Neutron-proton pairing and double-beta decay nuclear matrix elements

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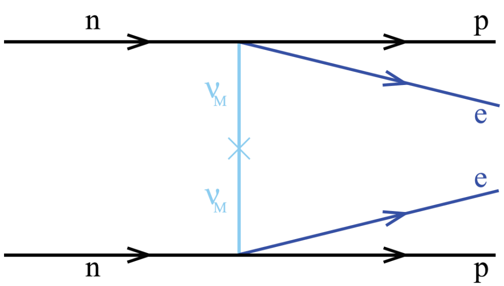
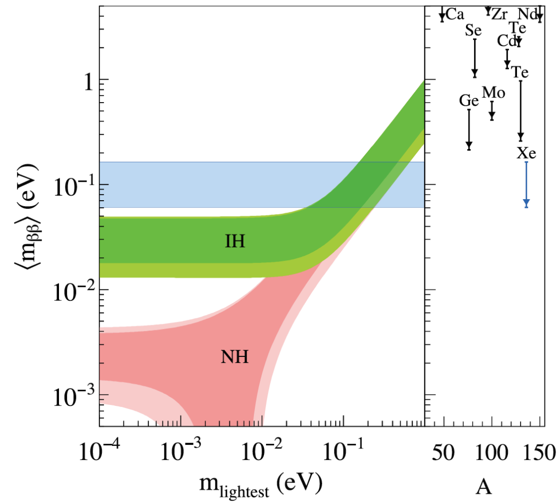
Conference on Neutrino and Nuclear Physics

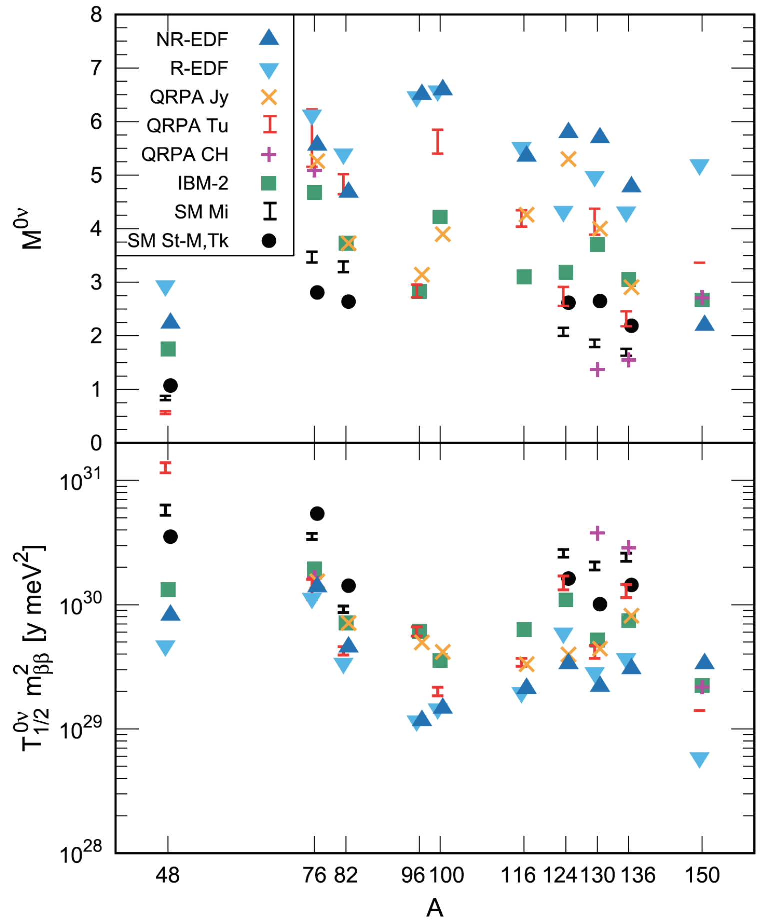
Double-beta decay and nuclear matrix element

neutrinoless double-beta decay

Engel and Menéndez, Rep. Prog. Phys. **80**, 046301 (2017)







nuclear matrix element (NME)

