Double beta decay NME from deformed QRPA with realistic forces

Dong-Liang Fang

Institute of Modern Physics, Chinese Academy of Science

中国科学院近代物理研究所

Institute of Modern Physics, Chinese Academy of Sciences

Outline

- Formalism
- Results
- Errors
- Conclusion and Outlook

Formalism

- Many-body Methods adopted for the calculations of NME
  - Closure without involvement of intermediate states
    - IBM, PHFB, DFT, CDFT,……
  - Non-Closure with intermediated states
    - Shell Model
    - QRPA: realistic forces; Skyrme force;……

Formalism

P. Ring et. al., Nuclear Many-Body Problem

- QRPA is a method used to describe the small amplitude vibrations for open shell nuclei
- pn-QRPA treats the states of intermediate odd-odd nuclei as iso-vector excitation of even-even ground states
- Only 1 phonon excitation is considered, no multi-phonon excitations, no phonon-phonon interactions
- QRPA is constructed on the quasi-particle grounds, particle number is not conserved

Formalism

- Solve the Schroedinger eq. with mean field potential (W.S. Potential)

- Solve the BCS equations to get the quasiparticle, where the residual interactions (G-matrix) are obtained by solving the Bruckner eq. (Overall renormalized paremeters g_{pair} are needed)

- Solve the QRPA equations to get the wave functions of the intermediate states (g_{ph} and g_{pp})

Formalism

- Introduction of deformed QRPA
  - Adiabatic approx. separate the intrinsic and rotation d.f.
  - Quasi-particle constructed on intrinsic frame
- Why deformation:
  - ^{150}Nd lies in the heavily deformed rare earth region
  - This nucleus has the largest phase space factor

Formalism

Kotila and Iachello, PRC85,034316

Nucleus	$G_{0\nu}^{(0)}$ (10^{-15} yr^{-1})	$G_{0\nu}^{(1)}$ (10^{-15} yr^{-1})	$Q_{\beta\beta}$ (MeV)
^{48}Ca	24.81	−23.09	4.27226(404)
^{76}Ge	2.363	−1.954	2.03904(16)
^{82}Se	10.16	−9.074	2.99512(201)
^{96}Zr	20.58	−18.67	3.35037(289)
^{100}Mo	15.92	14.25	3.03440(17)
^{110}Pd	4.815	−4.017	2.01785(64)
^{116}Cd	16.70	−14.83	2.81350(13)
^{124}Sn	9.040	−7.765	2.28697(153)
^{128}Te	0.5878	−0.3910	0.86587(131)
^{130}Te	14.22	−12.45	2.52697(23)
^{136}Xe	14.58	12.73	2.45783(37)
^{148}Nd	10.10	−8.506	1.92875(192)
^{150}Nd	63.03	−57.76	3.37138(20)
^{154}Sm	3.015	−2.295	1.21503(125)
^{160}Gd	9.559	−7.932	1.72969(126)
^{198}Pt	7.556	−5.868	1.04717(311)
^{232}Th	13.93	−10.95	0.84215(246)
^{238}U	33.61	28.13	1.14498(125)

- Recent results on phase space factor

Formalism

Kotila and Iachello, PRC85,034316

Nucleus	$G_{0\nu}^{(0)}$ (10^{-15} yr^{-1})	$G_{0\nu}^{(1)}$ (10^{-15} yr^{-1})	$Q_{\beta\beta}$ (MeV)
^{48}Ca	24.81	−23.09	4.27226(404)
^{76}Ge	2.363	−1.954	2.03904(16)
^{82}Se	10.16	−9.074	2.99512(201)
^{96}Zr	20.58	−18.67	3.35037(289)
^{100}Mo	15.92	14.25	3.03440(17)
^{110}Pd	4.815	−4.017	2.01785(64)
^{116}Cd	16.70	−14.83	2.81350(13)
^{124}Sn	9.040	−7.765	2.28697(153)
^{128}Te	0.5878	−0.3910	0.86587(131)
^{130}Te	14.22	−12.45	2.52697(23)
^{136}Xe	14.58	12.73	2.45783(37)
^{148}Nd	10.10	−8.506	1.92875(192)
^{150}Nd	63.03	−57.76	3.37138(20)
^{154}Sm	3.015	−2.295	1.21503(125)
^{160}Gd	9.559	−7.932	1.72969(126)
^{198}Pt	7.556	−5.868	1.04717(311)
^{232}Th	13.93	−10.95	0.84215(246)
^{238}U	33.61	28.13	1.14498(125)

