$0\nu\beta\beta$ decay NMEs with the generator coordinate method

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Generator Coordinate Method (GCM)

Generator Coordinate Method: an approach that treats large-amplitude fluctuations, which is essential for nuclei that cannot be approximated by a single mean field.

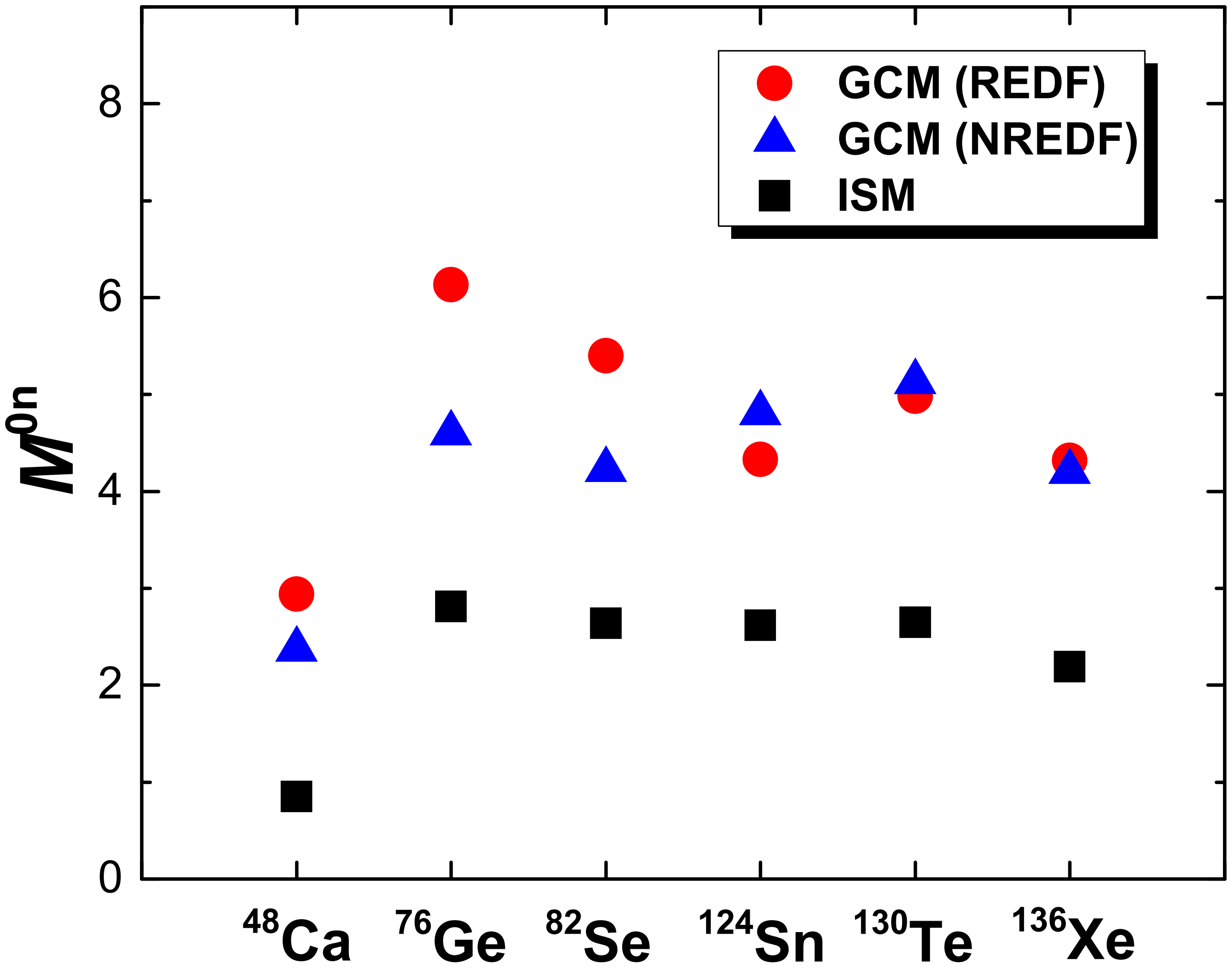
How it works:

Construct a set of mean-field states by constraining coordinates, e.g., quadrupole moment. Then diagonalize Hamiltonian in space of symmetry-restored nonorthogonal vacua with different amounts of quadrupole deformation.

GCM based on EDF has been applied to double-beta decay, however…

Comparison between GCM and SM

Current results with EDF-based GCM



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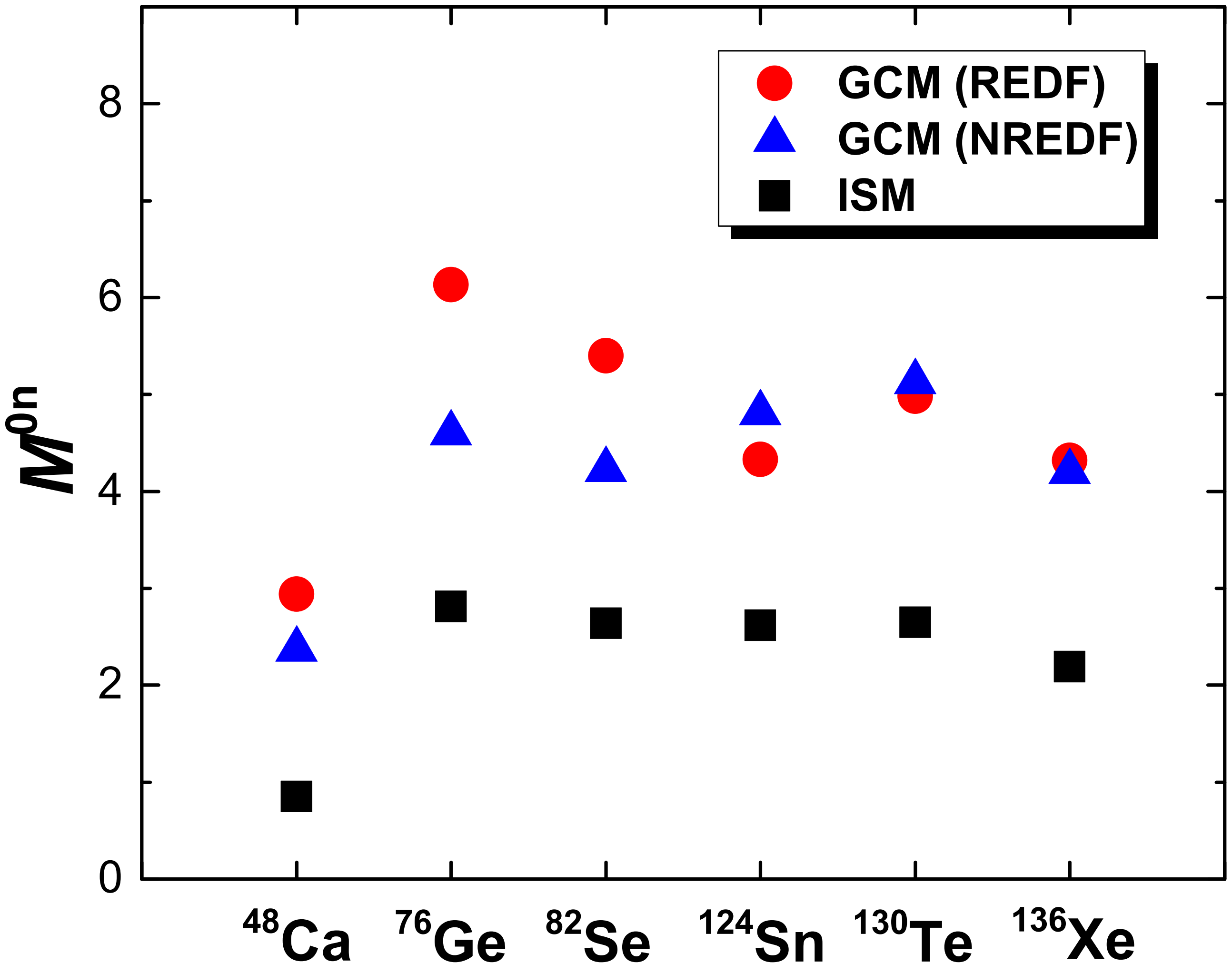


Both the shell model and the EDF-based GCM could be missing important physics.

The discrepancy may be because:

- The GCM omits correlations.
- The shell model omits many single-particle levels

Our long-term goal is to combine the virtues of both frameworks through an EDF-based or *ab-initio* GCM that includes all the important shell model correlations and a large single-particle space.

To get closer to the ultimate goal:

We can use SM Hamiltonian in the GCM

Our short-term goal is more modest: a shell-model Hamiltonian-based GCM in one and two (and possibly more) shells.

At a minimum, we can use these as a first step in the MR-IMSRG (see J. M. Yao's talk).

Our Current Procedure

① Using a shell-model Hamiltonian

② HFB states $|\Phi(q)\rangle$ with multipole constraints *q*.

We are trying to include all possible collective correlations.

