Shape coexistence and beta decay in proton-rich A~70 nuclei within beyond-mean-field approach

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Outline

- *complex* EXCITED VAMPIR beyond-mean-field model

- shape-coexistence effects on *structure and dynamics of* ^{70}*Se*

- shape-coexistence effects on
  - *superallowed Fermi β-decay of the ground state of* ^{70}*Br*
  - *Gamow-Teller β-decay of the* 9^+ *isomer of* ^{70}*Br*

A~70 *proton-rich nuclei exhibit*

drastic changes in structure with number of nucleons, spin, excitation energy

generated by

- ***shape coexistence and shape mixing***
- ***competing T=0 and T=1 pairing correlations***
- ***isospin-symmetry-breaking interactions***

Challenges for theory

- ***realistic effective Hamiltonians in adequate model spaces, beyond-mean-field methods***
- ***comprehensive understanding of structure phenomena and β-decay properties***

complex VAMPIR model family

- **the model space is defined by a finite dimensional set of spherical single particle states**

- **the effective many-body Hamiltonian is represented as a sum of one- and two-body terms**

- **the basic building blocks are Hartree-Fock-Bogoliubov (HFB) vacua**

- **the HFB transformations are essentially *complex* and allow for proton-neutron, parity and angular momentum mixing being restricted by time-reversal and axial symmetry**

(T=1 and T=0 neutron-proton pairing correlations already included at the mean-field level)

- **the broken symmetries (s=N, Z, I, p) are restored by projection before variation**

**** The models allow to use rather large model spaces and realistic effective interactions***

Beyond mean field variational procedure

complex VAMPIR

$$E^s[F_1^s] \;=\; \frac{\langle F_1^s|\hat{H}\hat{\Theta}_{00}^s|F_1^s\rangle}{\langle F_1^s|\hat{\Theta}_{00}^s|F_1^s\rangle} \qquad |\psi(F_1^s);sM\rangle \;=\; \frac{\hat{\Theta}_{M0}^s|F_1^s\rangle}{\sqrt{\langle F_1^s|\hat{\Theta}_{00}^s|F_1^s\rangle}}$$

complex EXCITED VAMPIR

$$|\psi(F_2^s);sM\rangle \;=\; \hat{\Theta}_{M0}^s\left\{|F_1^s\rangle\alpha_1^2 \;+\; |F_2^s\rangle\alpha_2^2\right\}$$

$$|\psi(F_i^s);sM\rangle \;=\; \Sigma_{j=1}^{i}\,|\phi(F_j^s)\rangle\,\alpha_j^i \qquad \text{for} \quad i=1,...,n-1$$

$$|\phi(F_i^s);sM\rangle \;=\; \Theta_{M0}^s|F_i^s\rangle$$

$$|\psi(F_n^s);sM\rangle \;=\; \Sigma_{j=1}^{n-1}\,|\phi(F_j^s)\rangle\,\alpha_j^n + |\phi(F_n^s)\rangle\,\alpha_n^n$$

$$\alpha_n^n \;=\; \langle\phi^n|[1-\Sigma_{j,l=1}^{n-1}\,|\phi^j\rangle\,(A^{-1})_{jl}\langle\phi^l|]|\phi^n\rangle^{-1/2}$$

$$\alpha_j^n \;=\; -\Sigma_{l=1}^{n-1}\,(A^{-1})_{jl}\langle\phi^l|\phi^n\rangle\alpha_n^n$$

$$A_{jl} \;\equiv\; \langle\phi^j|\phi^l\rangle \quad i,l=1,...,n-1$$

$$\hat{S} \equiv \Sigma_{j,l=1}^{n-1} |\phi^j\rangle (A^{-1})_{jl} \langle \phi^l|$$

$$E_1^n \equiv \langle \psi^n | \hat{H} | \psi^n \rangle = \frac{\langle \phi^n | (1 - \hat{S}) \hat{H} (1 - \hat{S}) | \phi^n \rangle}{\langle \phi^n | (1 - \hat{S}) | \phi^n \rangle}$$

$$(H - E^{(n)} N) f^n = 0$$

$$(f^{(n)})^+ N f^{(n)} = 1$$

$$|\Psi_\alpha^{(n)}; sM > = \sum_{i=1}^{n} |\psi_i; sM > f_{i\alpha}^{(n)}, \qquad \alpha = 1, ..., n$$

A ~ 70 mass region

^{40}Ca - core

model space for protons and neutrons

$1p_{1/2}$ $1p_{3/2}$ $0f_{5/2}$ $0f_{7/2}$ $1d_{5/2}$ $0g_{9/2}$

(charge-symmetric basis + Coulomb contributions to the π-spe from the core)

renormalized G-matrix (OBEP- Bonn CD)

- ***pairing properties enhanced by short range Gaussians for:***

T = 1 : pp (*-35 MeV*), np (*-20 MeV*), nn (*-35 MeV*)

T = 0: np (*-35 MeV*)

- ***onset of deformation influenced by monopole shifts:***

$<0g_{9/2}\ 0f;\ T=0\ |G|\ 0g_{9/2}\ 0f;T=0>$ $(0f_{5/2},\ 0f_{7/2})$

$<1d_{5/2}\ 1p;\ T=0\ |G|\ 1d_{5/2}\ 1p;T=0>$ $(1p_{1/2},\ 1p_{3/2})$

- ***Coulomb interaction between valence protons added***

Shape mixing in the analogue states of the

A = 70 isovector triplet: ${}_{36}\mathrm{Kr}_{34} - {}_{35}\mathrm{Br}_{35} - {}_{34}\mathrm{Se}_{36}$

A. Petrovici, Phys. Rev. C 91, 014302 (2015)
Phys. Scr.92, 064003 (2017)

^{70}Se

$I(\hbar)$	Prolate content	Oblate content
0^+	41(4)(1)(1) %	51(1) %
2^+	56(2) %	39(2) %
4^+	52(2) %	43(2) %
6^+	76(3)(1)(1) %	17(1) %

- *ground state > dominated by oblate components in ^{70}Se, but prolate ones in ^{70}Br*