- Recent results on phase space factor

Formalism

- Nuclear matrix elements for 2νββ under intrinsic frame

$$M^{2\nu}_{\rm GT} = \sum_{K=0,\pm1} \sum_{m_i m_f} \frac{\langle 0^+_f | \bar{\beta}^-_K | K^+, m_f \rangle \langle K^+, m_f | K^+, m_i \rangle \langle K^+, m_i | \beta^-_K | 0^+_i \rangle}{\bar{\omega}_{K,m_i m_f}}$$

- NME for 0νββ

$$M^{0\nu}(K^\pi) = \sum_{m_i,m_f} \langle 0^+_f | c^\dagger_p c_n | K^\pi m_f \rangle \langle K^\pi m_f | K^\pi m_i \rangle \ \langle K^\pi m_i | c^\dagger_{p'} c_{n'} | 0^+_i \rangle$$
$$\times \sum_J \sum_{\substack{\eta_p \eta_{p'} \\ \eta_n \eta_{n'}}} F^{JK}_{p\eta_p n\eta_n} F^{JK}_{p'\eta_{p'} n'\eta_{n'}} \sum_{\mathcal{J}} (-1)^{j_n + j_{p'} + J + \mathcal{J}} \hat{\mathcal{J}} \begin{Bmatrix} j_p & j_n & J \\ j_{n'} & j_{p'} & \mathcal{J} \end{Bmatrix} \langle p(1),\, p'(2); \mathcal{J} \| \mathcal{O}_\ell(1,2) \| n(1),\, n'(2); \mathcal{J} \rangle$$

- Overlaps :

$$\langle K^\pi m_f | K^\pi m_i \rangle = \sum_{l_i l_f} \left[X^{m_f}_{l_f K^\pi} X^{m_i}_{l_i K^\pi} - Y^{m_f}_{l_f K^\pi} Y^{m_i}_{l_i K^\pi} \right] \mathcal{R}_{l_f l_i} \langle {\rm BCS}_f | {\rm BCS}_i \rangle$$