③ Angular momentum and particle number projection

$$|JMK;NZ;q\rangle = \hat{P}^J_{MK}\hat{P^N}\hat{P^Z}|\Phi(q)\rangle$$

④ Configuration mixing within GCM:

$$|\Psi^J_{NZ\sigma}\rangle = \sum_{K,q} f^{JK}_\sigma(q)|JMK;NZ;q\rangle$$

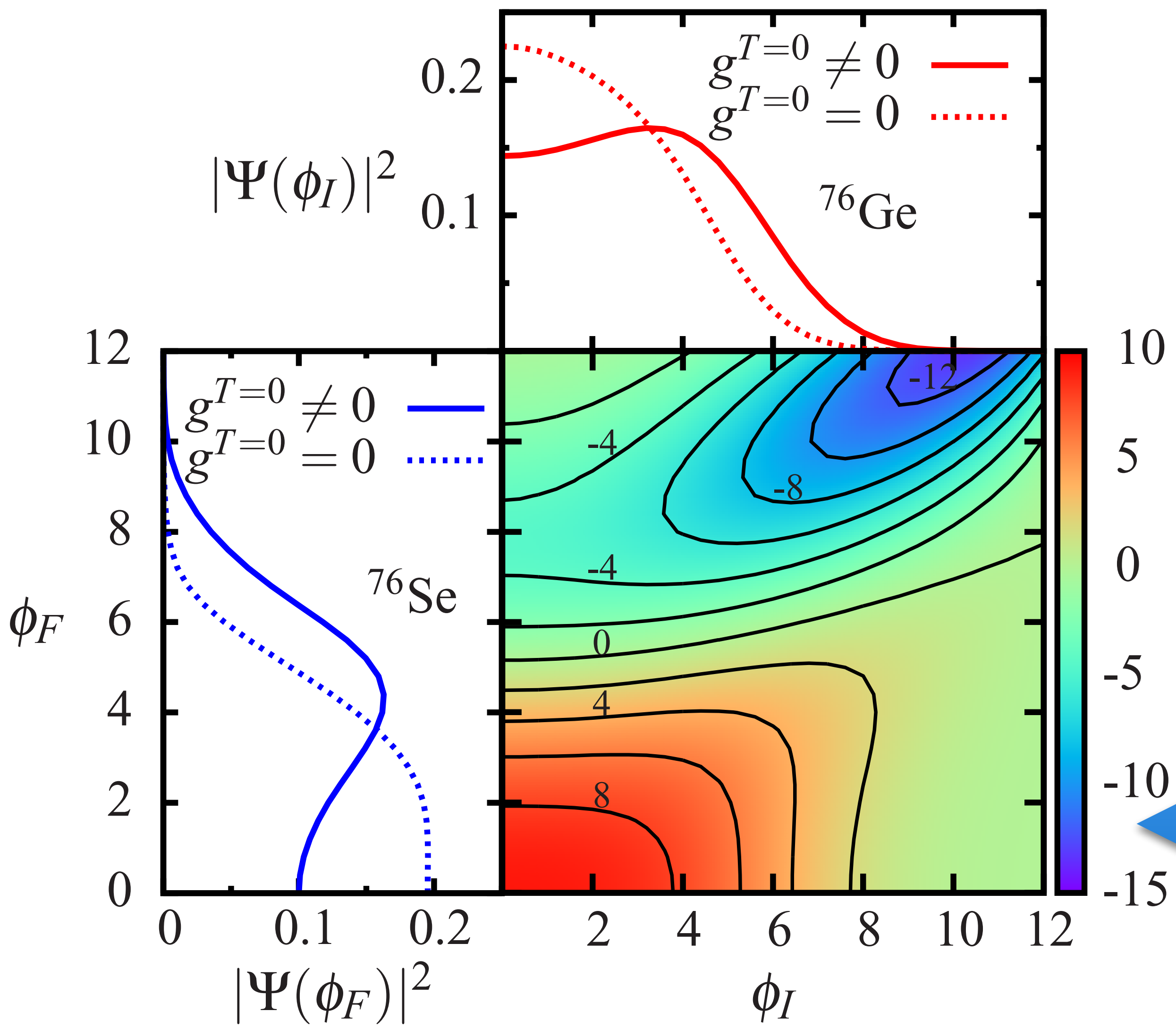
$$\sum_{K',q'}\{\mathcal{H}^J_{KK'}(q;q') - E^J_\sigma \mathcal{N}^J_{KK'}(q;q')\}f^{JK'}_\sigma(q') = 0 \longrightarrow f^{JK}_\sigma(q)$$

$$M^{0\nu\beta\beta}_\xi = \langle\Psi^{J=0}_{N_f Z_f}|\hat{O}^{0\nu\beta\beta}_\xi|\Psi^{J=0}_{N_i Z_i}\rangle$$

Level 1 GCM: Axial shape and pn pairing fluctuation

$$H' = H - \lambda_Z N_Z - \lambda_N N_N - \lambda_0 Q_{20} - \frac{\lambda_P}{2}(P_0 + P_0^\dagger)$$

isoscalar *pn* pairing constrained



ϕ is the isoscalar pairing amplitude

$$\phi = \langle P_0 + P_0^\dagger \rangle / 2$$

$$P_0^\dagger = \frac{1}{\sqrt{2}} \sum_l \hat{l} [c_l^\dagger c_l^\dagger]^{L=0,S=1,T=0}_{M_S=0}$$

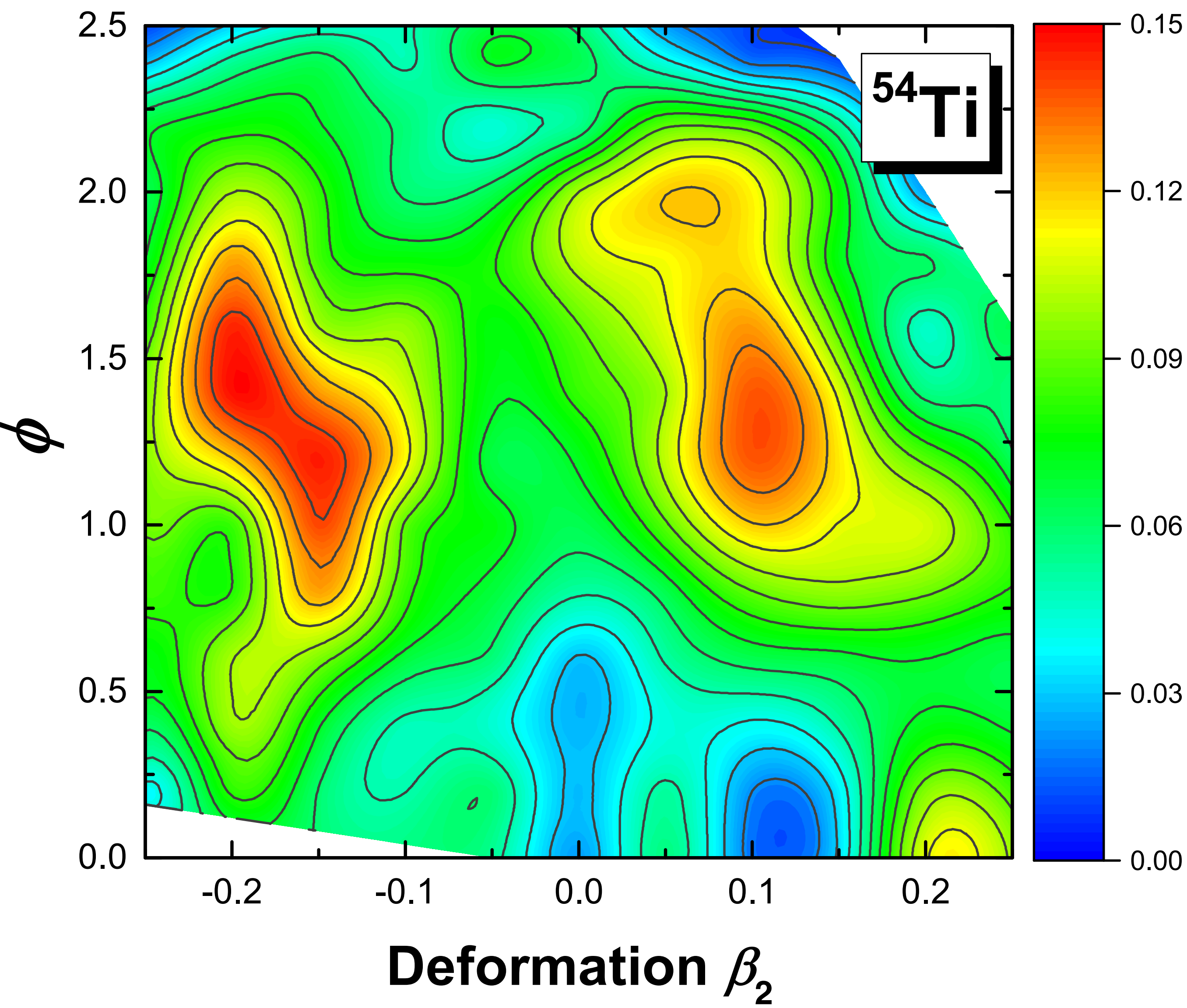
The wave functions are pushed into a region with large isoscalar pairing amplitude.