^{70}Br

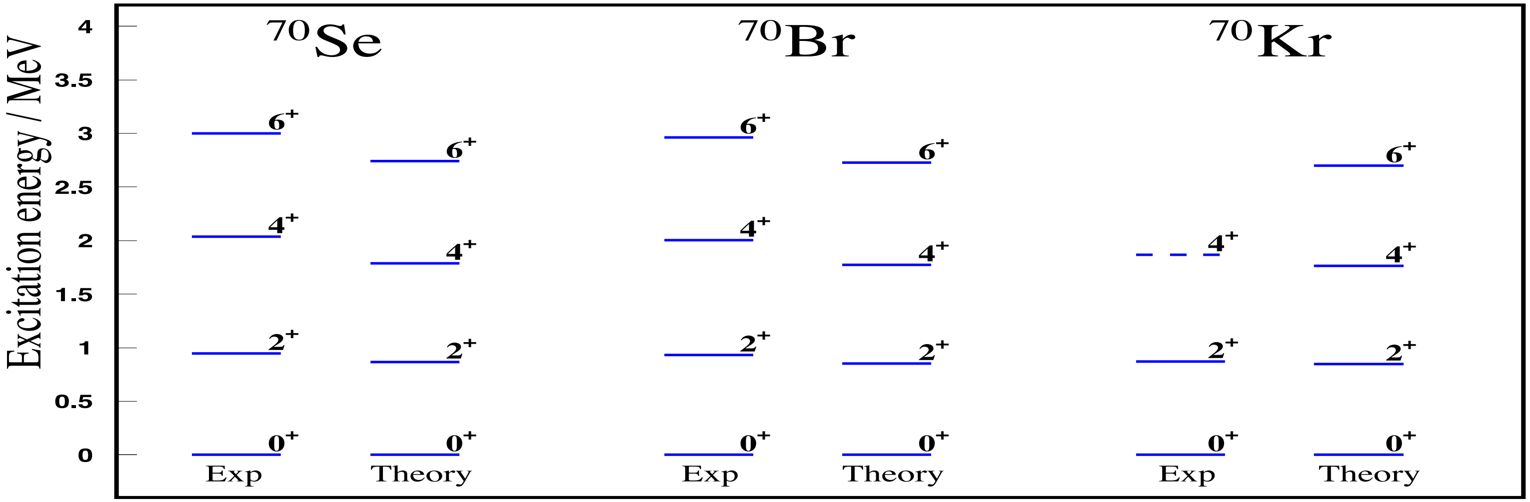
$I(\hbar)$	Prolate content	Oblate content
0^+	68(1) %	26(2)(1) %
2^+	66(2) %	29(1) %
4^+	68(2)(1) %	26(1) %
6^+	81(4)(2)(1)(1) %	10(1) %

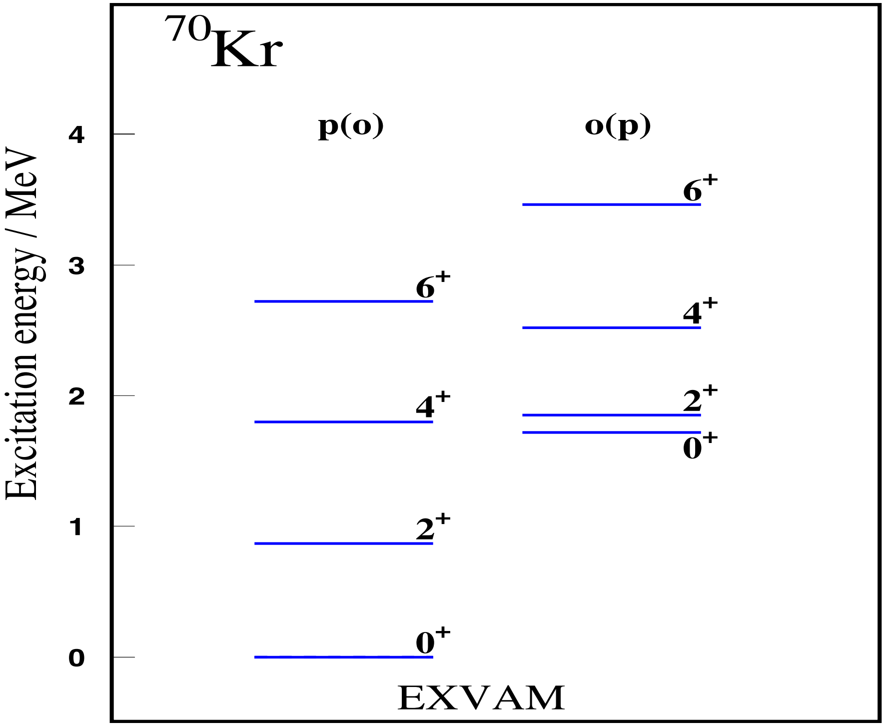
- *similar structure for ^{70}Br and ^{70}Kr*

^{70}Kr

$I(\hbar)$	Prolate content	Oblate content
0^+	69(3) %	24(3) %
2^+	70(3) %	24(1) %
4^+	75(3) %	19(2) %
6^+	86(3)(2) %	7(2) %

Shape-coexistence effects in low-energy spectra





Shape mixing in the lowest two bands of ^{70}Kr

wave functions

- ***yrast states dominated by prolate deformed configurations***
- ***yrare states manifest oblate dominated content***

$I(\hbar)$	***Prolate mixing***	***Oblate mixing***
0_1^+	*69(3)%*	*24(3)%*
0_2^+	*23(14)(4)(3)(1)(1)%*	*48(3)(1)%*
2_1^+	*70(3)%*	*24(1)%*
2_2^+	*25(1)(1)%*	*72(1)%*
4_1^+	*75(3)%*	*19(2)%*
4_2^+	*19(1)%*	*78%*
6_1^+	*86(3)(2)%*	*7(2)%*
6_2^+	*8(1)(1)%*	*87(1)%*

spectroscopic quadrupole moments (efm^2)

