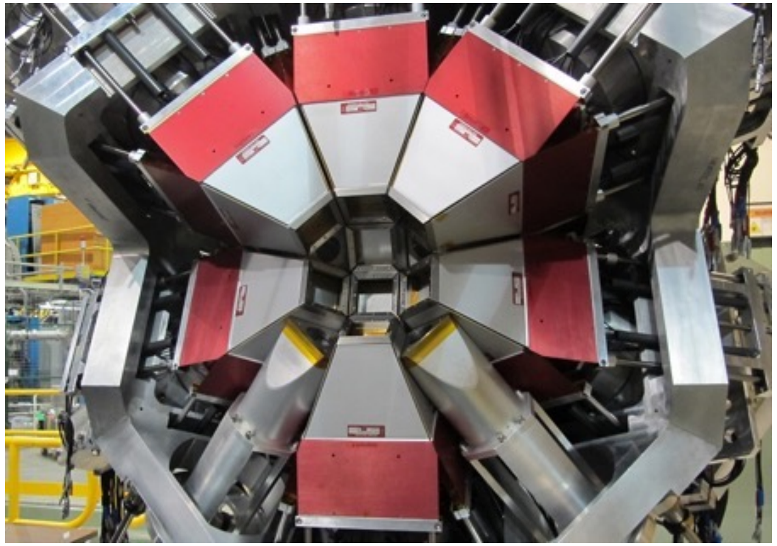
Analysis Techniques

Results

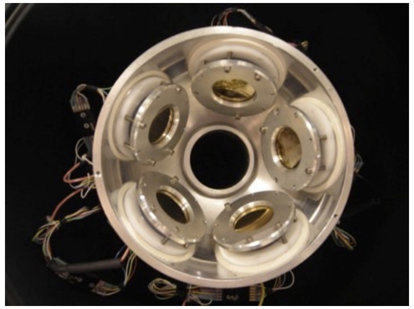
Summary

GRIFFIN
(15 HPGe clovers)

→ γ

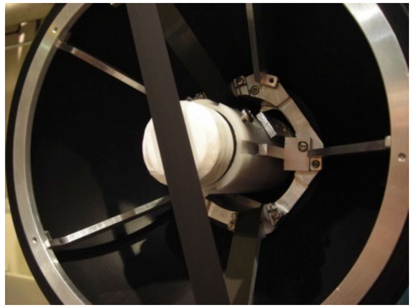


➤ A.B. Garnsworthy *et al.*, NIM A 918, 9 (2019).
➤ A.B. Garnsworthy *et al.*, NIM A 853, 85 (2017).



PACES
(5 cooled Si(Li)s)

→ e^-



Zero Degree Scintillator

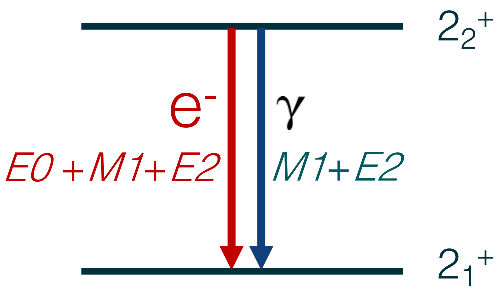
→ β

8 $LaBr_3(Ce)$ scintillators

→ Fast timing of γ rays to measure state lifetimes

What we need to determine *E0* strengths

- Experimental ICC with PACES electron spectra $\alpha_{K,\mathrm{exp}}$
- *E2/M1* Mixing Ratio with $\gamma\gamma$ angular correlations δ
- State Lifetime from literature τ



E0 Strength Measurements in 2_2^+-2_1^+ transitions: Internal Conversion Coefficient measurements