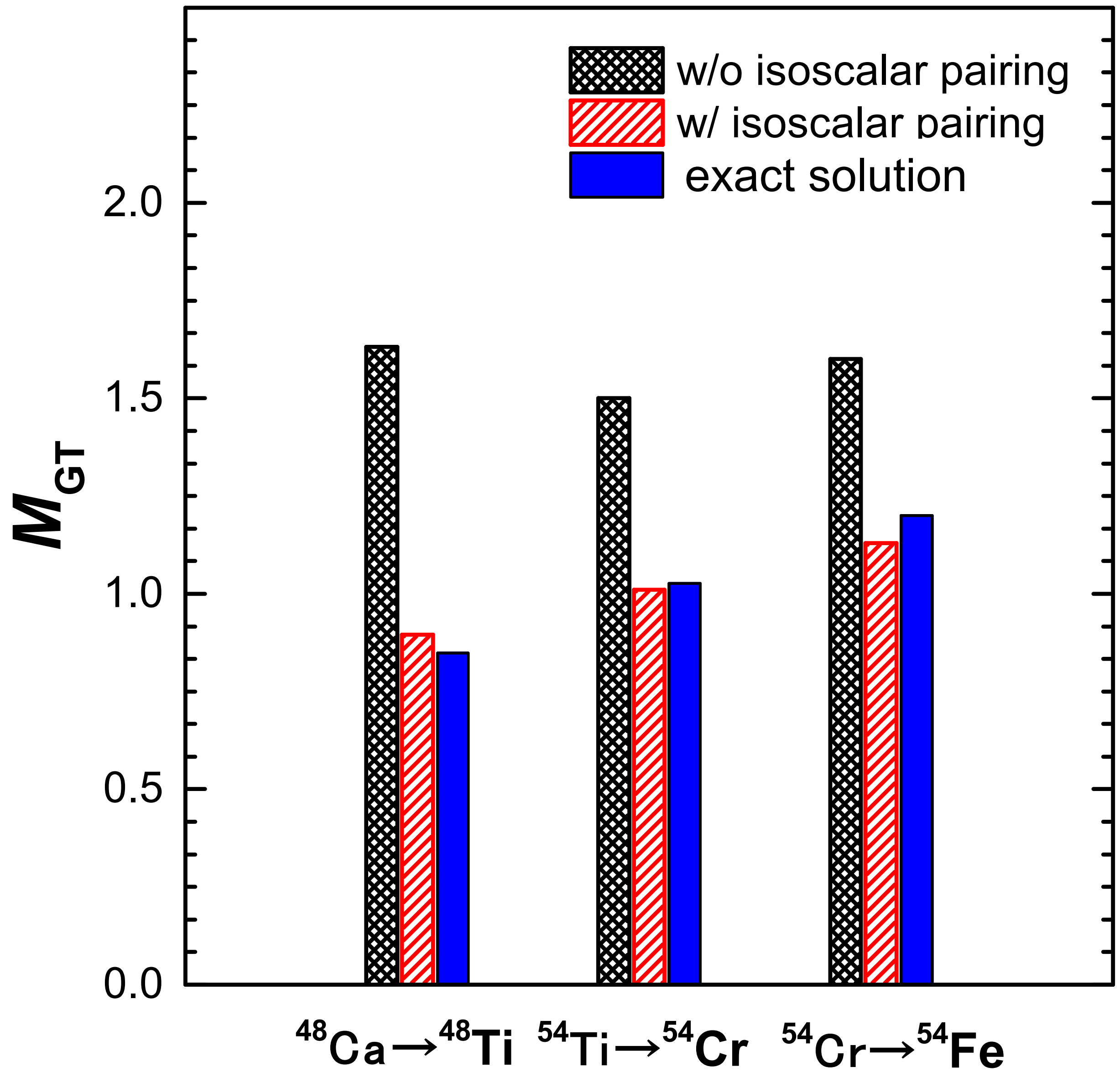
→ ***reduce the 0νββ NMEs.***

N. Hinohara and J. Engel, PRC 90, 031301(R) (2014)

Level 1 GCM: Axial shape and pn pairing fluctuation

We use the KB3G interaction for *the pf* shell





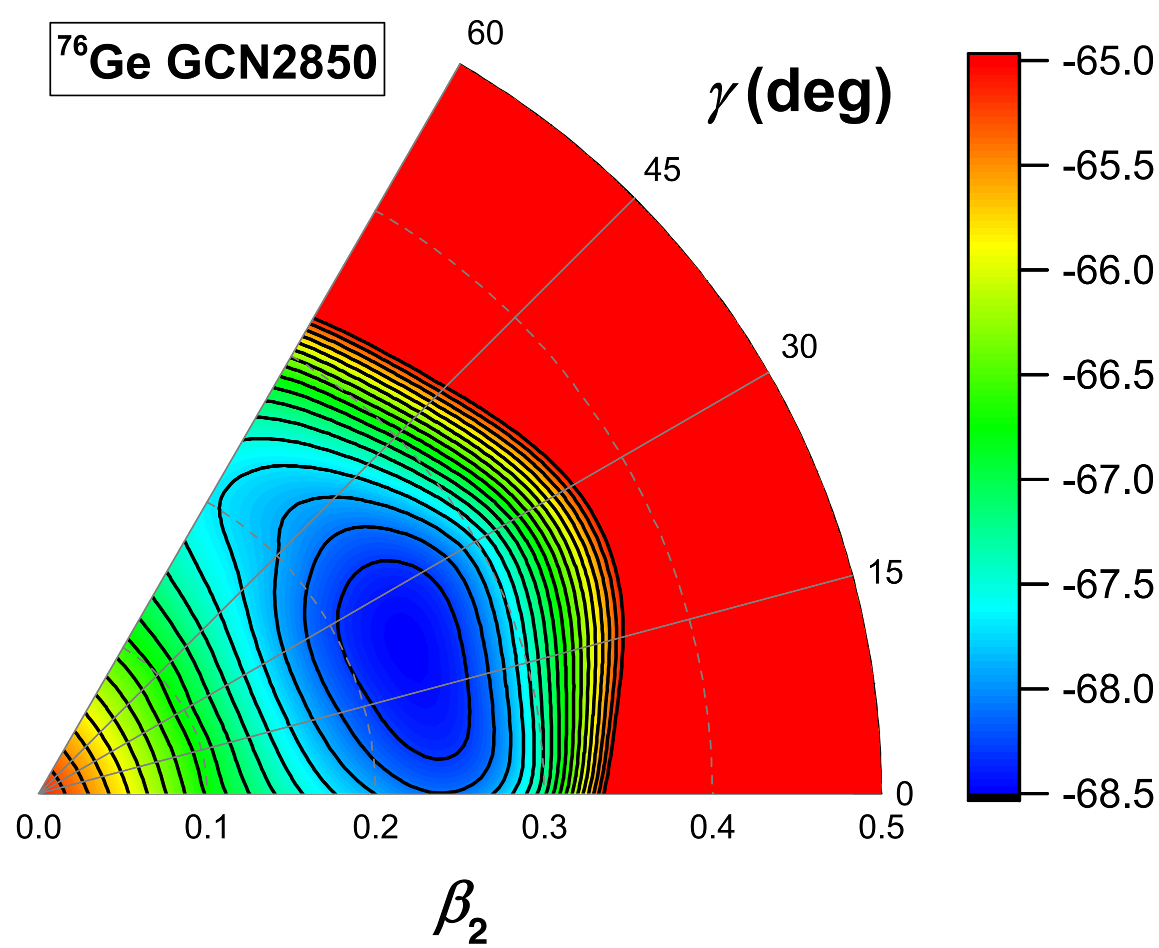
collective wave function shows peaks at nonzero isoscalar-pairing amplitude.

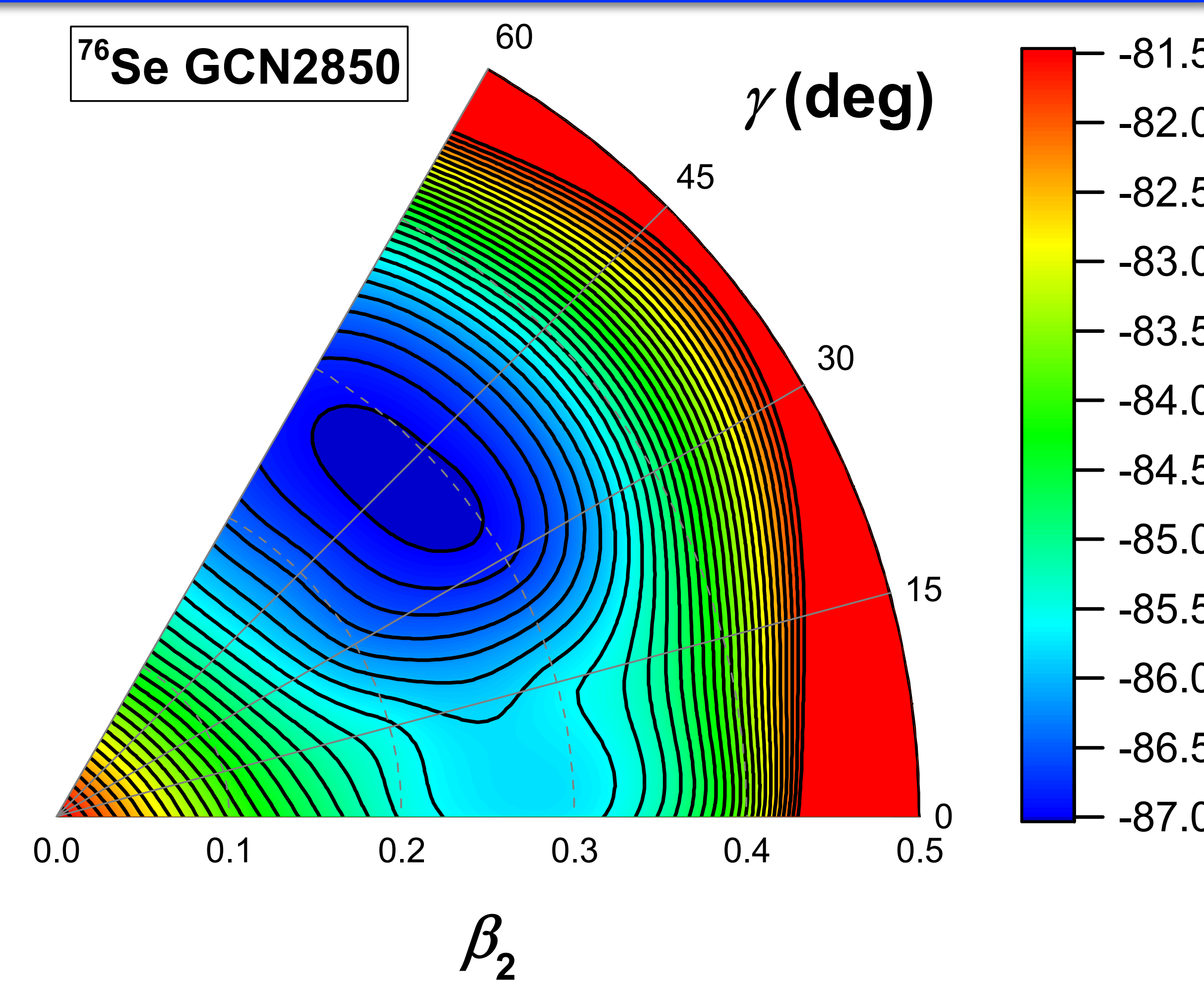
→ **Reduction of NME**

Level 2 GCM: Triaxial deformation

$$H' = H - \lambda_Z N_Z - \lambda_N N_N - \lambda_0 Q_{20} - \frac{\lambda_P}{2}(P_0 + P_0^\dagger) - \lambda_2 Q_{22}$$

triaxial deformation constrained





With GCN2850 or JUN45 interaction, projected potential energy surfaces for ^{76}Ge and ^{76}Se give minima with triaxial deformation.