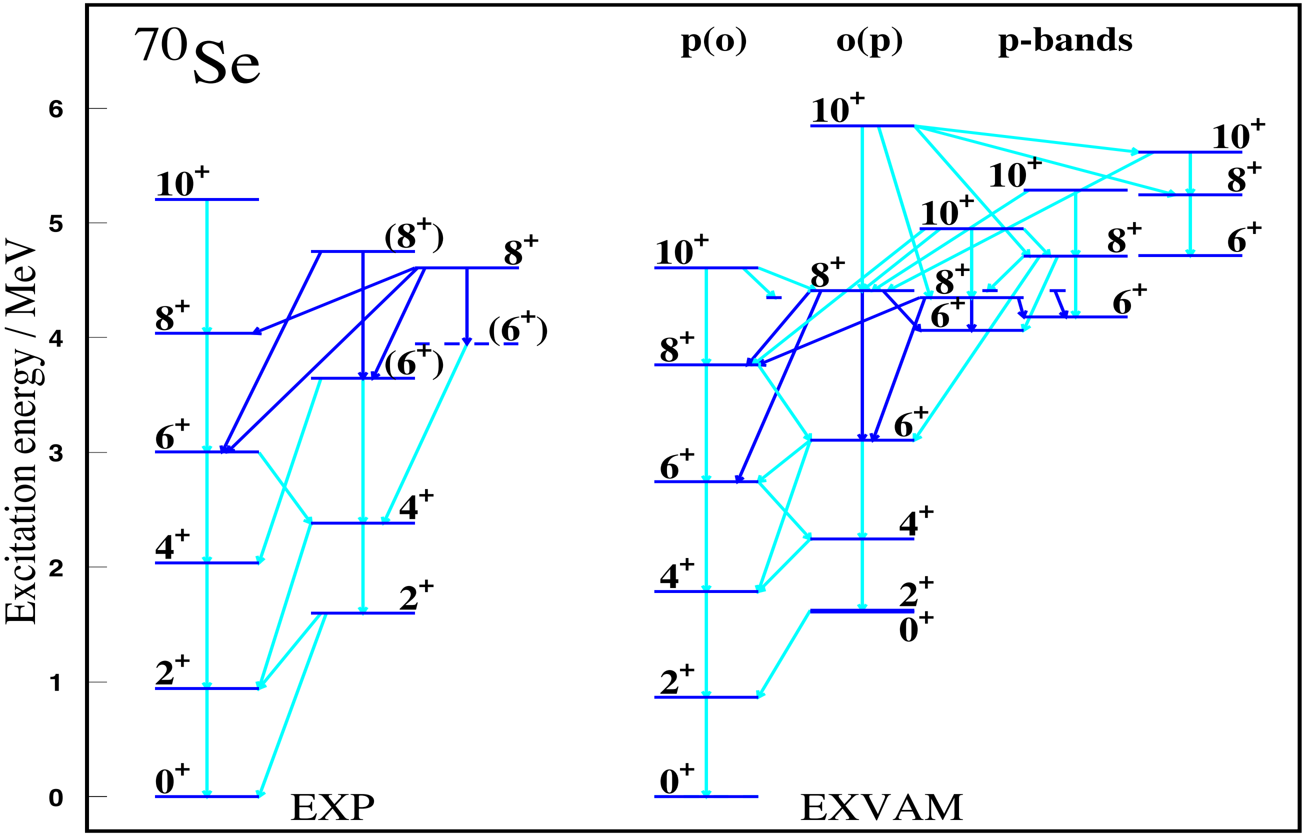
$I(\hbar)$	
2_1^+	-22
2_2^+	16
4_1^+	-36
4_2^+	29
6_1^+	-58
6_2^+	47

B(E2;ΔI=2) (e^2fm^4)

$I(\hbar)$	***p(o)-band***	***o(p)-band***
2^+	*589(12)*	*418*
4^+	*873(13)*	*795*
6^+	*910(44)*	*818(33)*

confirmed by recent experimental data

Shape mixing in the lowest bands of ^{70}Se



Wave functions and electromagnetic properties for ^{70}Se

- *yrast states dominated by prolate deformed configurations*
- *yrare states manifest oblate dominated content*

$I(\hbar)$	Prolate content	Oblate content
2_1^+	58%	42%
2_2^+	41%	59%
4_1^+	54%	46%
4_2^+	45%	55%
6_1^+	81%	19%
6_2^+	19%	81%

$I(\hbar)$	Prolate mixing	Oblate mixing
8_1^+	84(3)(2)(2) %	2 %
8_2^+	47(11)(7)(4)(4)(3)(2) %	18 %
8_3^+	12(5)(2)(2) %	73 %
10_1^+	51(39)(2)(2) %	
10_2^+	40(40)(7)(5)(2)(2)(2) %	
10_5^+	10(2) %	84%

Precise quadrupole moments could test the oblate-prolate mixing scenario

$I(\hbar)$		$I(\hbar)$	
2_1^+	-7	8_1^+	-66
2_2^+	4	8_2^+	-42
4_1^+	-7	8_3^+	28
4_2^+	0	10_1^+	-64
6_1^+	-43	10_2^+	-71
6_2^+	33	10_5^+	41

$B(E2;\Delta I=2)$ (e^2fm^4)

$I(\hbar)$	p(o)-band	o(p)-band	Exp
2^+	473	476	342(19)
4^+	706	733	370(24)
6^+	738(92)	730(58)	530(96)
8^+	781(78)	404(109)(49)(154)	
10^+	564(86)(55)	477(109)(53)(147)	

Self-consistent weak interaction rates

Fermi transition probabilities

$$B_{if}(F) = \frac{1}{2J_i+1}\frac{g_V^2}{4\pi}|M_F|^2$$

$$\begin{aligned} M_F &\equiv (\xi_f J_f||\hat{1}||\xi_i J_i) \\ &= \delta_{J_i J_f}\sum_{ab} M_F(ab)(\xi_f J_f||[c_a^\dagger \tilde{c}_b]_0||\xi_i J_i) \end{aligned}$$

$$M_F(ab) = (a||\hat{1}||b)$$

Gamow-Teller transition probabilities

$$B_{if}(GT) = \frac{1}{2J_i+1}\frac{g_A^2}{4\pi}|M_{GT}|^2$$

$$\begin{aligned} M_{GT} &\equiv (\xi_f J_f||\hat{\sigma}||\xi_i J_i) \\ &= \sum_{ab} M_{GT}(ab)(\xi_f J_f||[c_a^\dagger \tilde{c}_b]_1||\xi_i J_i) \end{aligned}$$

$$M_{GT}(ab) = 1/\sqrt{3}(a||\hat{\sigma}||b)$$

Independent chains of variational calculations for the parent and daughter nuclei

Shape coexistence effects on weak interaction rates

Isospin-symmetry-breaking and shape-coexistence effects on superallowed Fermi β-decay