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta},Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

half life of 0νββ

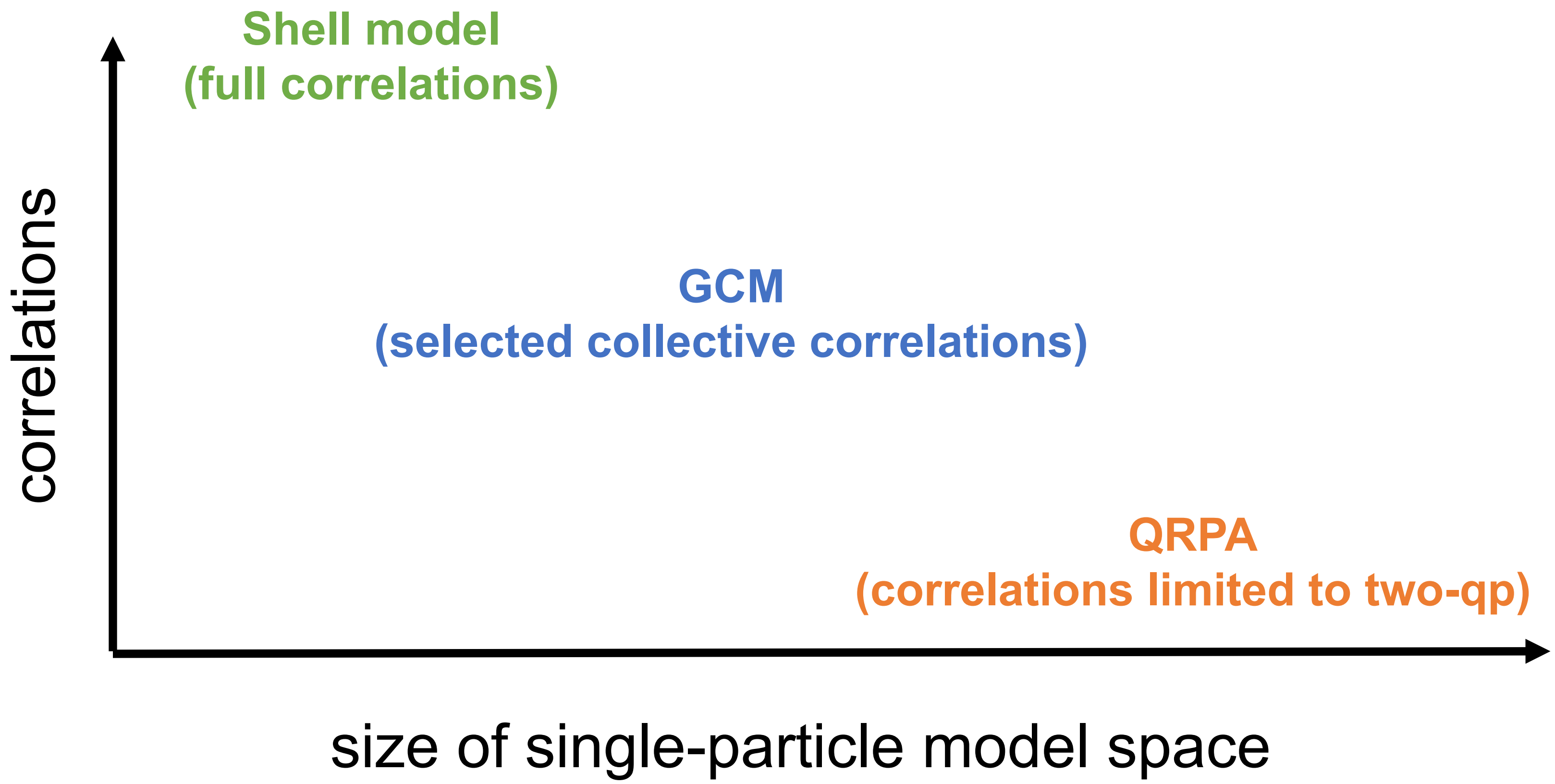
phase space factor

effective mass of electric neutrino

- Precise evaluation of the NME is necessary for neutrino mass determination
- Currently a factor of 2-3 differences in the theoretical calculations
- goal: Understanding and reducing the uncertainty