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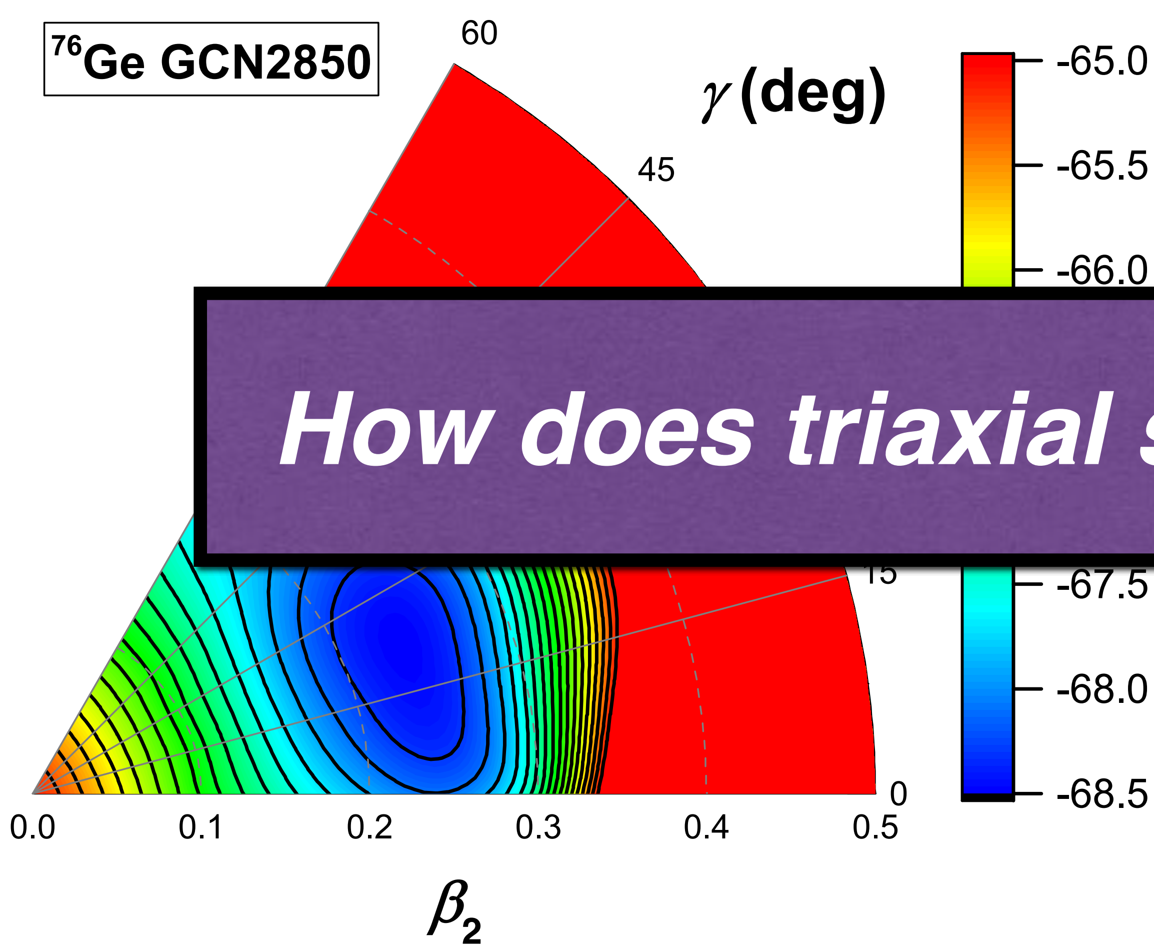

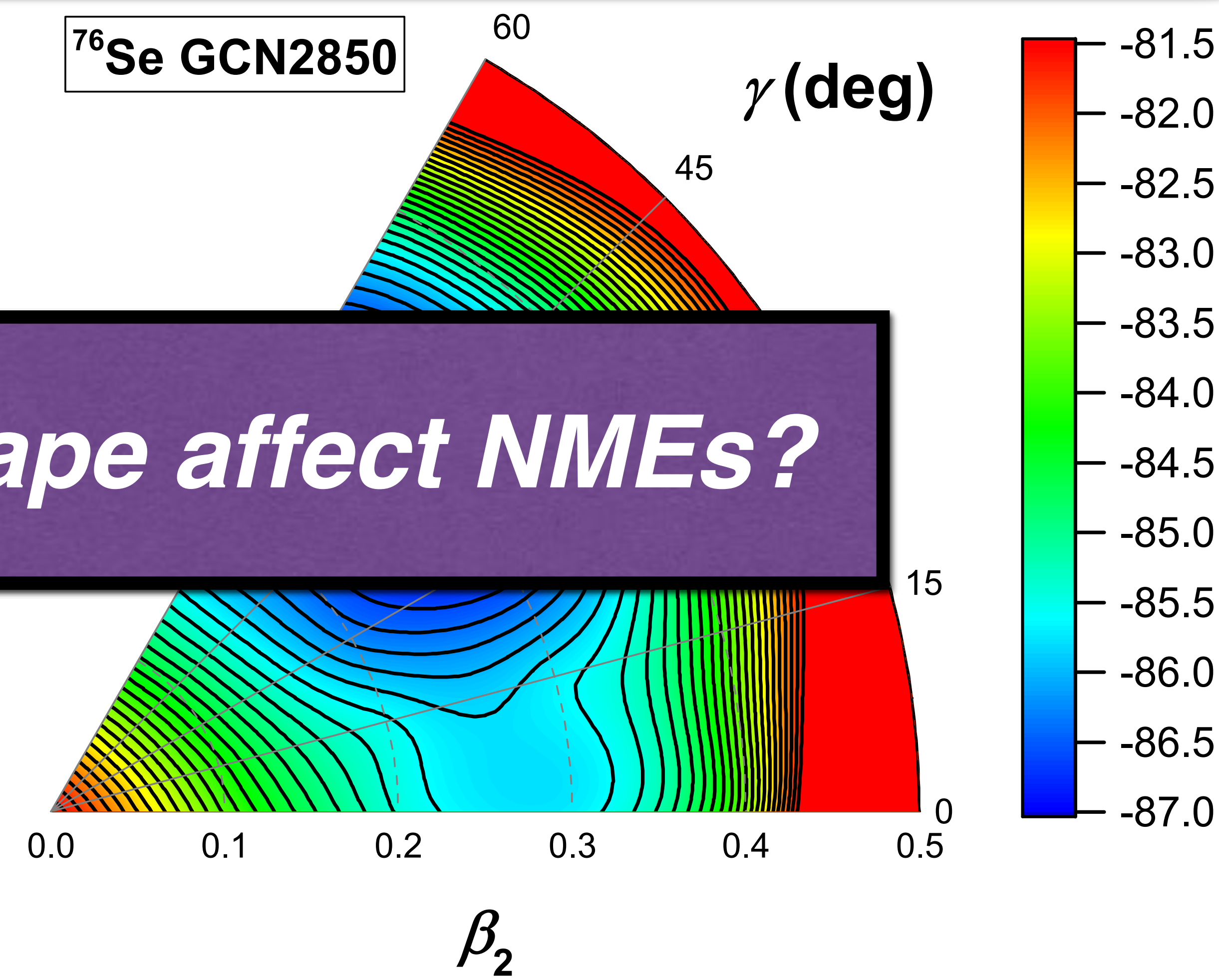

How does triaxial shape affect NMEs?

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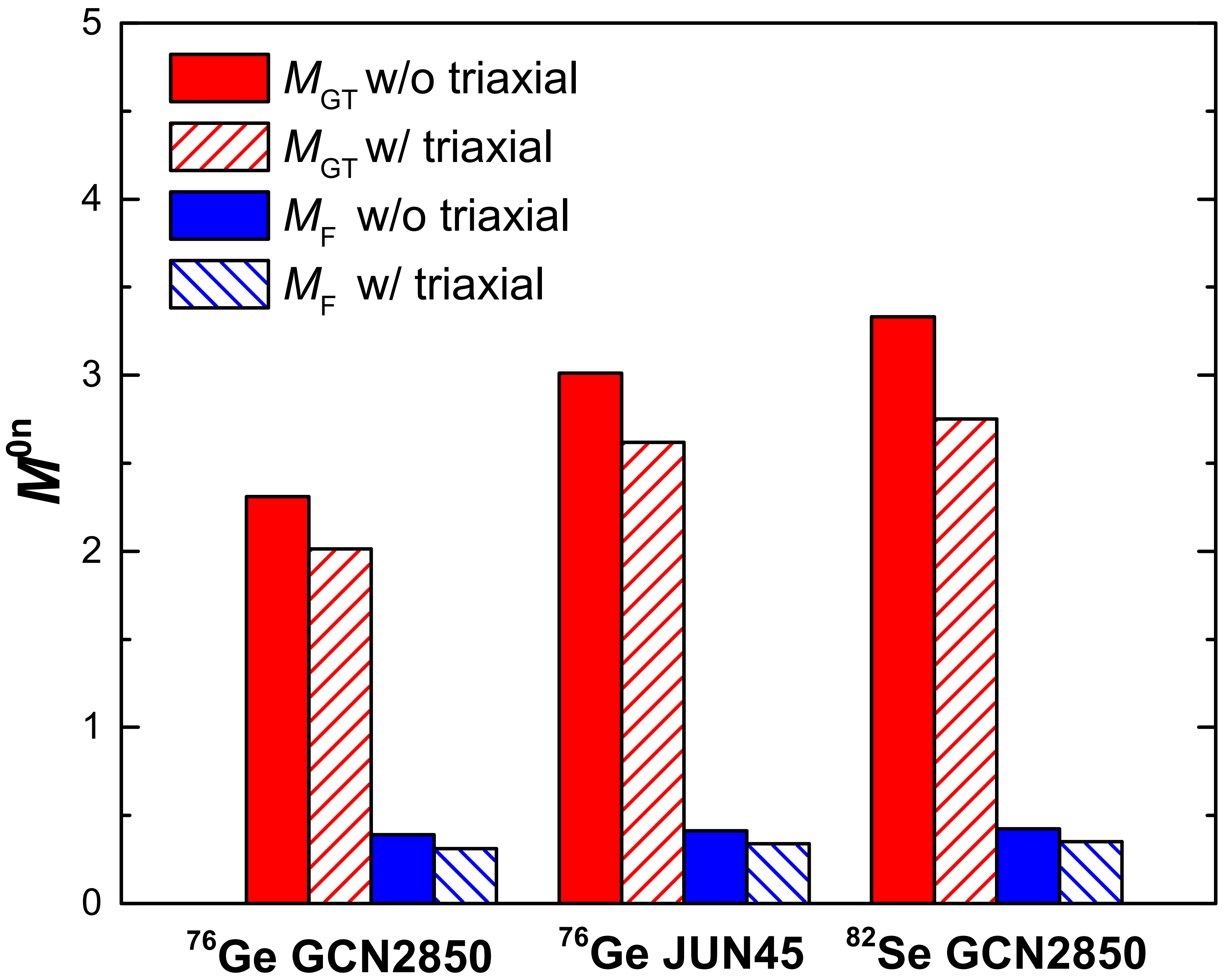
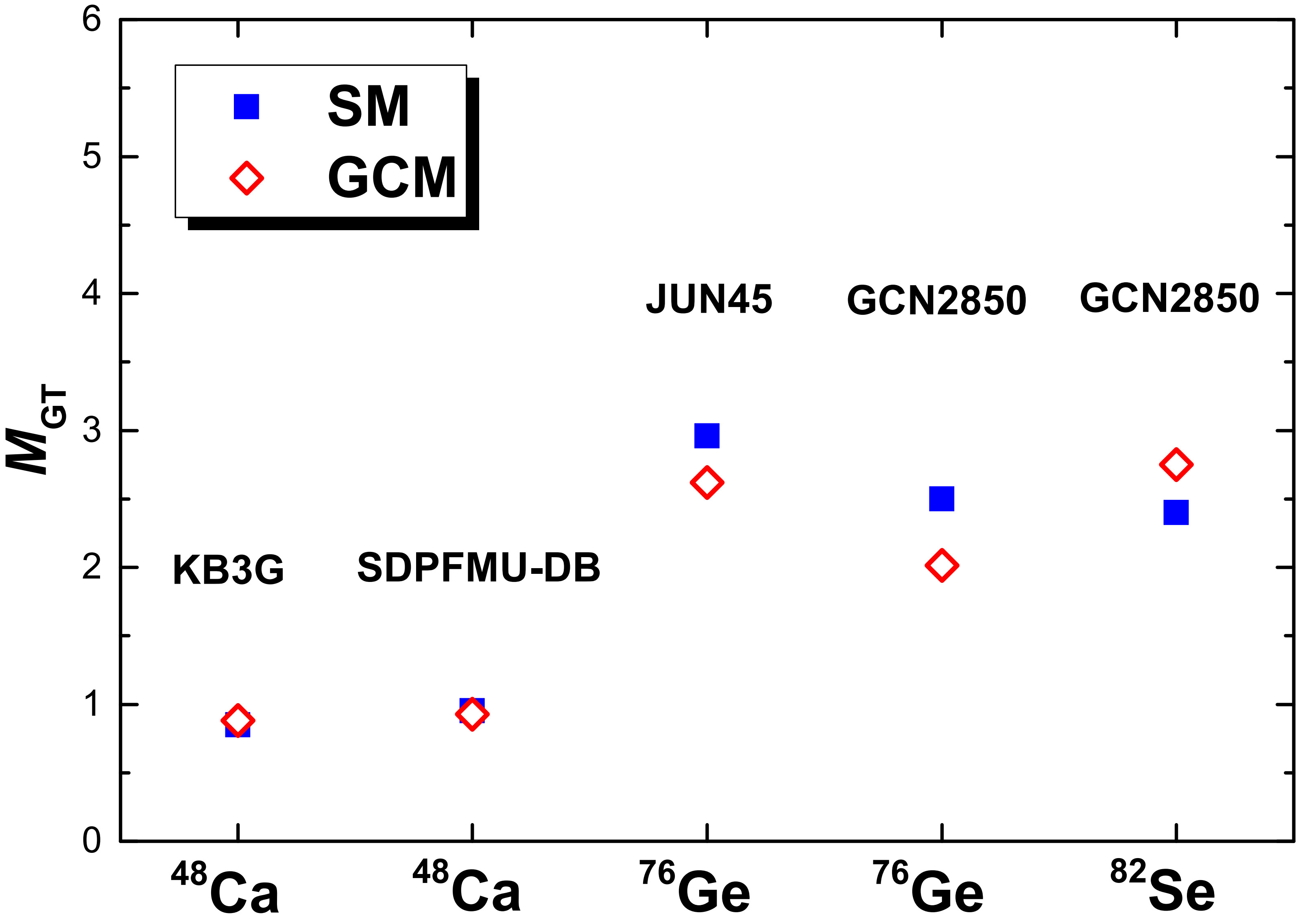
Level 2 GCM: triaxial deformation