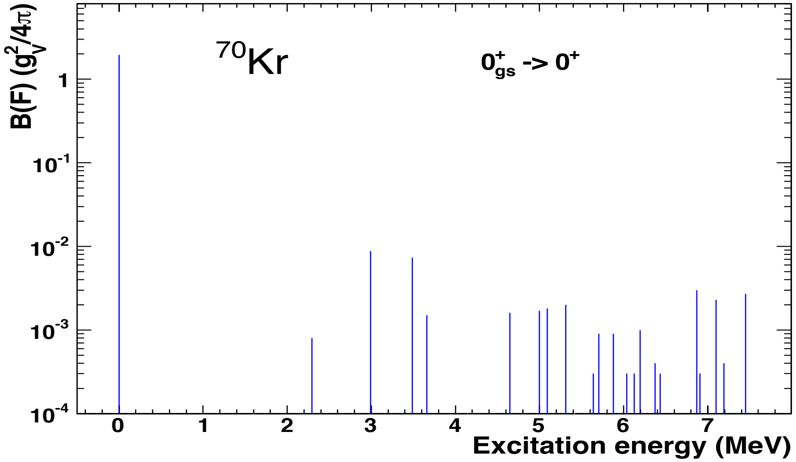
A. Petrovici, J. Phys.: Conf. Series 724 (2016) 012038

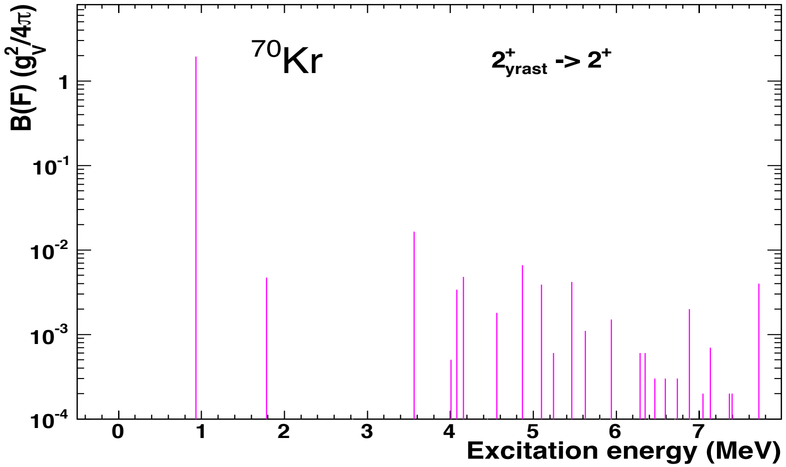
test of the CVC hypothesis
test of the unitarity of CKM matrix