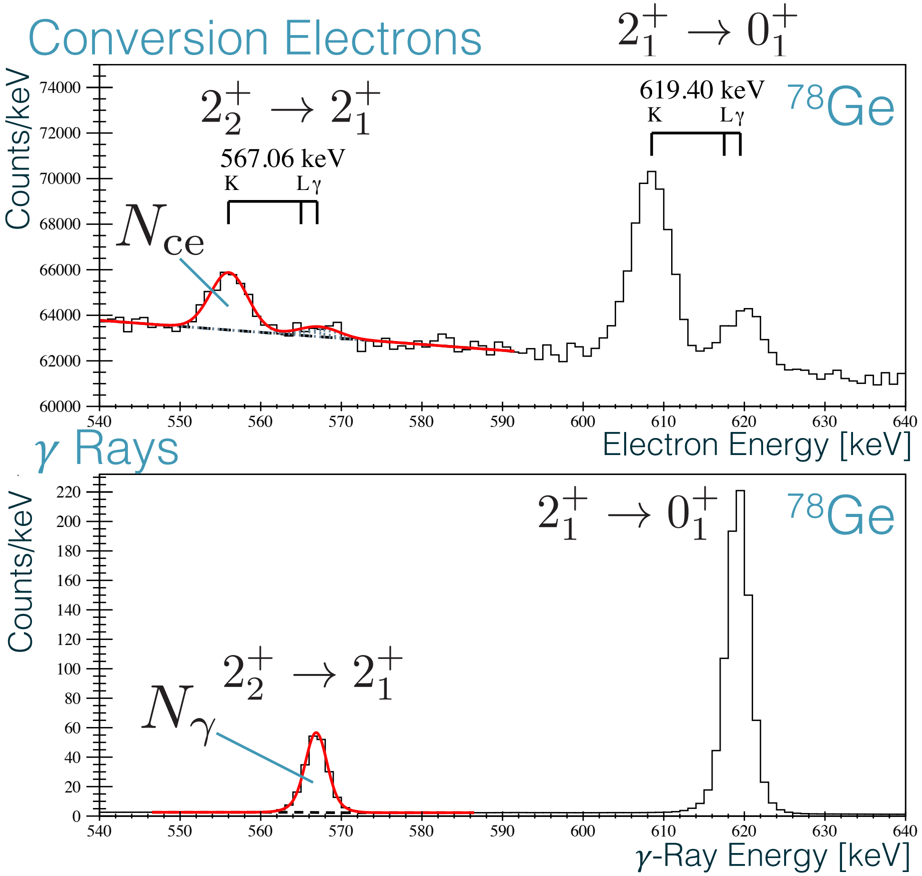
Motivation

Experimental Details

Analysis Techniques

Results

Summary



$$\alpha_{K,\mathrm{exp}} = \frac{N_{\mathrm{ce}}/\epsilon_{\mathrm{ce}}}{N_\gamma/\epsilon_\gamma}$$

Nucleus	$\alpha_{\mathrm{K,BrIcc}}$*	$\alpha_{\mathrm{K,exp}}$	$\alpha_{\mathrm{K,exp}}/\alpha_{\mathrm{K,BrIcc}}$
^{72}Ge	0.001 053(15)	0.001 16(6)	1.10(6)
^{74}Ge	0.001 125(16)	0.0011(3)	1.0(2)
^{76}Ge	0.001 475(21)	0.001 61(14)	1.09(10)
^{78}Ge	0.001 361(20)	0.001 31(4)	0.96(4)

* http://bricc.anu.edu.au, T. Kibédi *et al.*, NIM A 589 (2008)

E0 Strength Measurements in 2_2^+-2_1^+ transitions: $\gamma\gamma$ Angular Correlations to Measure Mixing Ratios