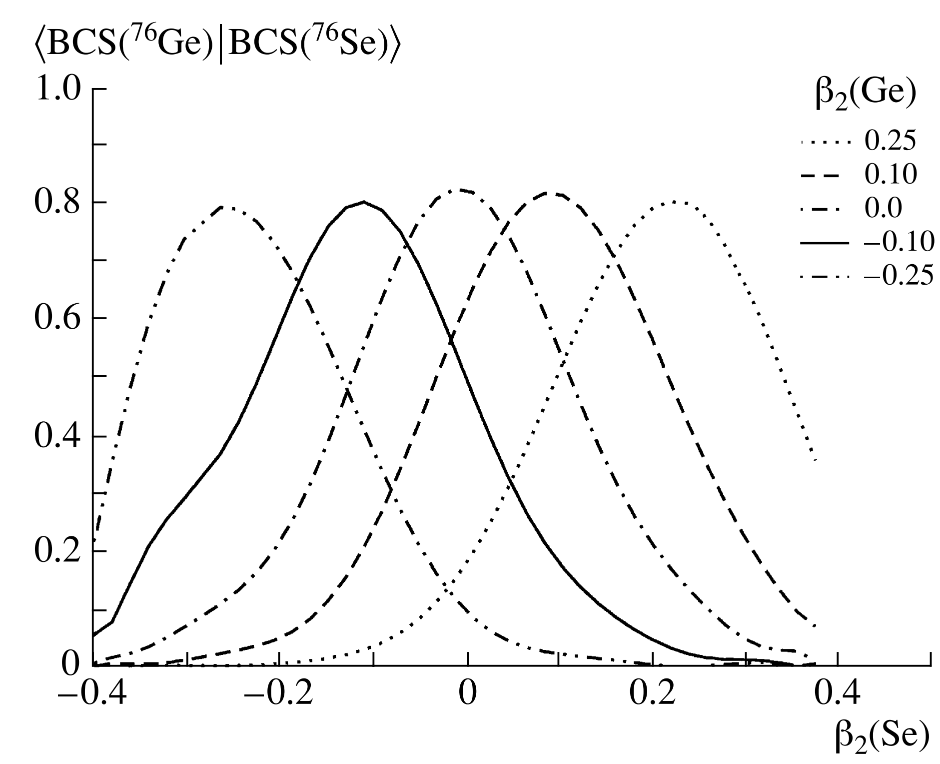
Formalism

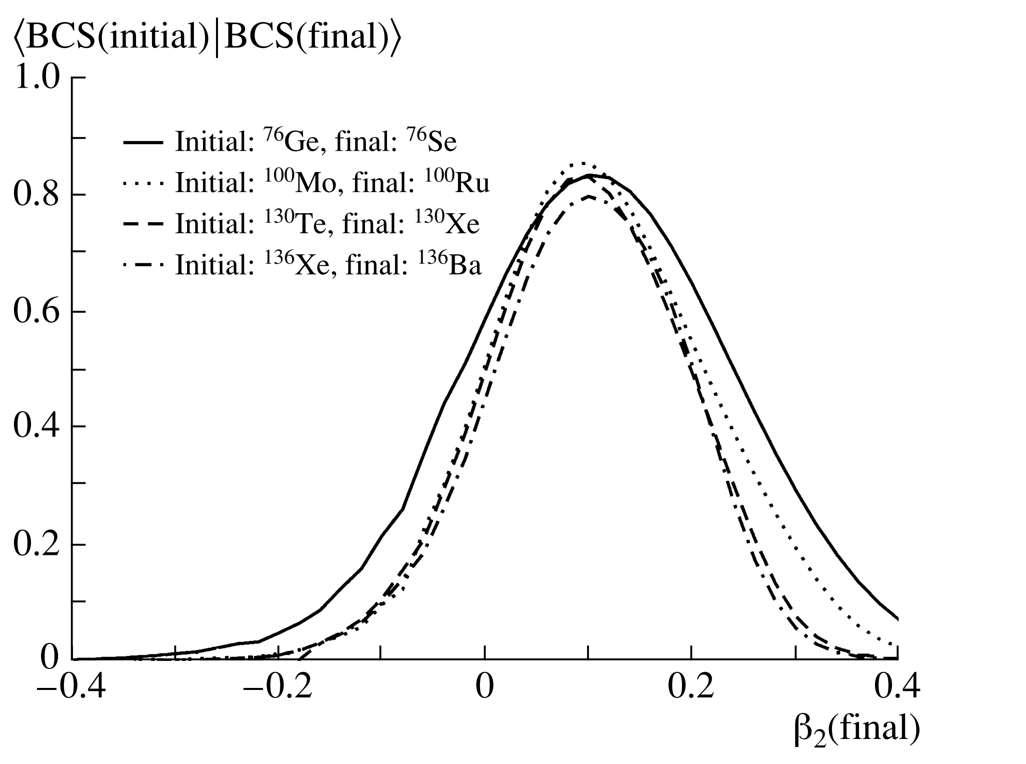
F. Simkovic et. al., PRC60,055502(1999)

- Induced weak hadron Current $$J^{\mu}(\vec{x})=\sum_{n=1}^{A}\tau_n^{+}[g^{\mu 0}J^{0}(\vec{q}^{\,2})+g^{\mu k}J_n^{k}(\vec{q}^{\,2})]\delta(\vec{x}-\vec{r}_n)$$
- With $$J^{0}(\vec{q}^{\,2})=g_V(q^2),\quad \vec{J}_n(\vec{q}^{\,2})=g_M(\vec{q}^{\,2})i\frac{\vec{\sigma}_n\times\vec{q}}{2m_p}+g_A(\vec{q}^{\,2})\vec{\sigma}-g_P(\vec{q}^{\,2})\frac{\vec{q}\,\vec{\sigma}_n\cdot\vec{q}}{2m_p}$$
- Therefore $$M_{\text{type}}^{I}=\langle H_{\text{type}-\mathrm{F}}^{I}(r_{12})+H_{\text{type}-\mathrm{GT}}^{I}(r_{12})\sigma_{12}+H_{\text{type}-\mathrm{T}}^{I}(r_{12})S_{12}\rangle$$
- Where $$S_{12}=3(\vec{\sigma}_1\cdot\hat{\mathbf{r}}_{12})(\vec{\sigma}_2\cdot\hat{\mathbf{r}}_{12})-\sigma_{12},\quad \sigma_{12}=\vec{\sigma}_1\cdot\vec{\sigma}_2$$
- And $$H_{\text{type-}K}^{\text{light}}(r_{12})=\frac{2}{\pi g_A^2}\frac{R}{r_{12}}\int_0^{\infty}\frac{\sin(qr_{12})}{q+E_J^m-(E_{\text{g.s.}}^{i}+E_{\text{g.s.}}^{f})/2}\,h_{\text{type}-K}(q^2)dq$$
- $$H_{\text{type-}K}^{\text{heavy}}(r_{12})=\frac{1}{m_p m_e}\frac{2}{\pi g_A^2}\frac{R}{r_{12}}\int_0^{\infty}\sin(qr_{12})h_{\text{type-}K}(q^2)q\,dq$$