$$ft(1+\delta_R)(1-\delta_c) = \frac{K}{2G_v^2(1+\Delta_R^v)}$$

δc – isospin-symmetry-breaking correction

^{70}Kr *Q_{EC} = 10.480 MeV*





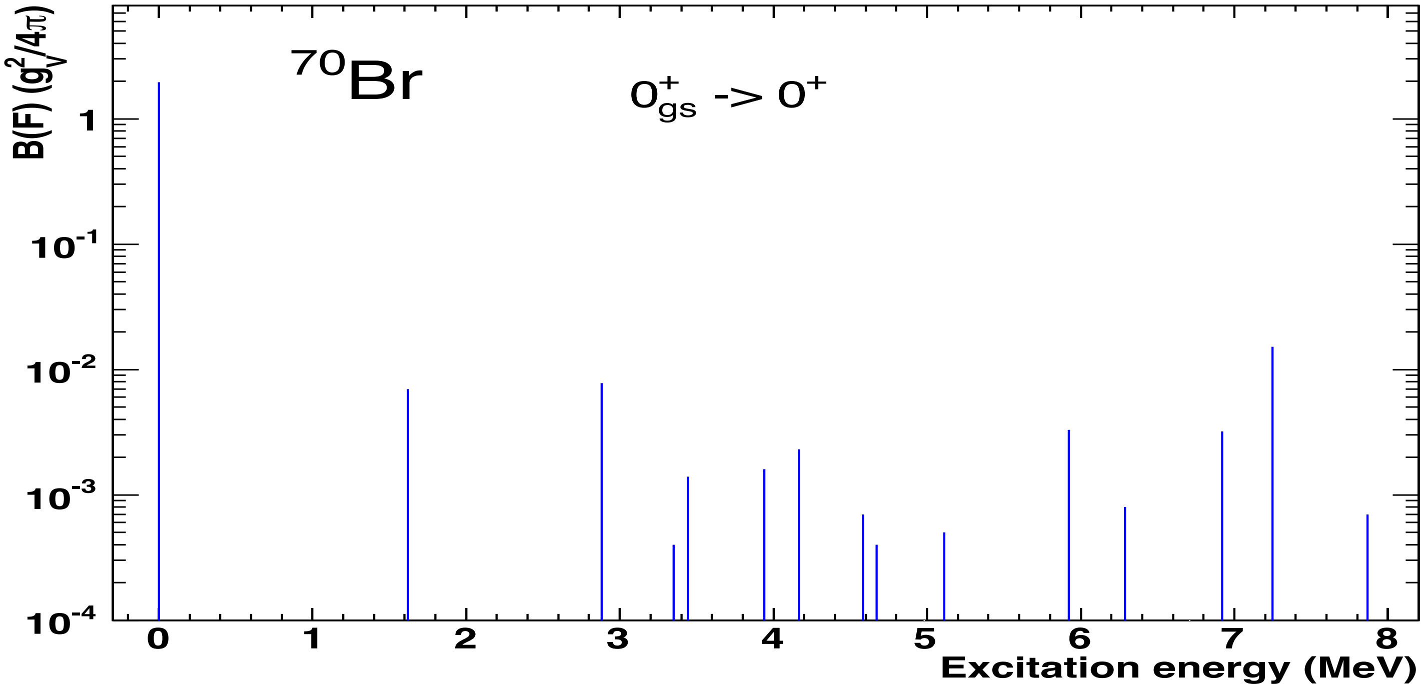
1% ≤ δ_c ≤ 2.5%

Nonanalog branches:
0^+_{IV} , 0^+_V ≤ 0.4 %

1% ≤ δ_c ≤ 3 %

Nonanalog branches:
2^+_{IV} ≤ 1.3 %

Shape coexistence effects on superallowed Fermi β-decay of ^{70}Br



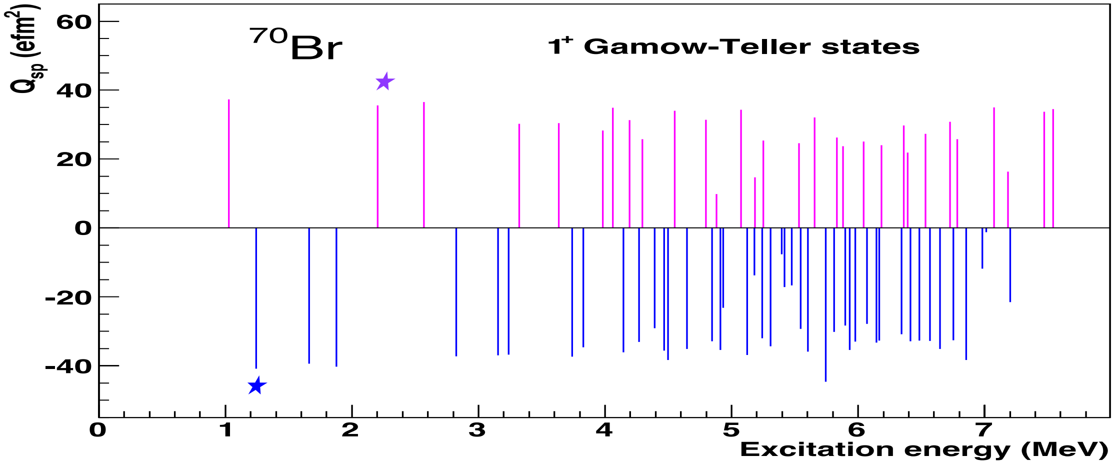
^{70}Br $Q_{EC} = 9.970$ *MeV*

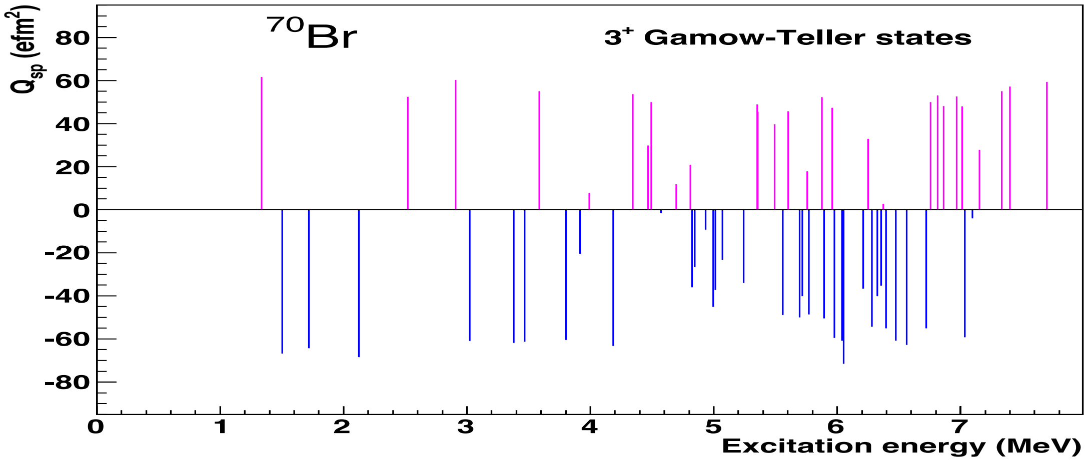
$\delta_c \leq 2\%$

Shape coexistence and Gamow-Teller β-decay of ^{70}Kr

A. Petrovici and O. Andrei, Phys. Rev. C92, 064305 (2015)

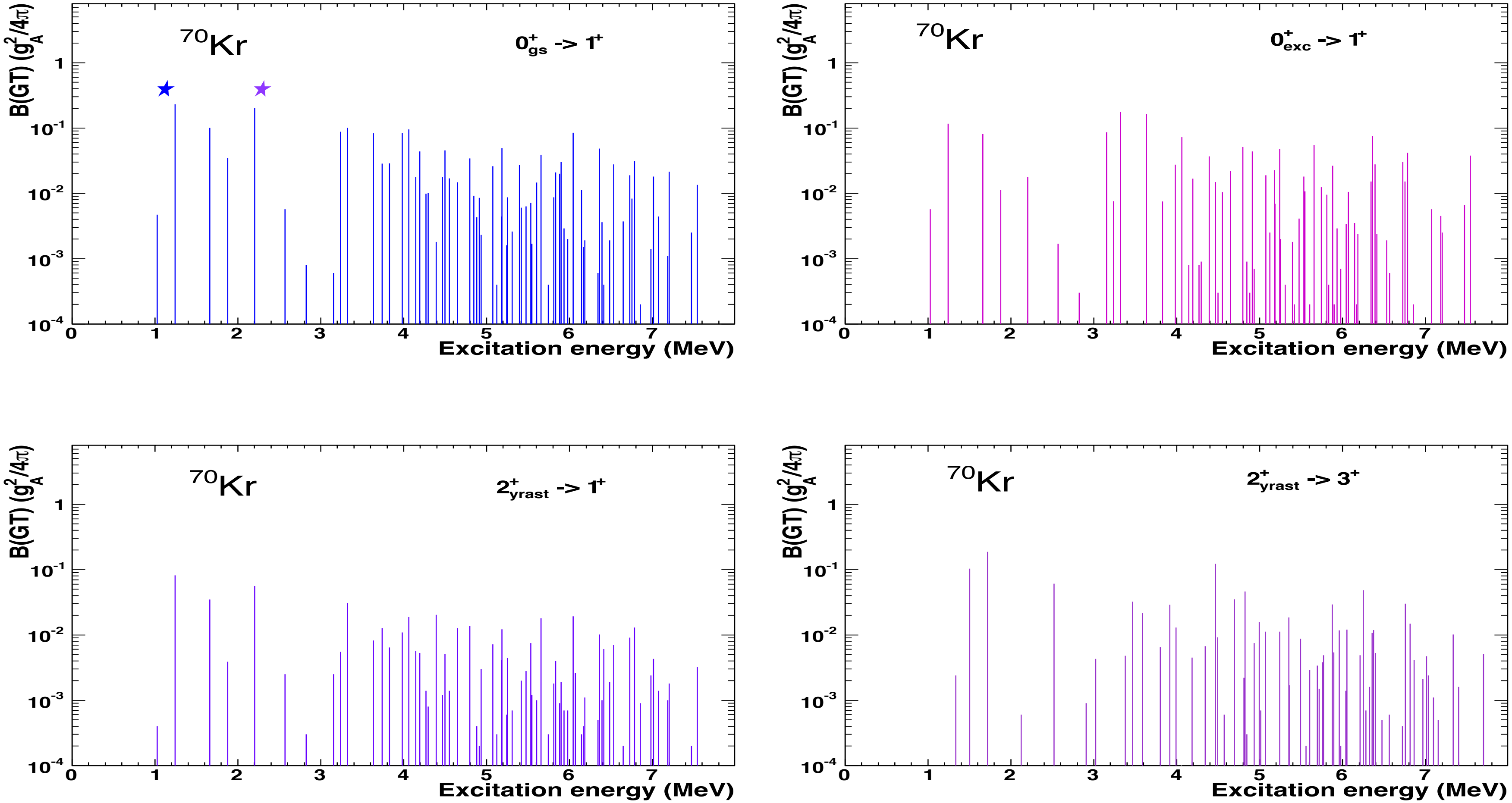
Large variety of deformations in daughter states revealed by spectroscopic quadrupole moments