Origin of differences

- decay operator
- many-body theory (correlations)
- single-particle model space
- effective interactions

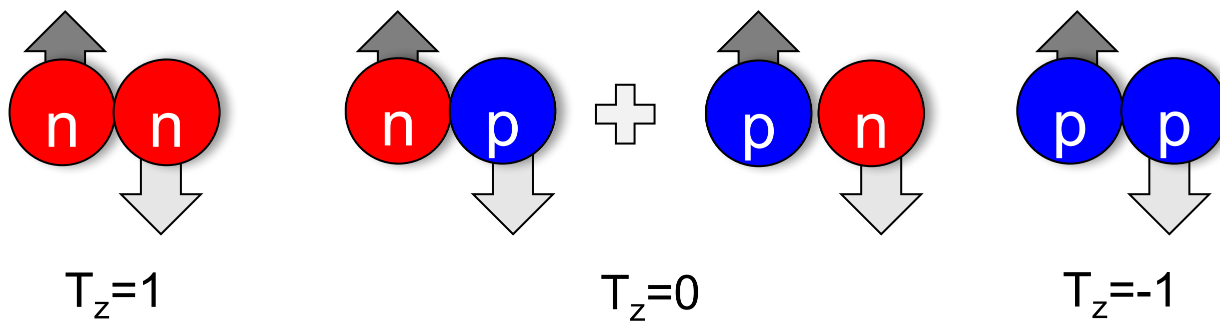


Origin of differences

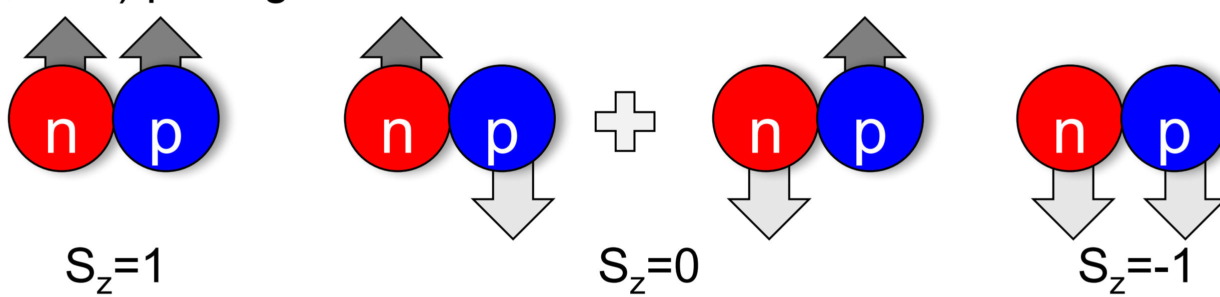
- ☐ decay operator
- ☐ many-body theory (correlations)
- ☐ single-particle model space
- ☐ effective interactions

neutron-proton pairing

Isovector (T=1, S=0) pairings → Fermi matrix element (np)



Isoscalar (T=0, S=1) pairings → Gamow-Teller matrix element



- ☐ strengths not constrained well from the ground state properties (isoscalar pairing)
- ☐ suppresses the nuclear matrix elements (QRPA),not included in EDF-based GCM

Understanding the differences

Shell model / GCM / QRPA calculations using different

- decay operator
- single-particle model space
- effective interactions

→ a factor of 2-3 differences

in this talk...