15%~20% reduction for both GT and Fermi part of NME if triaxial shape fluctuation is included.

Benchmarking: 0νββ NMEs given by GCM and SM



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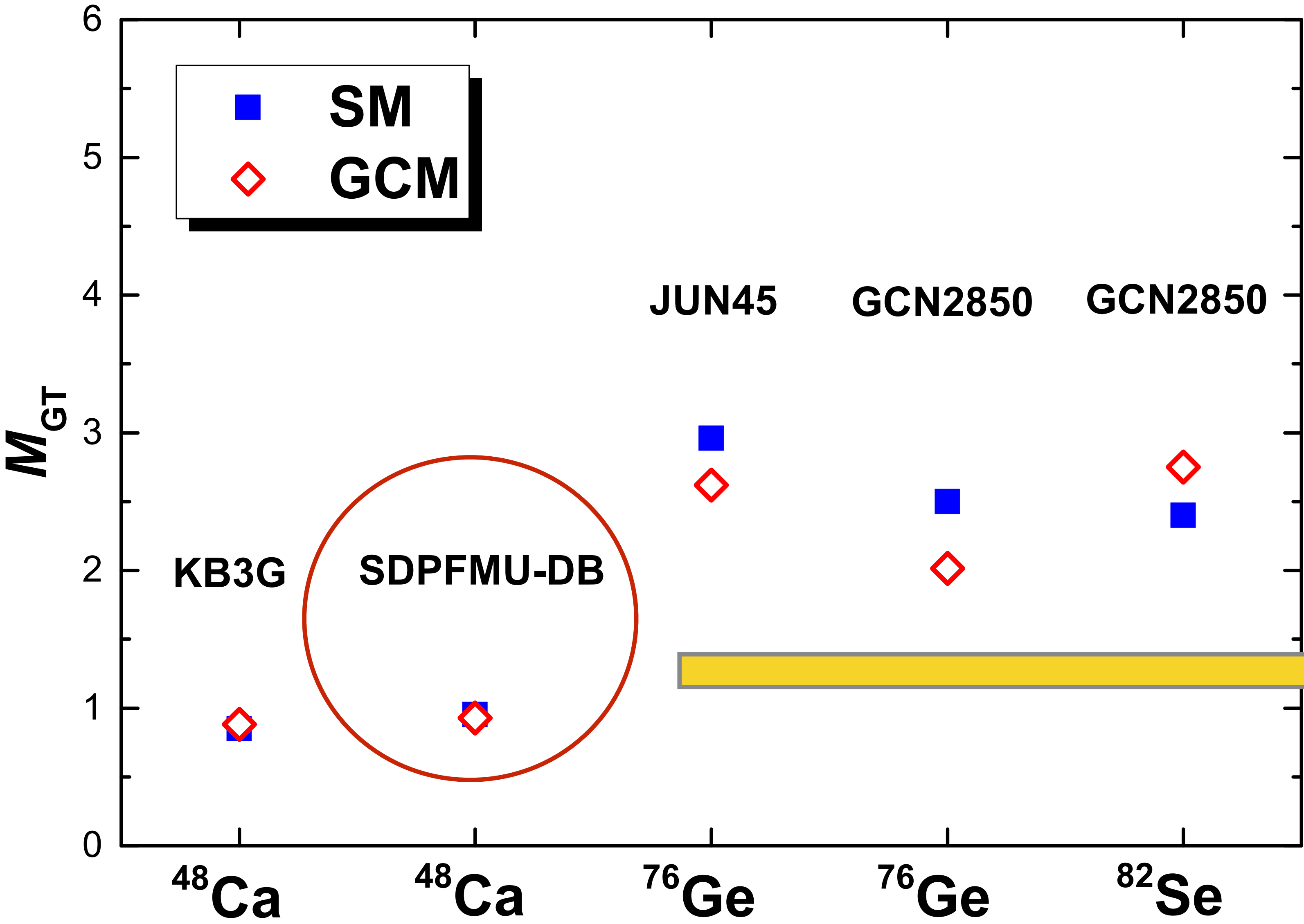


A full *sdpf*-shell GCM calculation

The NMEs given by SM and GCM are in good agreement, indicating that **the GCM captures most important valence-shell correlations.**

Multi-shell GCM

- In principle, effective *pfsdg*-shell interaction based on chiral EFT can be calculated by many-body perturbation theory (MBPT), similarity renormalization group (SRG) or couple cluster (CC).
- We employ two effective *pfsdg*-shell interactions calculated by MBPT, which are provided by J. D. Holt.

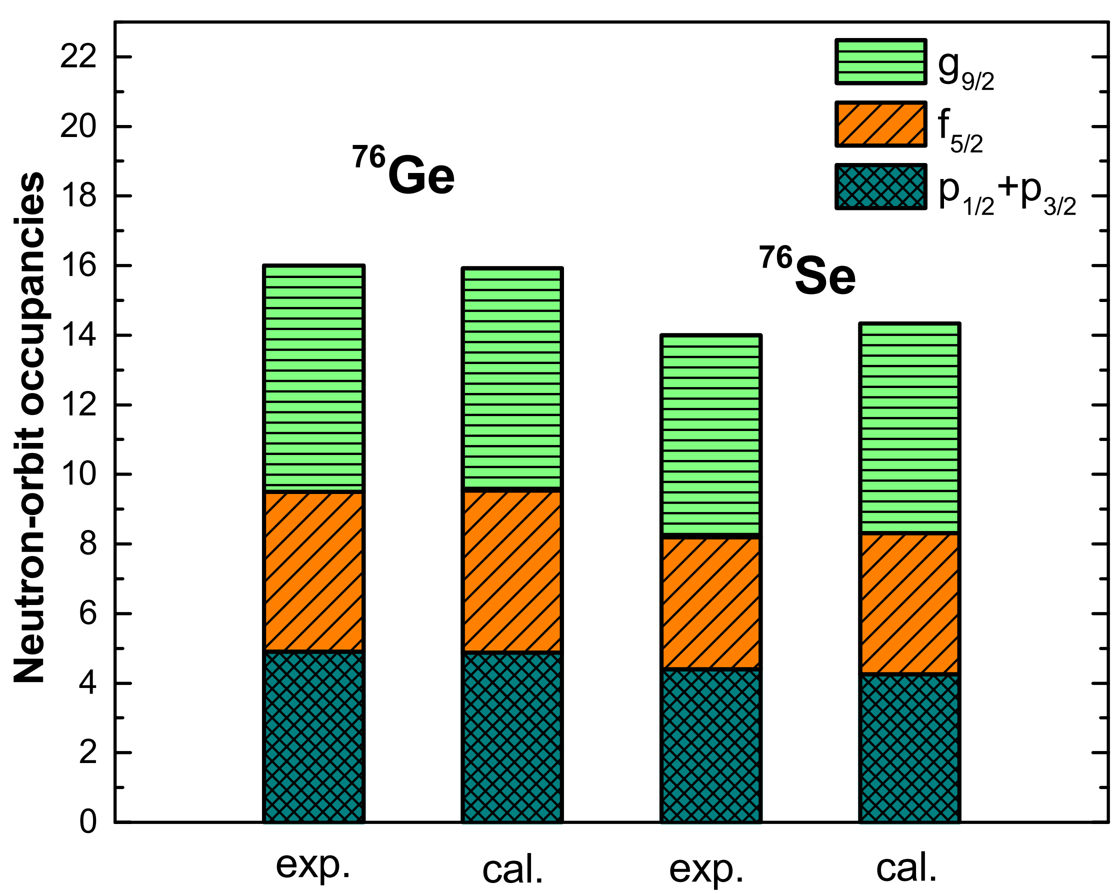
***pfsdg*-1**: 3N forces normal ordered with respect to ^{40}Ca
***pfsdg*-2**: 3N forces normal ordered with respect to ^{56}Ni