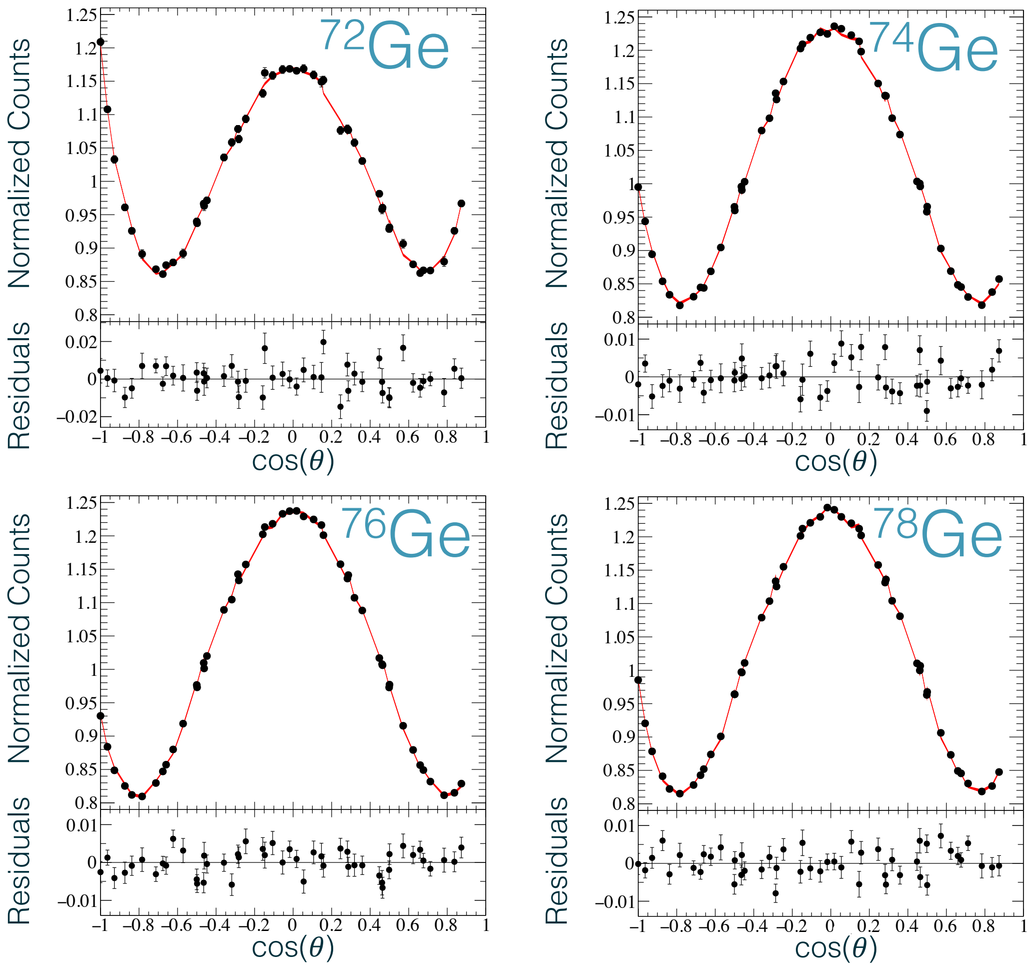
Motivation

Experimental Details

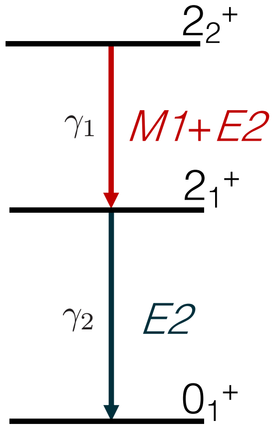
Analysis Techniques

Results

Summary



- 51 angular bins θ at GRIFFIN.
    - ➤ Smith, MacLean *et al.*, NIM A 922 47 (2019).



Nucleus	E_{γ_1}-E_{γ_2}	Counts	δ_1^{exp}
^{72}Ge	630-834	2.44×10^6	+26(2)
^{74}Ge	608-596	1.48×10^7	+2.87(3)
^{76}Ge	546-563	2.81×10^7	+1.85(2)
^{78}Ge	567-619	3.10×10^7	+2.46(3)

E0 Strength Measurements in Ge isotopes

Motivation

Experimental Details

Analysis Techniques

Results

Summary

- 2_2^+-2_1^+ transitions

Nucleus	$I_i^\pi \to I_f^\pi$	$T_{1/2}(I_i^\pi)$	$\rho^2_{\rm exp}(E0) \times 10^3$	$\rho^2_{\rm lit}(E0) \times 10^3$ *
^{72}Ge	$2_2^+ \to 2_1^+$	4.5^{+8}_{-6} ps	100(50)	–
^{74}Ge	$2_2^+ \to 2_1^+$	5.4(8) ps	<0.22	–
^{76}Ge	$2_2^+ \to 2_1^+$	8.0(15) ps	<120	–
^{78}Ge	$2_2^+ \to 2_1^+$	12(6) ps	<6.5	–

- 0_2^+-0_1^+ transitions

Nucleus	$I_i^\pi \to I_f^\pi$	$T_{1/2}(I_i^\pi)$	$\rho^2_{\rm exp}(E0) \times 10^3$	$\rho^2_{\rm lit}(E0) \times 10^3$ *
^{72}Ge	$0_2^+ \to 0_1^+$	444.2(8) ns	–	8.3(4)
^{74}Ge	$0_2^+ \to 0_1^+$	$6\ ^{+15}_{-3}$ ps	<450	<5.3
^{76}Ge	$0_2^+ \to 0_1^+$	>0.8 ps	–	–
^{78}Ge	$0_2^+ \to 0_1^+$	25(11) ps	<120	–

* Kibédi *et al.*, Prog. Part. Nucl. Phys. 123, 103930 (2022)