- GCM / QRPA calculations using the same operator, model space, interaction
- GCM / shell model calculations using the same operator, model space, interaction
- calculations using different interaction (w/, w/o neutron-proton pairing) within the same approach

Generator coordinate method

Generator Coordinate Method (GCM)

superposition of the projected mean fields (GCM basis) along generator coordinates q

$$|\Psi(N, Z, I=0, M=0)\rangle = \sum_q f_k(q) |\phi^{N,Z}_{I=0,M=0}(q)\rangle$$

initial/final ground state

weight function

Hill-Wheeler equation: Schrödinger eq. for many-body states

$$\hat{H}|\Psi_k\rangle = E_k|\Psi_k\rangle \quad \Longleftrightarrow \quad \sum_{q'} \{\mathcal{H}(q,q') - E_k \mathcal{I}(q,q')\} f_k(q') = 0$$

Hamiltonian kernel

$$\mathcal{H}(q,q') = \langle \phi^{N,Z}_{I=0,M=0}(q) | \hat{H} | \phi^{N,Z}_{I=0,M=0}(q') \rangle$$

Norm kernel

$$\mathcal{I}(q,q') = \langle \phi^{N,Z}_{I=0,M=0}(q) | \phi^{N,Z}_{I=0,M=0}(q') \rangle$$

Nuclear matrix element (closure approximation)

$$M_{0\nu} = \langle \Psi(N-2, Z+2, I=0) | \hat{M}_{0\nu} | \Psi(N, Z, I=0) \rangle = \sum_{qq'} f^*_{N-2,Z+2,I=0}(q) \mathcal{T}(q,q') f^*_{N,Z,I=0}(q')$$

$$\mathcal{T}(q,q') = \langle \phi^{N-2,Z+2}_{I=0,M=0}(q) | \hat{M}_{0\nu} | \phi^{N,Z}_{I=0,M=0}(q') \rangle$$

- step 1: constrained HFB calculation to generate GCM basis
- step 2: projected two-body matrix elements (computationally demanding)
- step 3: Hill-Wheeler eq. to determine f(q) for the ground states

Choice of generator coordinates

choice of the GCM basis (generator coordinates) is very important

generator coordinates to be considered (important collective correlations)

- correlations important for ground states
  - quadrupole deformation and like-particle isovector pairing amplitudes
- correlations important for double-beta decay
  - neutron-proton isovector pairing amplitude (1 component)
  - neutron-proton isoscalar pairing amplitudes (3 spin components)
  - Gamow-Teller correlation (particle-hole $\sigma\tau$, 9 components)

deformation / isoscalar (S=1) pairing: rotational symmetry breaking

→ **angular momentum projection (1D/3D)**

pairing and/or Gamow-Teller correlation: gauge symmetry breaking

→ **particle number projection**

neutron-proton pairing / Gamow-Teller correlations: np mixing in quasiparticles

→ **neutron-proton HFB**

Choice of generator coordinates

We assume axial symmetry of the system and
evaluate the Fermi and GT matrix elements separately

$$\langle f|M_{0\nu}|i\rangle \approx \langle f|M_{0\nu}^{\mathrm{GT}}|i\rangle - \frac{g_V^2}{g_A^2}\langle f|M_{0\nu}^{\mathrm{F}}|i\rangle$$

Fermi matrix element : quadrupole deformation (β) and isovector np amplitude
Gamow-Teller matrix element : β and isoscalar np amplitude (S_z=0)
(other two components are include through angular momentum projection)

GCM with neutron-proton pairing

- NH and Engel, Phys. Rev. C **90**, 031301(R) (2014)
- Menéndez, NH et al., Phys. Rev. C **93**, 014305 (2016)
- C.F. Jiao et al., arXiv:1707.03940, 1709.0531 (with triaxial deformation)

EDF-based GCM calculations do not include the neutron-proton pairing

^{76}Ge→^{76}Se 0νββ NME

NH and J. Engel, Phys. Rev. C **90**, 031301(R) (2014)

Comparison between the GCM and QRPA (spherical)