Computing Usage:

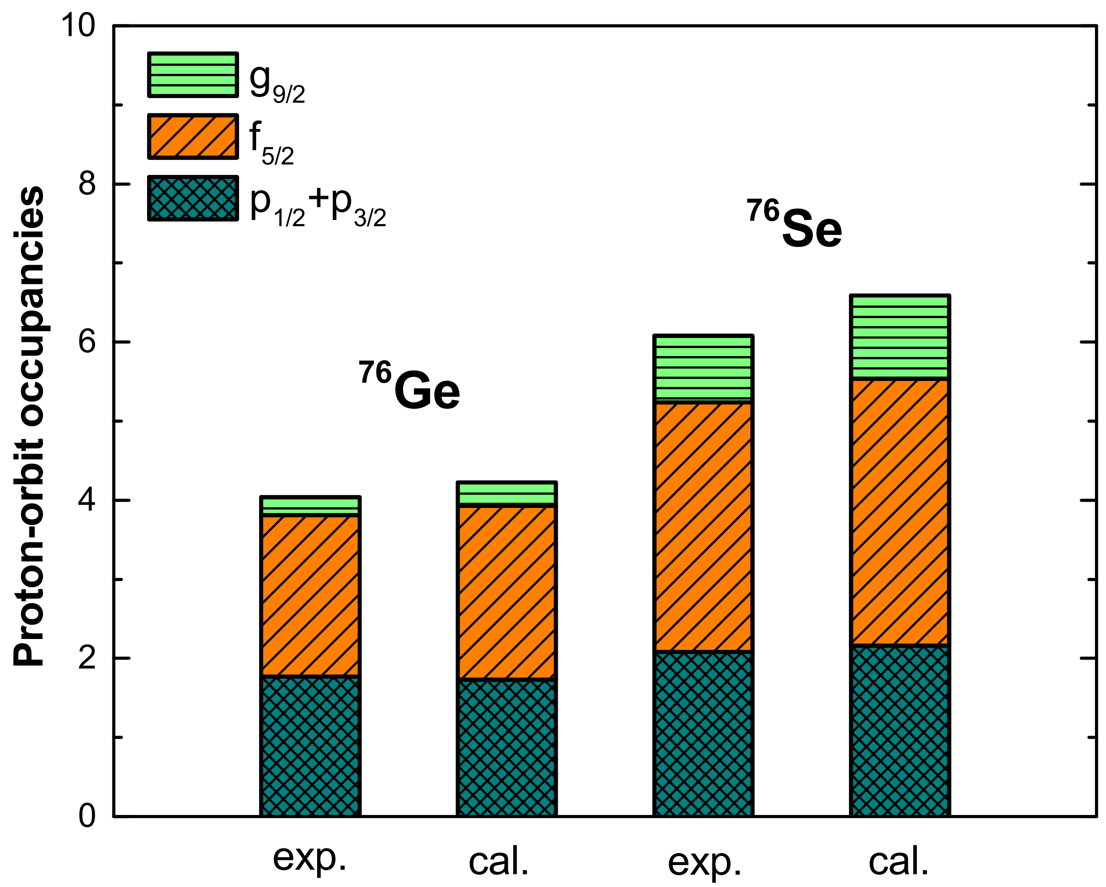
- Our calculation within *pf5g9* shell used about 15K CPU hours, including axial shape, triaxial shape, and isoscalar pairing as coordinates.
- Extension to *pfsdg* shell will increase time by a factor of 25, because of the increased number of orbits.