E0 Strength Measurements in I^{+}-I^{+} transitions: Discussion

Motivation

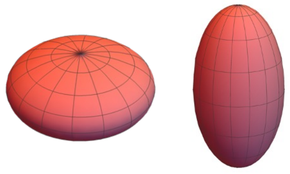
Experimental Details

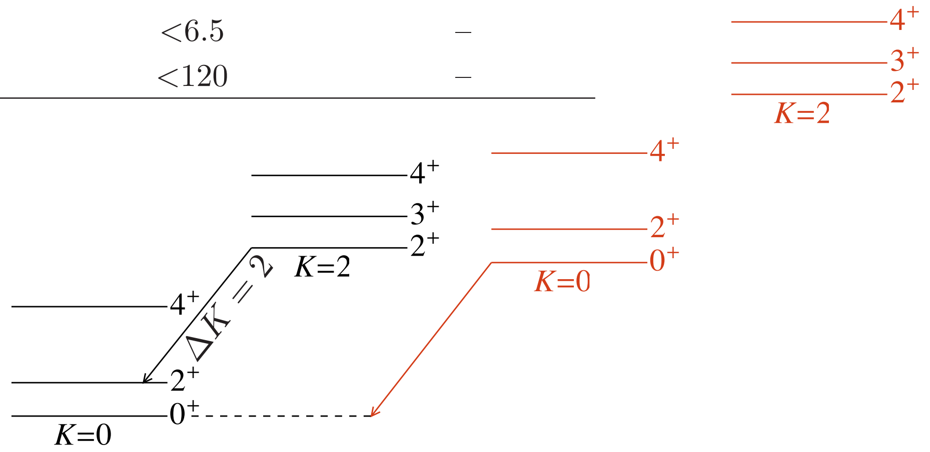
Analysis Techniques

Results

Summary

Nucleus	$I_i^\pi \to I_f^\pi$	$T_{1/2}(I_i^\pi)$	$\rho^2_{\mathrm{exp}}(E0)\times 10^3$	$\rho^2_{\mathrm{lit}}(E0)\times 10^3$
^{72}Ge	$2_2^+ \to 2_1^+$	4.5^{+8}_{-6} ps	100(50)	–
	$0_2^+ \to 0_1^+$	444.2(8) ns	–	8.3(4)
^{74}Ge	$2_2^+ \to 2_1^+$	5.4(8) ps	<0.22	–
	$0_2^+ \to 0_1^+$	$6\ ^{+15}_{-3}$ ps	<450	<5.3
^{76}Ge	$2_2^+ \to 2_1^+$	8.0(15) ps	<120	–
	$0_2^+ \to 0_1^+$	>0.8 ps	–	–
^{78}Ge	$2_2^+ \to 2_1^+$	12(6) ps	<6.5	–
	$0_2^+ \to 0_1^+$	25(11) ps	<120	–





E0 Strength Measurements in I^+-I^+ transitions: Discussion

Nucleus	$I_i^\pi \rightarrow I_f^\pi$	$T_{1/2}(I_i^\pi)$	$\rho^2_{exp}(E0) \times 10^3$	$\rho^2_{lit}(E0) \times 10^3$
^{72}Ge	$2_2^+ \rightarrow 2_1^+$	4.5^{+8}_{-6} ps	100(50)	–
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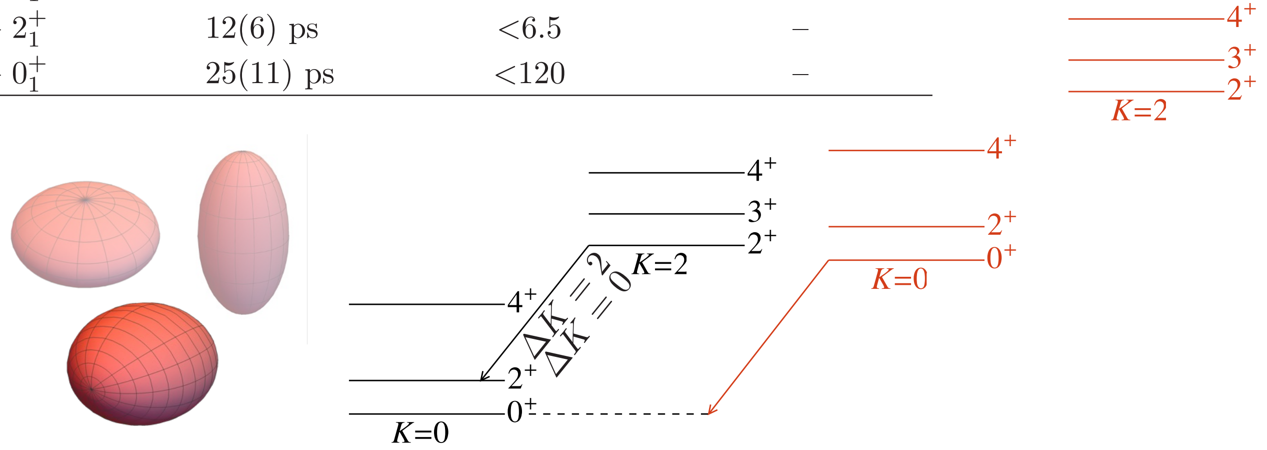

⟶ ρ^2(*E0*;2-2) values point to the fact that both triaxiality and configuration mixing are necessary to generate finite *E0* strength between I>0 states belonging to the same configuration.

Summary

Motivation

Experimental Details

Analysis Techniques

Results

Summary

- β-decay experiment at TRIUMF
  aimed at investigating the structure of Ge isotopes
- Analysis techniques involved:
  - Internal conversion coefficient measurement for 2_2^+-2_1^+ transitions
  - Angular correlation analysis
    to measure mixing ratio *E2*/*M1* of 2_2^+-2_1^+ transitions
- $\rho^2(E0)$ values indicate that a competition between triaxiality and configuration mixing can generate finite *E0* strength between I>0 states belonging to the same configuration.
- Future perspectives: fast-timing lifetime analysis to improve literature values, exploiting the $LaBr_3(Ce)$ collected data, and theoretical calculations.