Hamiltonian

$$H = h_0 - \sum_{\mu=-1}^{1} g_{\mu}^{T=1} S_{\mu}^{\dagger} S_{\mu} - \frac{\chi}{2} \sum_{K=-2}^{2} Q_{2K}^{\dagger} Q_{2K} - g^{T=0} \sum_{\nu=-1}^{1} P_{\nu}^{\dagger} P_{\nu} + g_{ph} \sum_{\mu,\nu=-1}^{1} F_{\nu}^{\mu\dagger} F_{\nu}^{\mu}$$

sp energy | isovector pairing | quadrupole (QQ) interaction | isoscalar pairing | Gamow-Teller interaction

single-particle model space: HO N_{sh}=3, 4 (pf + sdg) shells

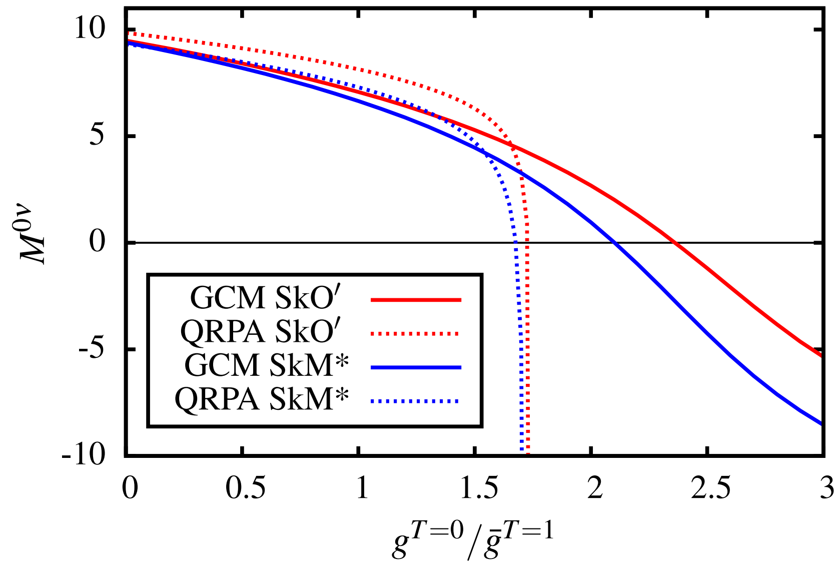
parameters

- sp energies、T=1 pp,nn pairing strength (indep.)、QQ force strength :
    - fitted to reproduce the Skyrme-HFB gaps and deformation (SkO' and SkM*)
- T=1 pn pairing strength: value that vanishes 2ν closure Fermi matrix element
- T=0 pn pairing: from total β+ strength of ^{76}Se
- Gamow-Teller interaction g_{ph} : GT- resonance peak energy of ^{76}Ge (Skyrme QRPA)

Comparison with QRPA

NH and J. Engel, Phys. Rev. C **90**, 031301(R) (2014)

generator coordinate: isoscalar pairing only, without QQ force $\phi = \frac{\langle P_0 + P_0^\dagger \rangle}{2}$



g_{pp} = 1.47(SkO'), 1.56 (SkM*)

QRPA: collapse near the phase transition $g_{pp}=g^{T=0}/g^{T=1}$ ~ 1.6
GCM: smooth dependence on isoscalar pairing

Skyrme	no gph/$g^{T=0}$	no $g^{T=0}$	1D full	QRPA
SkO'	14.0	9.5	5.4	5.6
SkM*	11.8	9.4	4.1	3.5