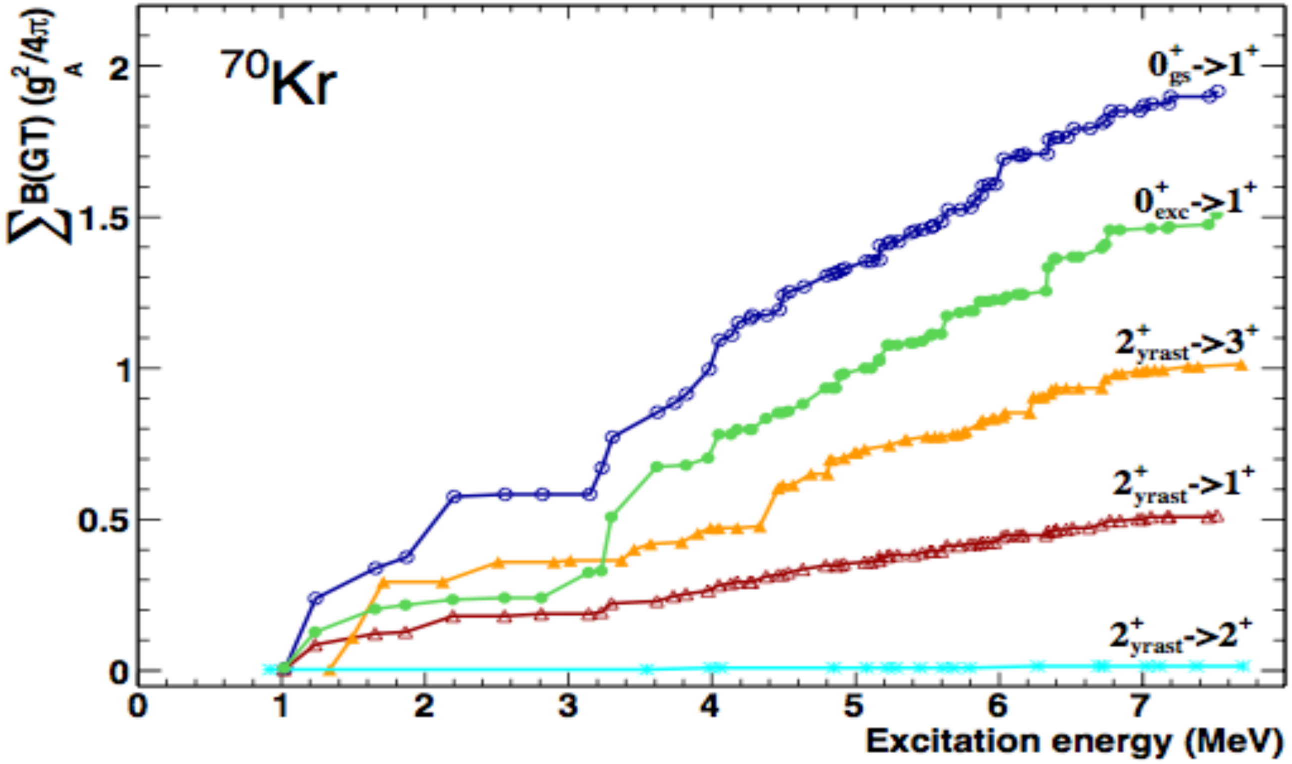


Gamow-Teller strength distributions for the decay of 0^+ and 2^+ states in ^{70}Kr

Specific shape mixing for each parent and daughter state influences the strength distributions



Contributions from $p^{\nu(\pi)}_{1/2}p^{\pi(\nu)}_{3/2}$, $p^{\nu}_{3/2}p^{\pi}_{3/2}$, $f^{\nu}_{5/2}f^{\pi}_{5/2}$, $f^{\nu(\pi)}_{5/2}f^{\pi(\nu)}_{7/2}$, $g^{\nu}_{9/2}g^{\pi}_{9/2}$ matrix elements
(coherent / cancelling effect)



Terrestrial half-lives

$$\frac{1}{T_{1/2}} = \frac{1}{D} \sum_{0<E_f<Q_{EC}} f(Z,E_f)[B_{if}(GT)+B_{if}(F)]$$

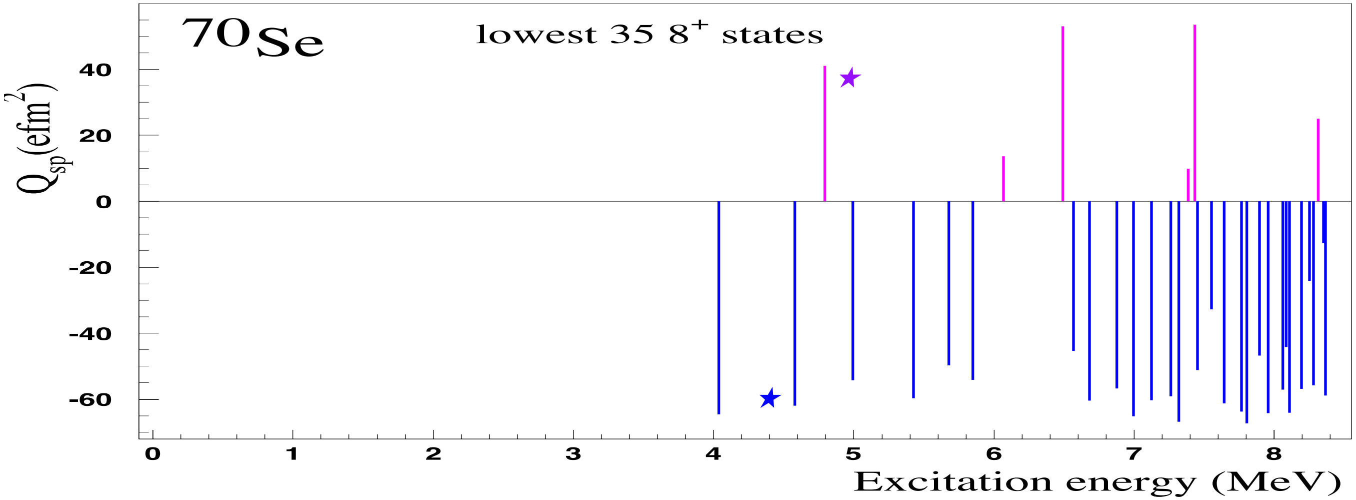
$T_{1/2}^{GT} = 258$ ms $T_{1/2}^{F} = 63$ ms