Thank You

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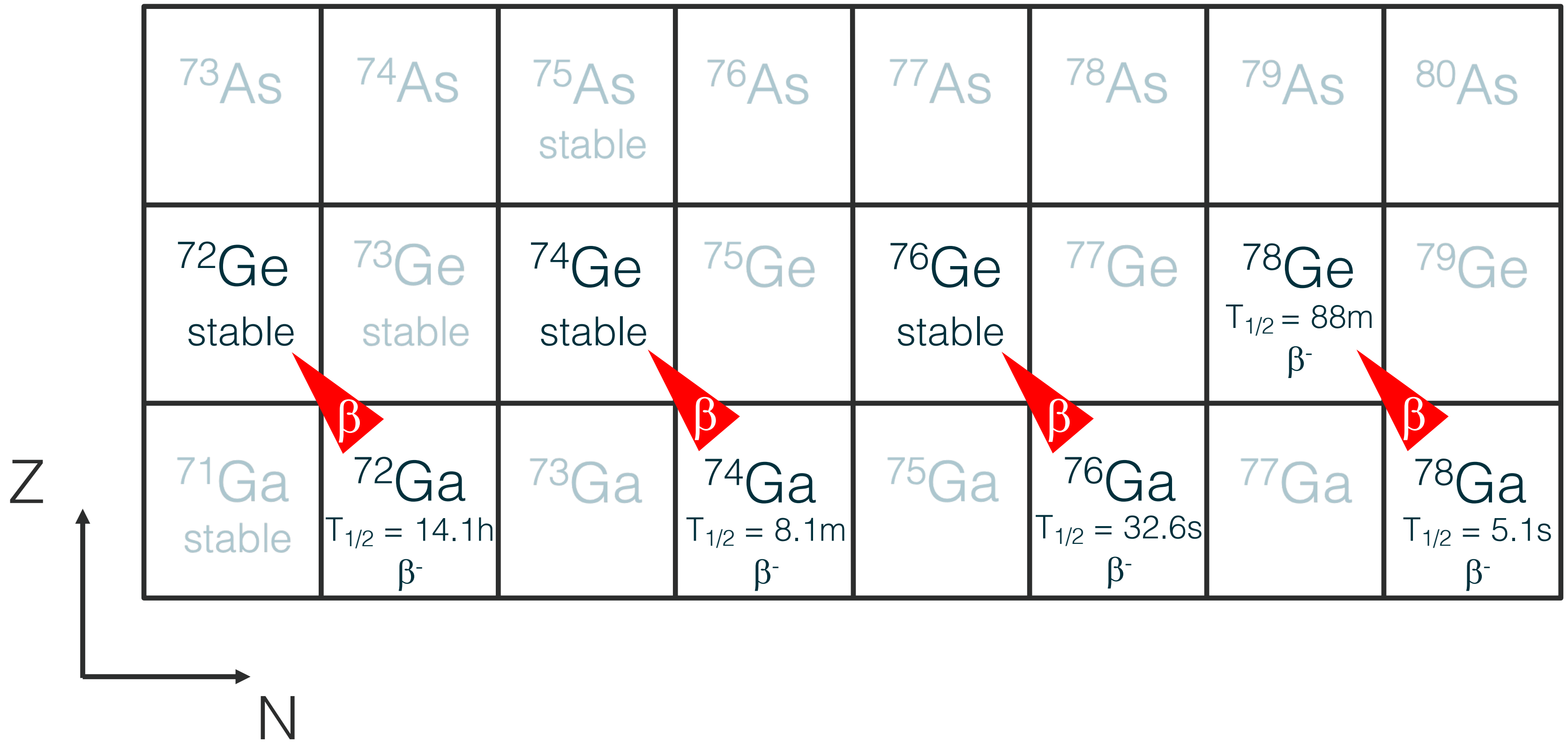