+ στ correlation

+ isoscalar pairing correlation

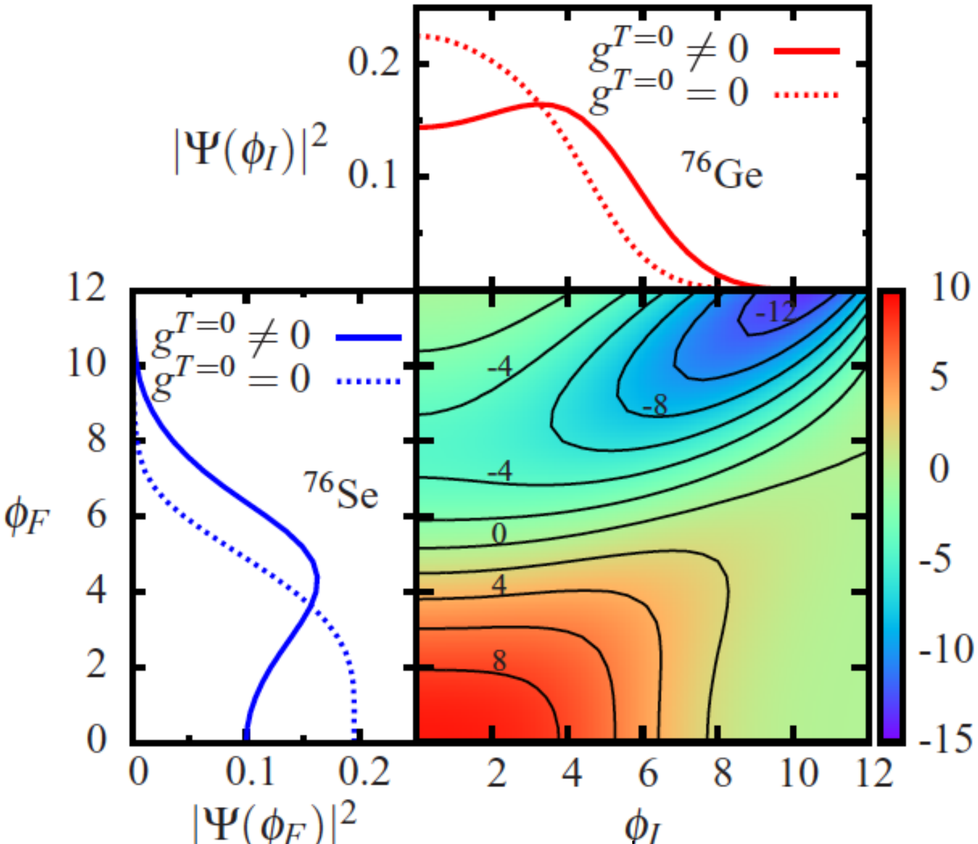
np correlations suppresses the NME in GCM as much as in QRPA

^{76}Ge→^{76}Se 0ν matrix element

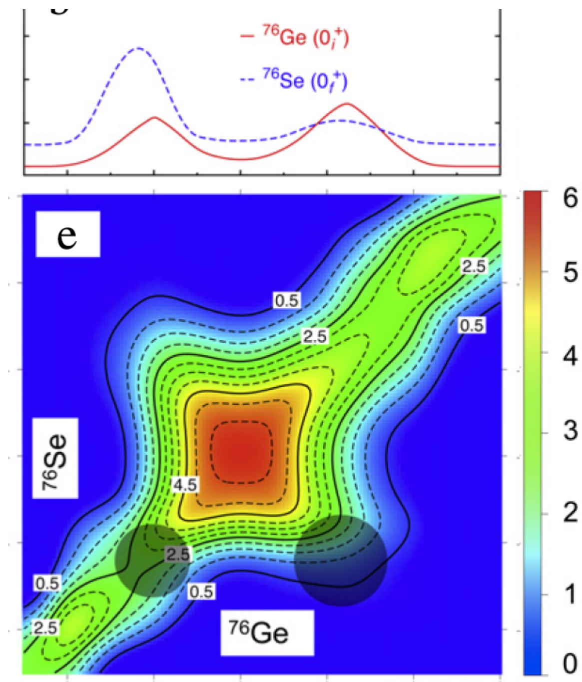
$$M^{0\nu} = \langle N-2, Z+2, I=0|\hat{M}^{0\nu}|N, Z, I=0\rangle = \sum_{qq'} \frac{f_F^*(q)\mathcal{T}(q,q')f_I(q')}{\sqrt{\mathcal{I}_F(q,q)\mathcal{I}_I(q',q')}} = \sum_{qq'} f_F^*(q)\tilde{\mathcal{T}}(q,q')f_I(q')$$

$$\mathcal{T}(q,q') = \langle \phi^{N-2,Z+2}_{I=0,M=0}(q)|\hat{M}_{0\nu}|\phi^{N,Z}_{I=0,M=0}(q')\rangle$$

matrix element and collective wave function squared



similar plot for β
(Rodriguez et al. PPNP66 2011)