Multi-shell GCM: SPEs optimization

Neutron-orbit occupancies

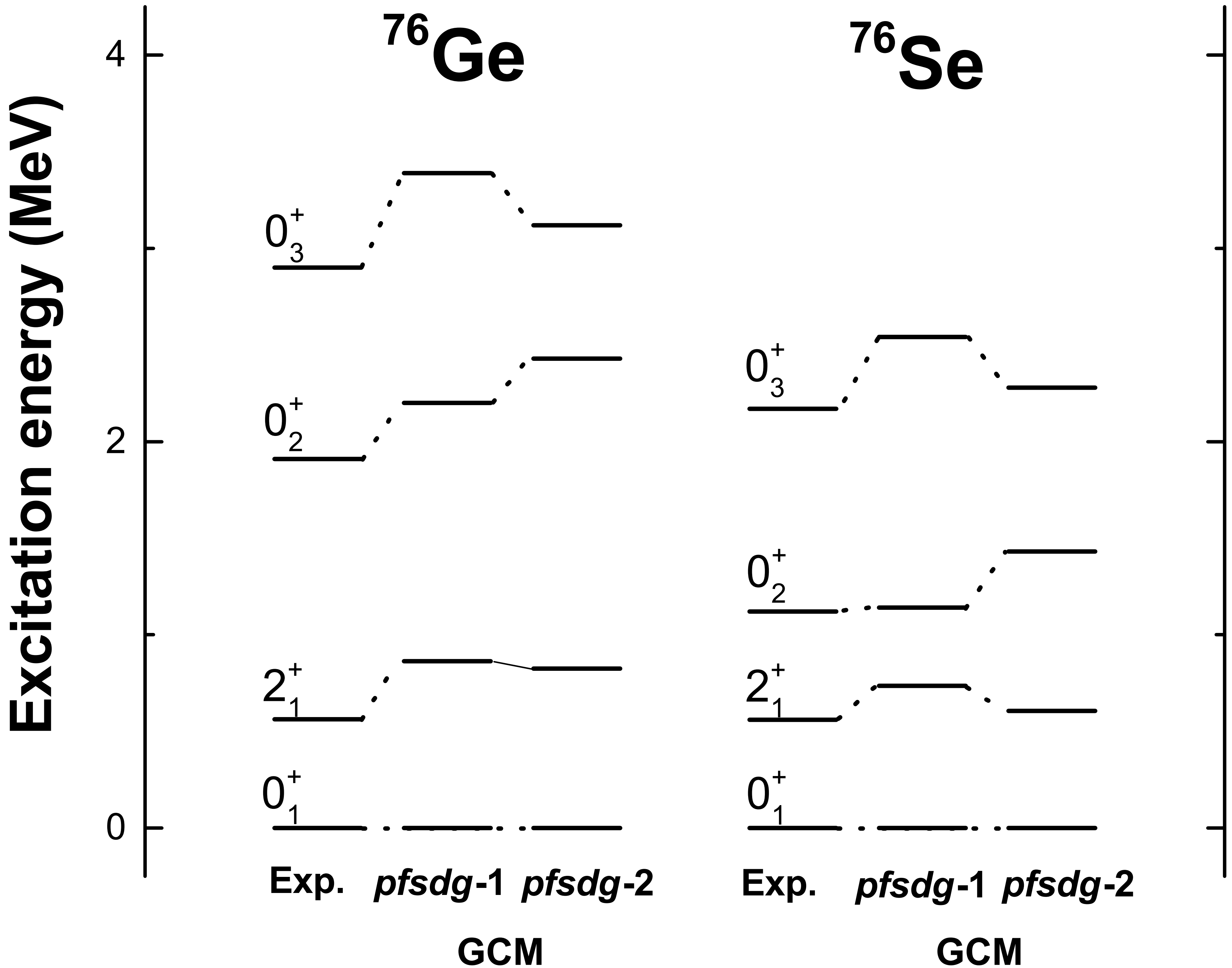


Proton-orbit occupancies

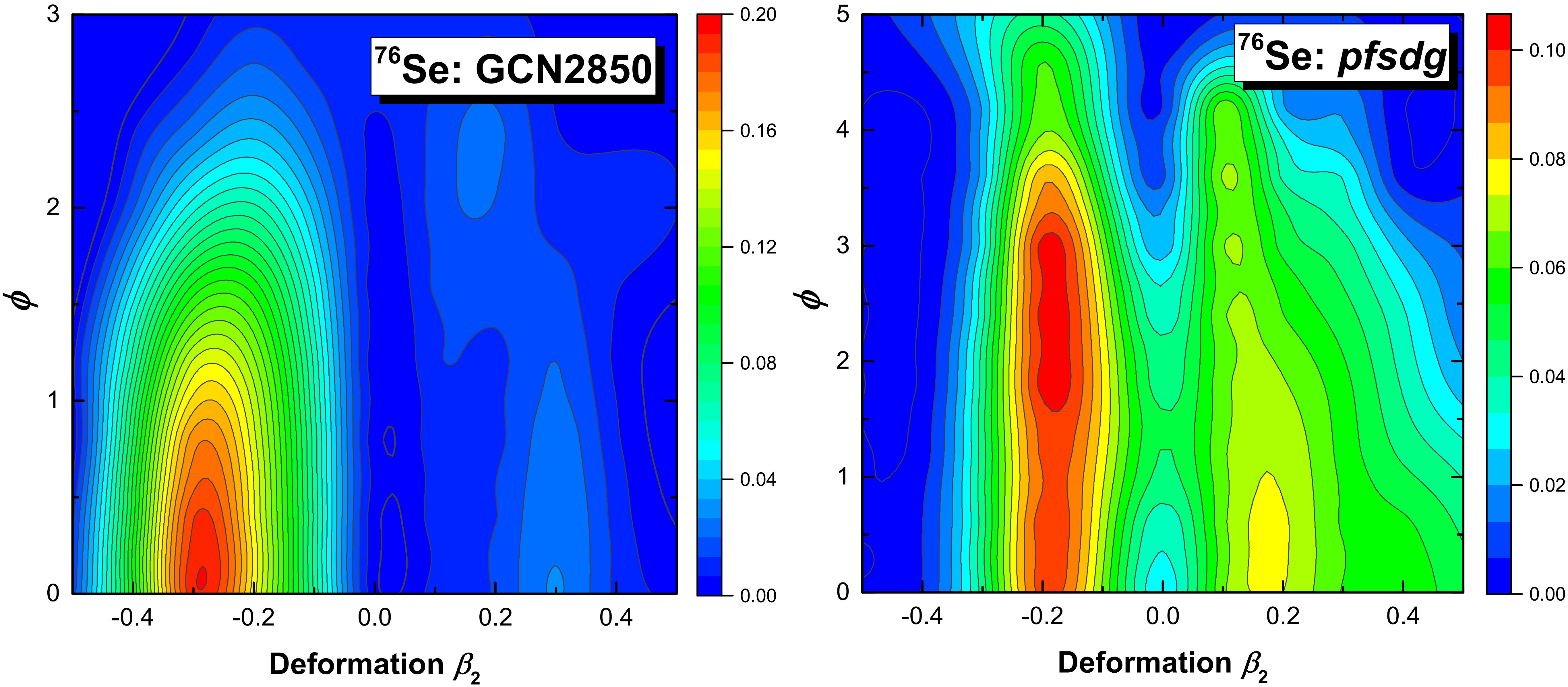


We optimize the single-particle energies for *pfsdg*-shell interactions by fitting the measured occupancies of valence neutron and proton orbits.

Multi-shell GCM: low-lying spectra

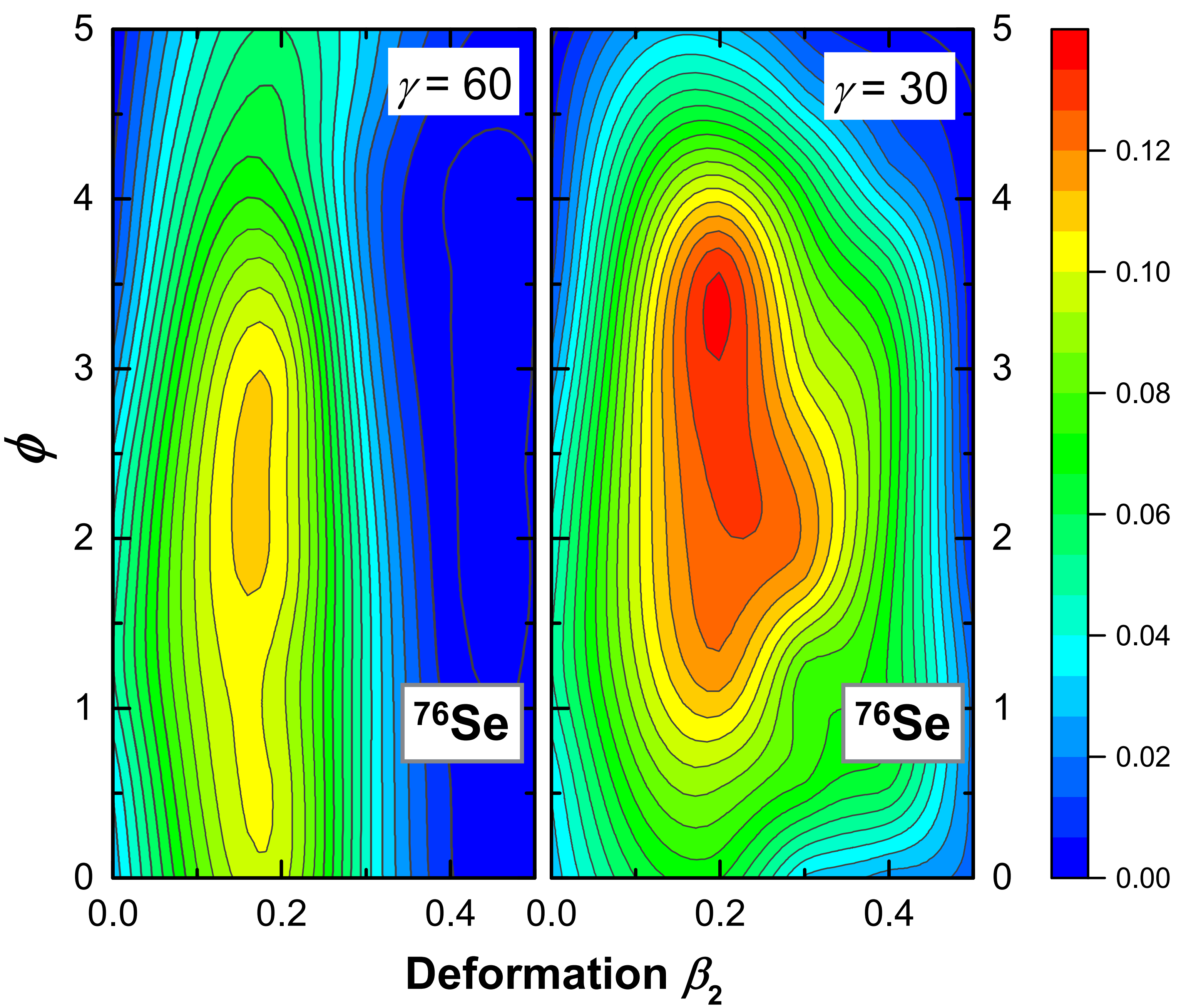


Multi-shell GCM: collective wave function



- Larger model space: larger isoscalar pairing in *pfsdg*-shell calculation
- How does triaxial shape influence NMEs?

Multi-shell GCM: triaxial deformation



With triaxially deformed configurations, the wave functions:

① are pushed to the region with larger isoscalar *pn* pairing.