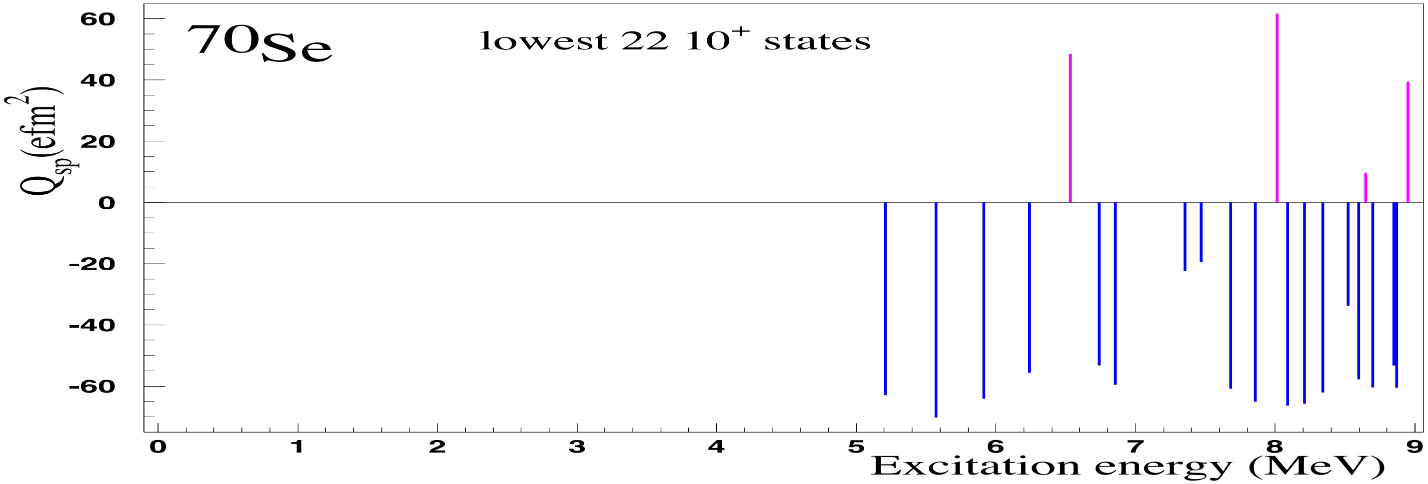
$T_{1/2}^{exp} = 52(17)$ ms

$T_{1/2}^{EXVAM} = 51$ ms

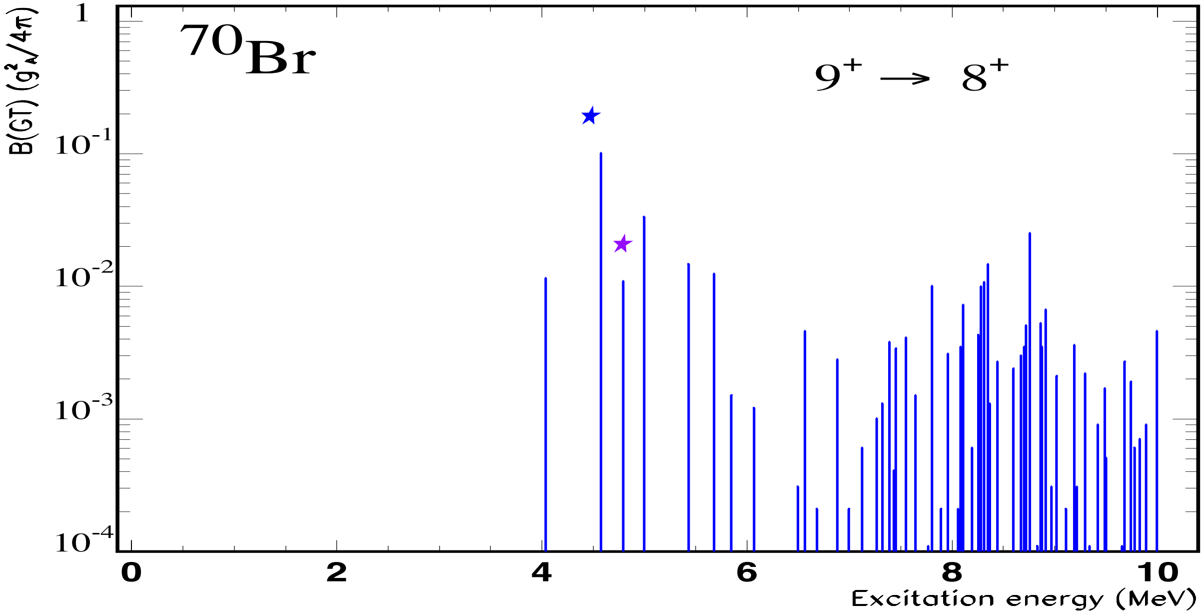
Shape coexistence and Gamow-Teller β-decay of the 9^+ isomer in ^{70}Br

- ***prolate configurations dominate the structure of the 9^+ isomer in ^{70}Br***
- ***large variety of deformations** revealed by spectroscopic quadrupole moments of **daughter states in ^{70}Se***