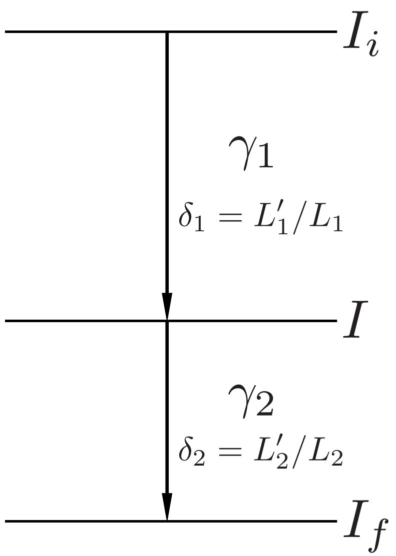
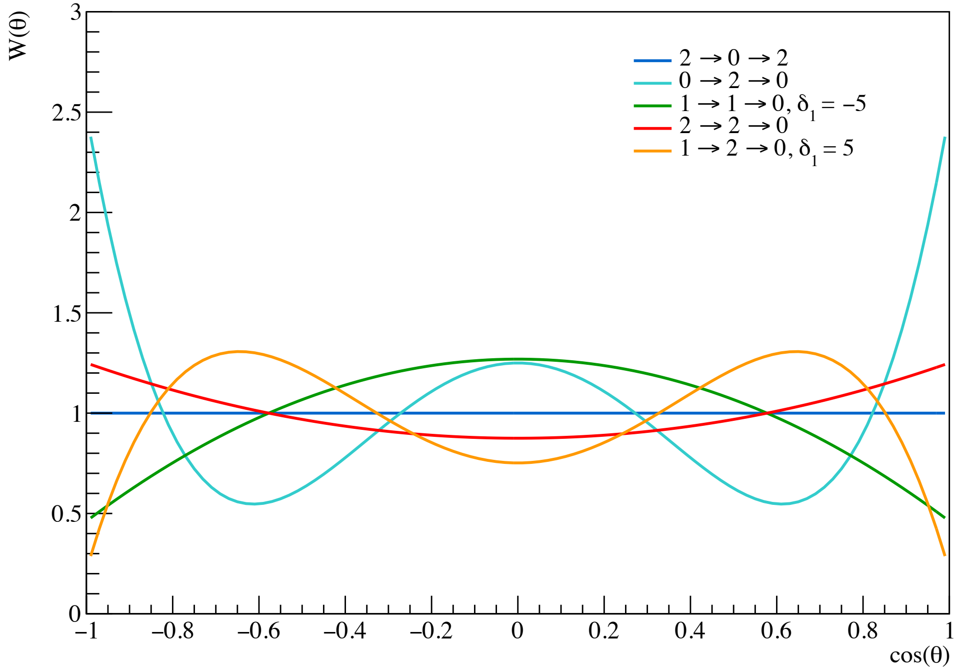
GRIFFIN