generator coordinate: $\phi = \frac{\langle P_0 + P_0^\dagger \rangle}{2}$

matrix element is large at the same deformation

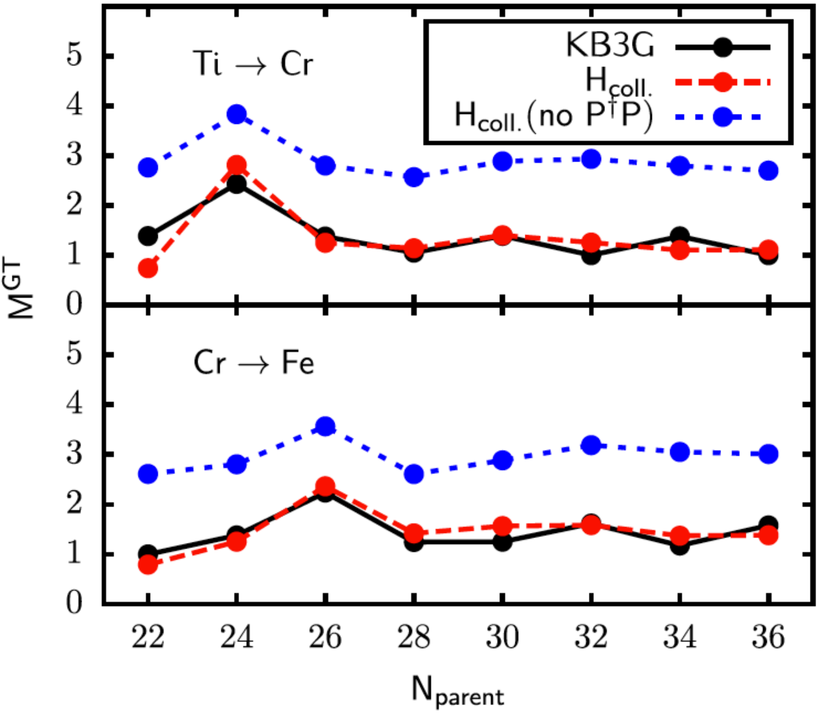
- deformation: reduces the matrix element due to small initial/final state overlap
- isoscalar pairing: reduces the matrix element due to negative contribution

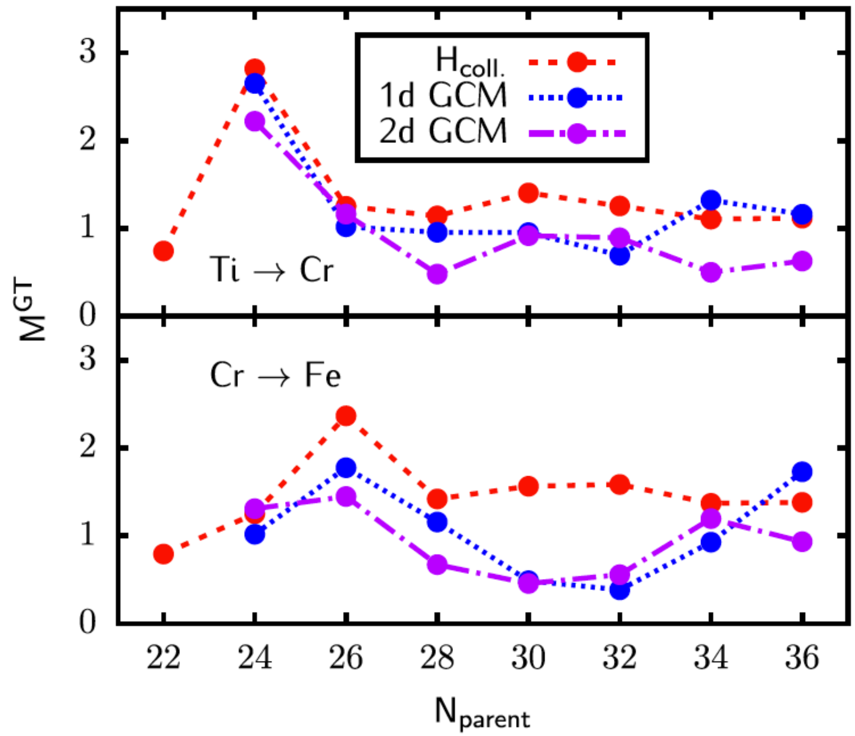
Comparison with shell model (pf shell)