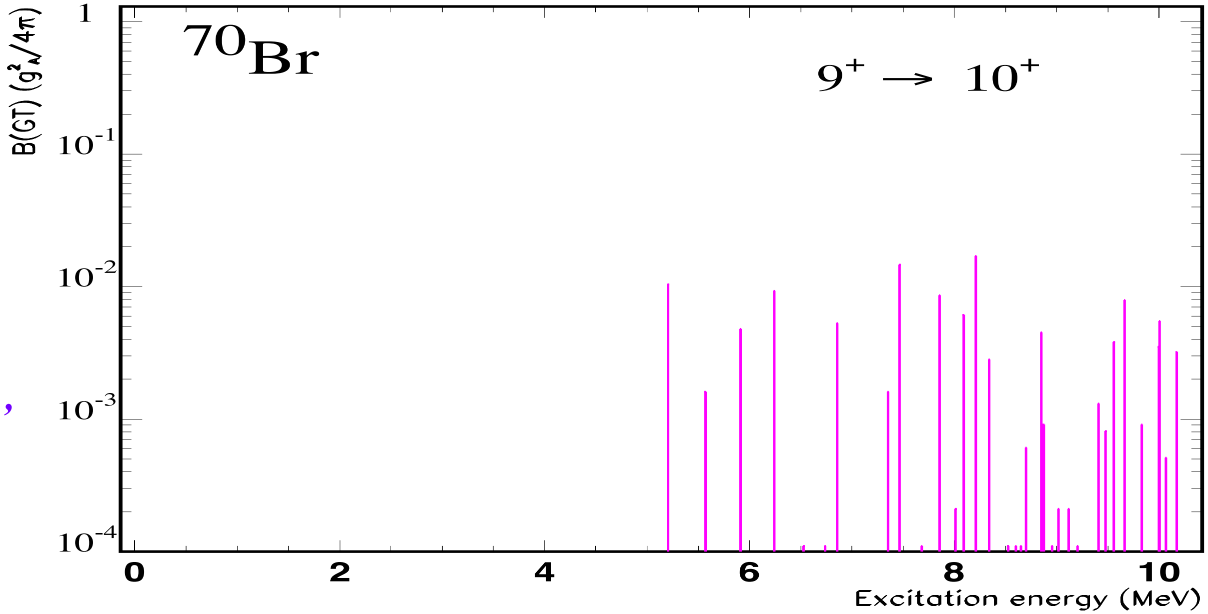




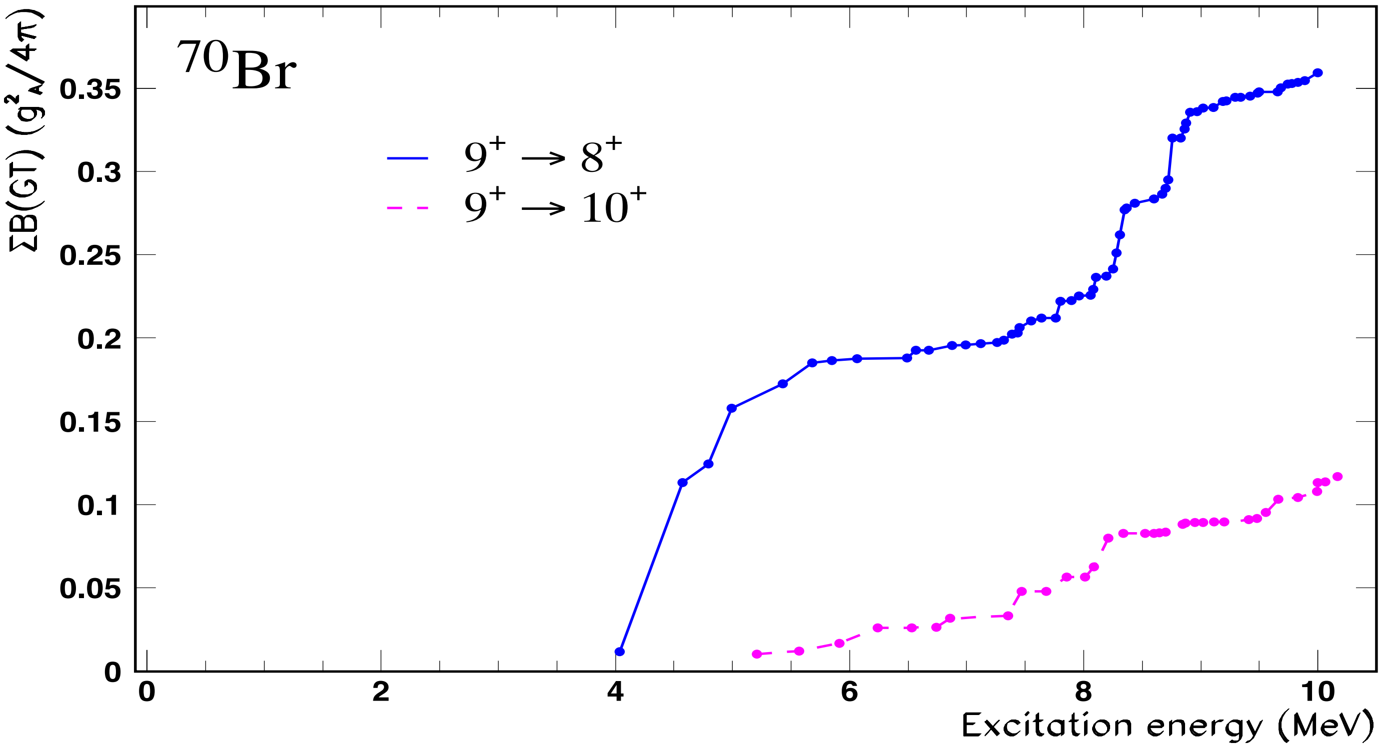
Gamow-Teller strength distributions for the decay of the 9^+ isomer in ^{70}Br



Specific shape mixing for parent and daughter states influences the strength distributions



Contributions from** $p^{\nu(\pi)}_{1/2}p^{\pi(\nu)}_{3/2}$, $p^{\nu}_{3/2}p^{\pi}_{3/2}$, $f^{\nu}_{5/2}f^{\pi}_{5/2}$, $d^{\nu}_{5/2}d^{\pi}_{5/2}$, $g^{\nu}_{9/2}g^{\pi}_{9/2}$ **matrix elements (coherent / cancelling effect)



9^+ isomer half-life

$$\frac{1}{T_{1/2}} = \frac{1}{K}\sum_{E_f} f(Z,E_f)B_{if}(GT)$$

Q_{EC} ***= 12.190 MeV*** **$T_{1/2}^{exp}$ = 2.2 (1) s** **$T_{1/2}^{EXVAM}$ = 2.3 s**

Summary

complex **EXCITED VAMPIR scenario concerning** ***shape-coexistence effects on***

- ***structure and dynamics of*** ^{70}***Se***
- ***superallowed Fermi β-decay of the ground state of*** ^{70}***Br***
- ***Gamow-Teller β-decay of the*** 9^{+} ***isomer of*** ^{70}***Br***