The Ge isotopic chain



γγ Angular Correlations





$$W(\theta) = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$$

$$a_k = a_k(I_i, I, I_f, L_1, L'_1, L_2, L'_2, \delta_1, \delta_2)$$

γγ Angular Correlations

Fitting experimental correlations

$$W(\theta_i)_{\mathrm{exp}} = a_0[1 + a_2 P_2(\cos\theta_i) + a_4 P_4(\cos\theta_i)]$$

$$a_k = \frac{\alpha_k + \beta_k\delta_1 + \gamma_k\delta_1^2}{1+\delta_1^2}$$

Non-linear fit by a_0, δ_1.

- delta measurements
- spin assignments

E0 Strength

Branching ratio of *E0*/*E2* transitions

Atomic factors

$$\rho^2(E0) = \frac{I_K(E0)}{I_K(E2)} \frac{\alpha_K(E2)}{\Omega_K(E0)} \frac{BR(E2_\gamma)}{\tau}$$

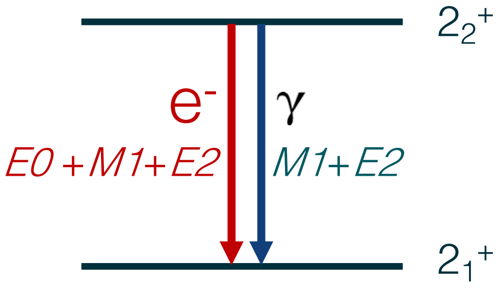
Branching ratio of *E2*

State lifetime

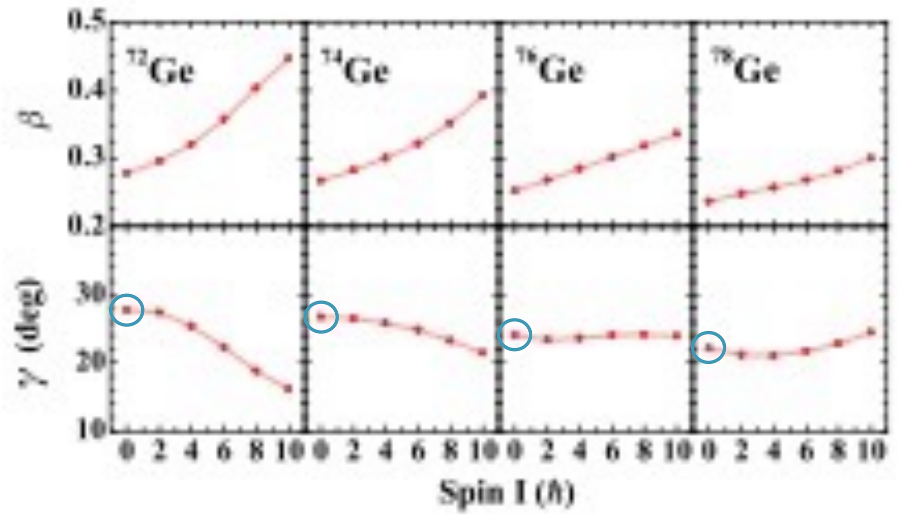
Experimental ICC

E2/*M1* Mixing ratio

$$\frac{I_K(E0)}{I_K(E2)} = \frac{\alpha_{K,\exp}(1+\delta^2) - \alpha_K(M1)}{\delta^2 \, \alpha_K(E2)} - 1$$



Triaxiality along the Ge Chain



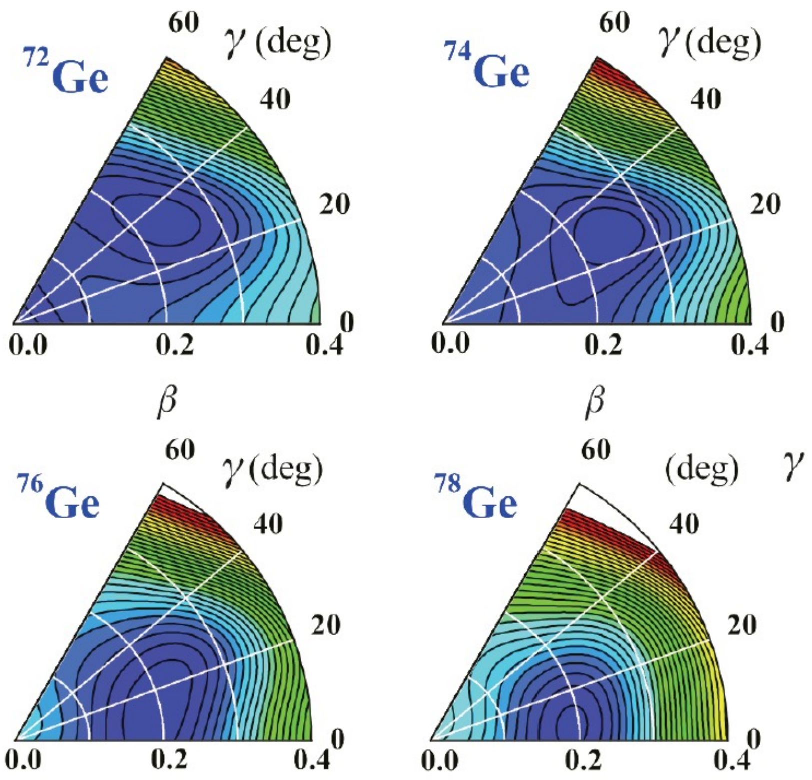
- ^{72}Ge: γ = 27.7°
- ^{74}Ge: γ = 26.7°
- ^{76}Ge: γ = 24.0°
- ^{78}Ge: γ = 22.2°

Five-dimensional collective Hamiltonian model based on constrained triaxial covariant functional theory with PC-PK1

➤ Sun *et al.*, Phys. Lett. B 734 308 (2014)

- ^{72}Ge (Coulex)
  - ➤ Ayangeakaa *et al.*, PLB 754 (2016)
- ^{76}Ge (Coulex)
  - ➤ Ayangeakaa *et al.*, PRL 123 (2019)
- ^{78}Ge (multinucleon transfer)
  - ➤ Forney *et al.*, PRL 120 (2018)