② spread widely to the region with larger deformation

Multi-shell GCM: triaxial deformation

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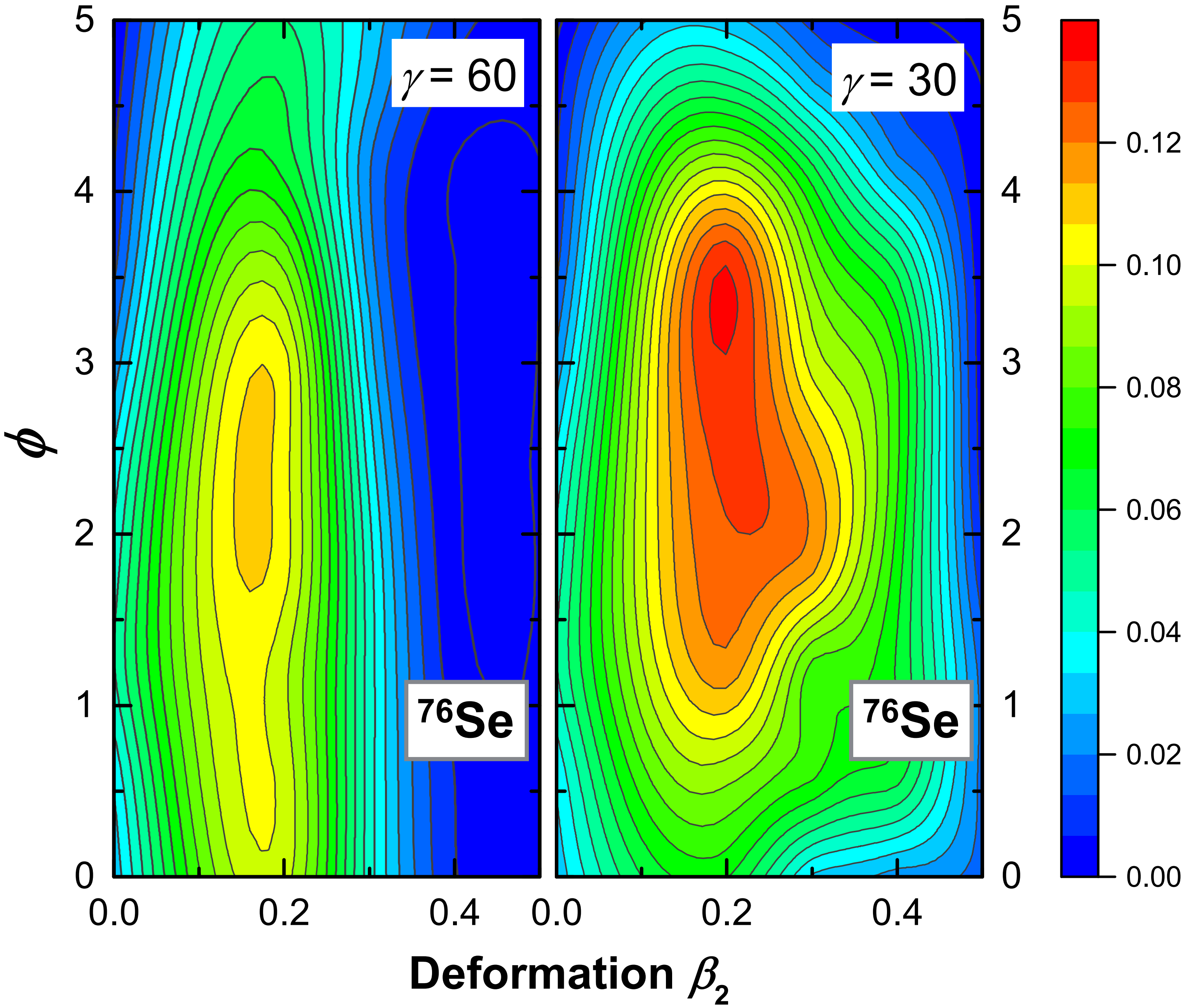
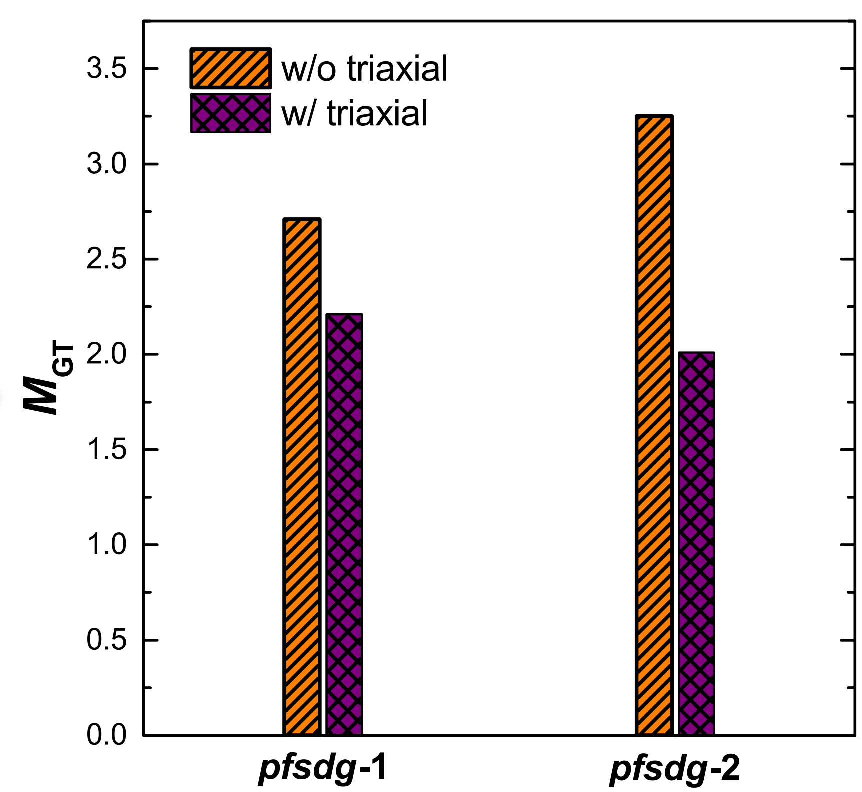
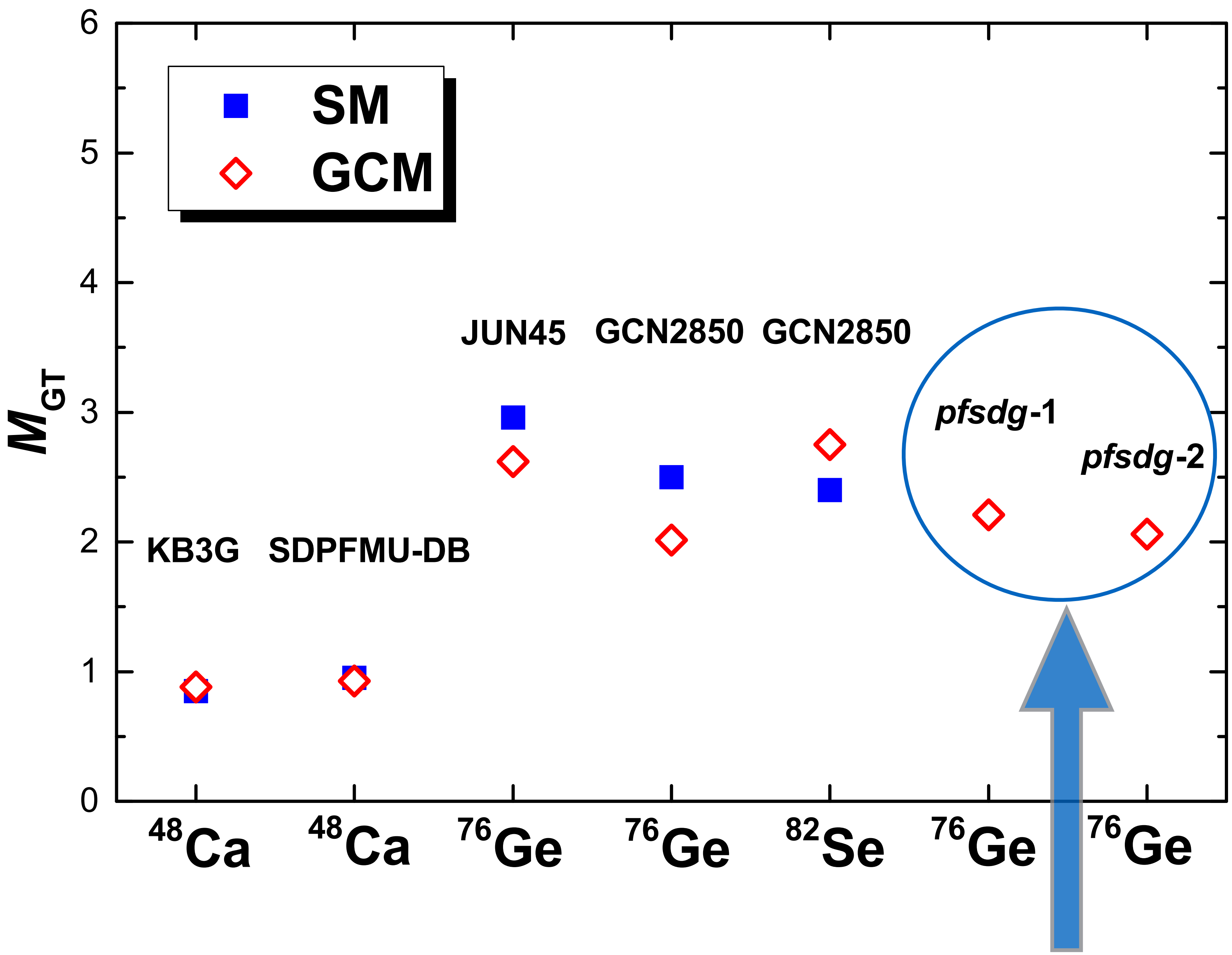




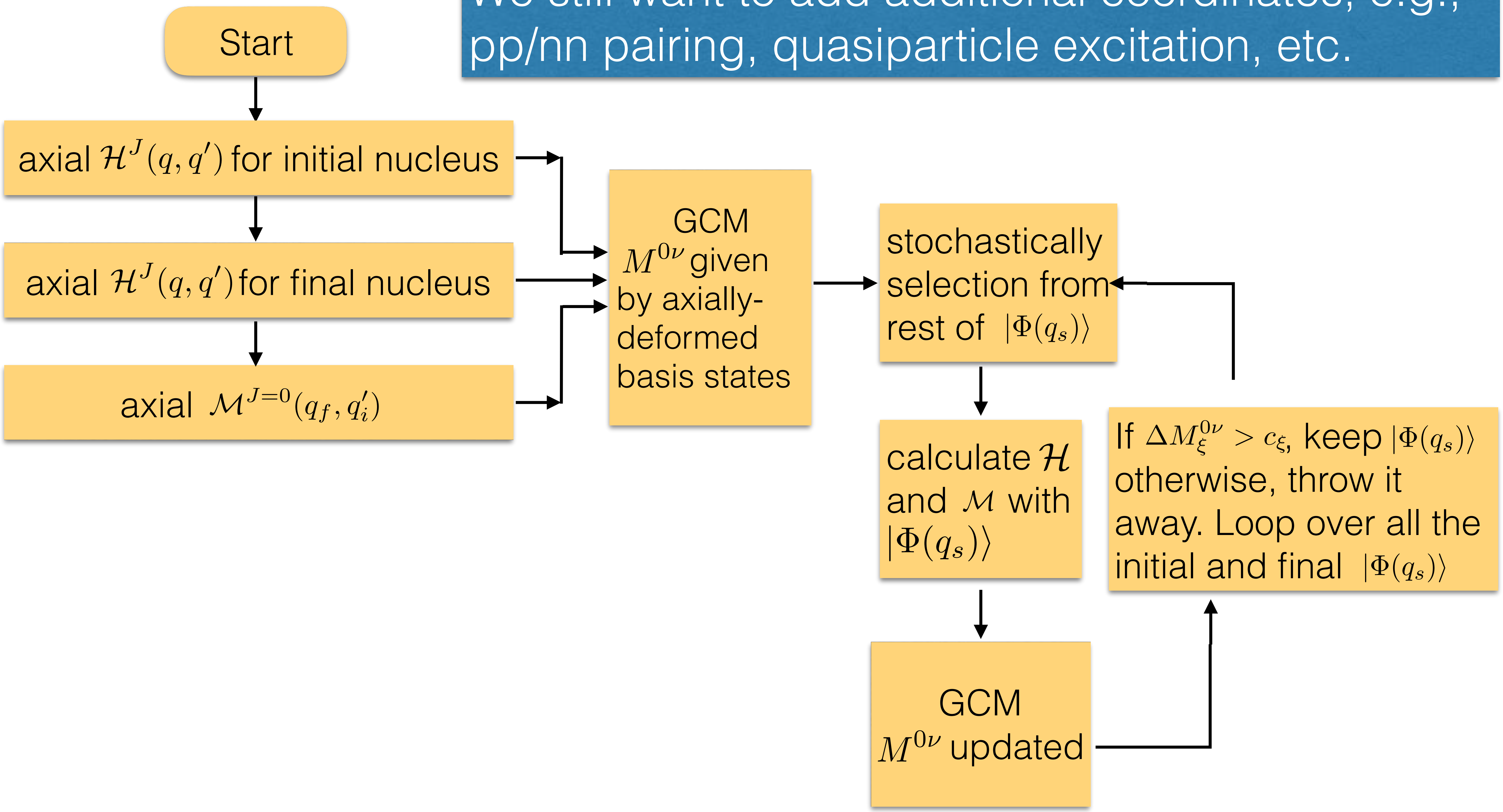
Multi-shell GCM



full *pfsdg*-shell GCM calculations

A relatively simple strategy for stochastic basis selection

We still want to add additional coordinates, e.g., pp/nn pairing, quasiparticle excitation, etc.



Summary

- We are trying to combine the virtues of the shell model and EDF calculations by including all collective correlations in the GCM.

- Tests against exact solutions in one shell indicate that we indeed have all important valence-space correlations.

- Calculation has been extended to two major shell (e.g., *pfsdg* shell) model space, which is out of scope of the conventional SM. Including triaxially deformed configurations significantly affect the calculated NMEs.

- To speed up the two-shell calculation, stochastic selection of basis states is under construction, and we are looking for more efficient methods.

Summary

Collaborators:

- Jonathan Engel, UNC
- Jiangming Yao, UNC
- Mihai Horoi, CMU
- Jason Holt, TRIUMF
- Javier Menendez, University of Tokyo
- Nobuo Hinohara, University of Tsukuba

Thank you for your attention!