Menéndez, NH et al., Phys. Rev. C **93**, 014305 (2016)

- model space: pf shell (one major shell)
- Hamiltonian: separable Hamiltonian derived from KB3G

Shell model with isoscalar pairing (red)
Shell model without isoscalar pairing (blue)





- realistic interaction contains the isoscalar pairing and it suppresses the NME (even in light systems!)
- GCM with isoscalar pairing: good approximation to shell model
- improvement necessary for the no-pairing gap states (around N_{ini}=28-32)

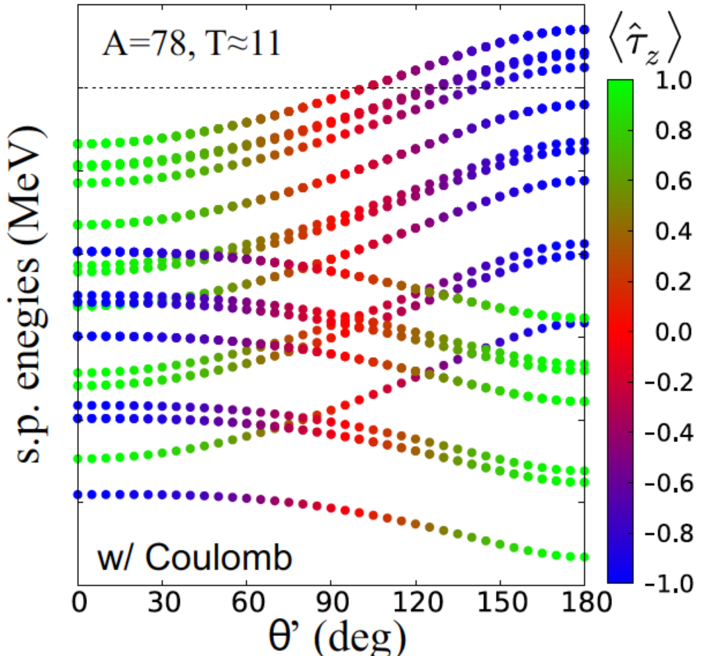
Extension to Skyrme DFT

neutron-proton pairing is important / How can we determine the coupling constant?

neutron-proton Skyrme DFT (and QRPA)

- isospin-invariant DFT (formulation : Perlińska et al., Phys. Rev. C **69**, 014316 (2004))
  - ph part: HFODD Sato, et al. Phys. Rev. C **88**, 061301 (2013)
  - HFBTHO Sheikh, NH et al., Phys. Rev. C **89**, 054317 (2014)
  - pairing part: in progress.. (HFBTHO)

T=11 isobaric analogue states



^{78}Ni ^{78}Sn

- determination of relevant coupling constants
  - optimization

    Mustonen and Engel, Phys. Rev. C **93**,104304 (2016)

- projection problem for GCM
  - when density-dependent term is present

    Dobaczewski et al., Phys. Rev. C **76**, 054315 (2007)

  - Regularization schemes

    Lacroix, Duguet, Bender Phys. Rev. C **79** (2009)
    Satula and Dobaczewski Phys. Rev. C **90**, 054303 (2014)

Summary

- Generator coordinate method with neutron-proton pairing for the $0\nu\beta\beta$ NME

- Calculations for ^{76}Ge $0\nu\beta\beta$ decay and comparison with QRPA

- Calculations for pf-shell nuclei (Ti and Cr) and comparison with shell model

- neutron-proton pairing is important in all three approaches

Collaborators

- Jonathan Engel (UNC-CH, USA)
- Javier Menéndez (U. Tokyo, Japan)
- Gabriel Martínez-Pinedo (GSI, Germany)
- Tomás Rodríguez (Madrid, Spain)

Computational Resources

COMA(PACS-IX)
Center for Computational Sciences, Univ. Tsukuba