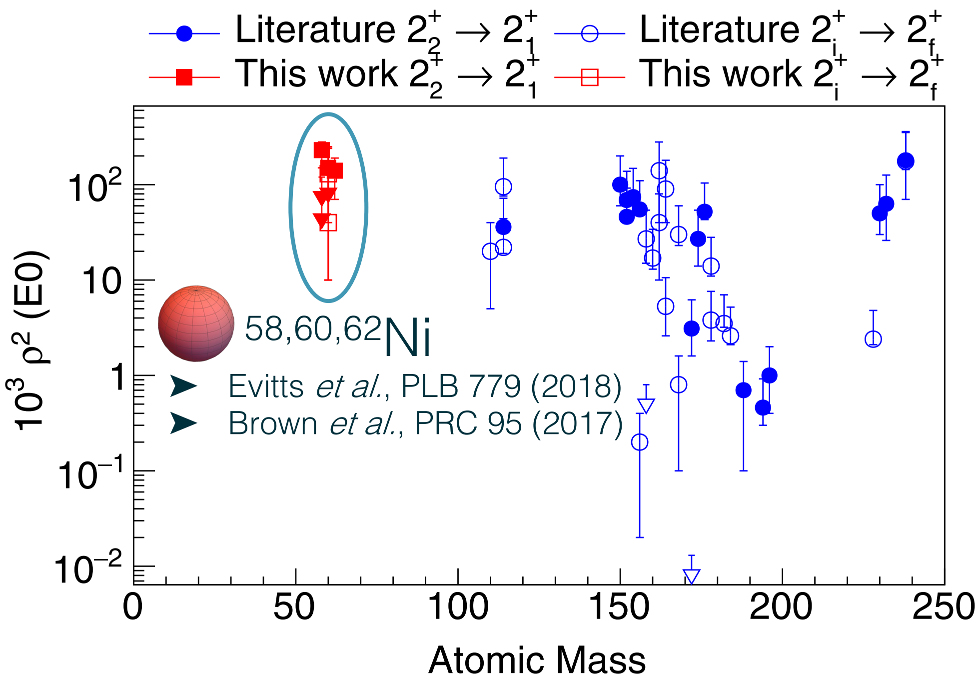
Triaxiality Evolution along the Ge Chain



Potential energy surfaces calculated using
constrained triaxial covariant functional theory with PC-PK1

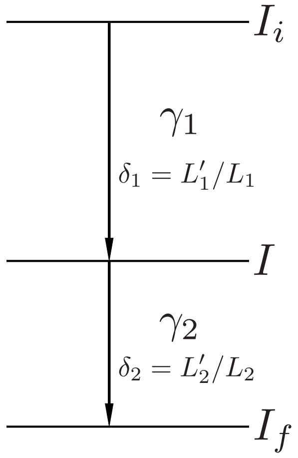
➤ Sun *et al.*, Phys. Lett. B 734 308 (2014)

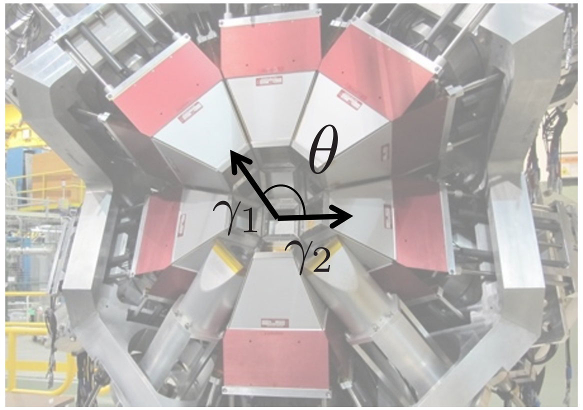
E0 Strength Measurements in the Nuclear Landscape



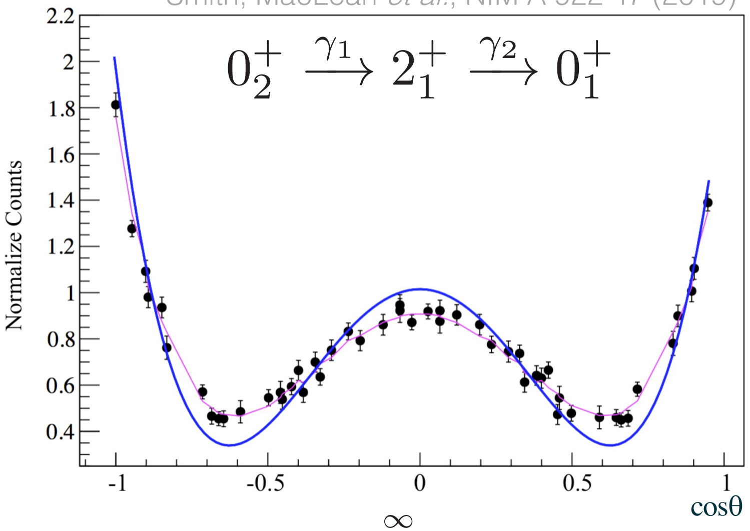
- ➤ Figure from L.J. Evitts *et al.*, PRC 99 (2019)
- ➤ Data from T. Kibédi *et al.*, At. Data Nucl. Data Tables 89, 77 (2005) and J.L. Wood *et al.*, Nucl. Phys. A 651, 323 (1999).

E0 Strength Measurements in 2_2^+-2_1^+ transitions: γγ Angular Correlations to Measure Mixing Ratios





Smith, MacLean *et al.*, NIM A 922 47 (2019)



$$W(\theta) = \sum_{\text{even } i}^{\infty} a_i P_i(\cos\theta)$$

- 51 angular bins θ at GRIFFIN.
- GEANT4 simulations allow to extract the multipolarity mixing ratio values or the spins, given a set of experimental data points.
  - Smith, MacLean *et al.*, NIM A 922 47 (2019).