Results

L. Pacerescu et al. Phys. Atom Nucl. 67,1210(2004)

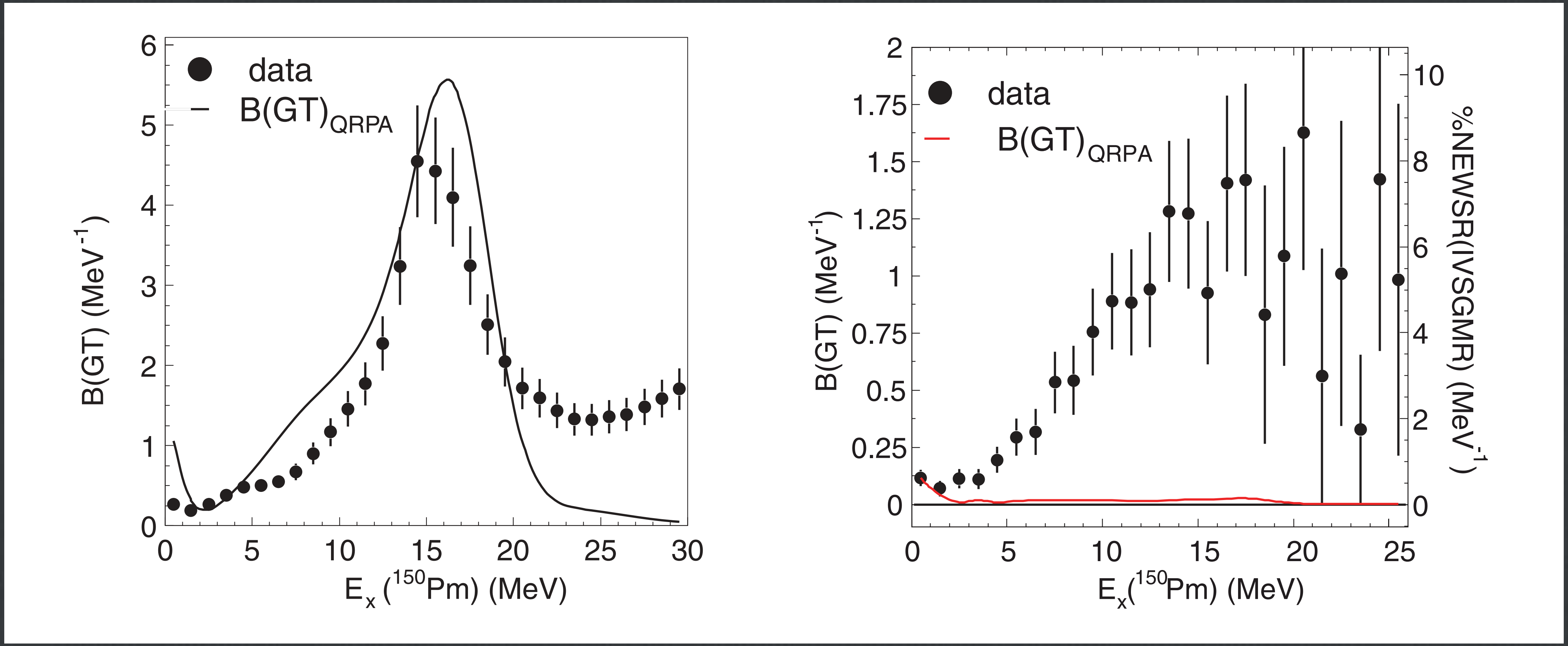




- BCS overlaps

Results

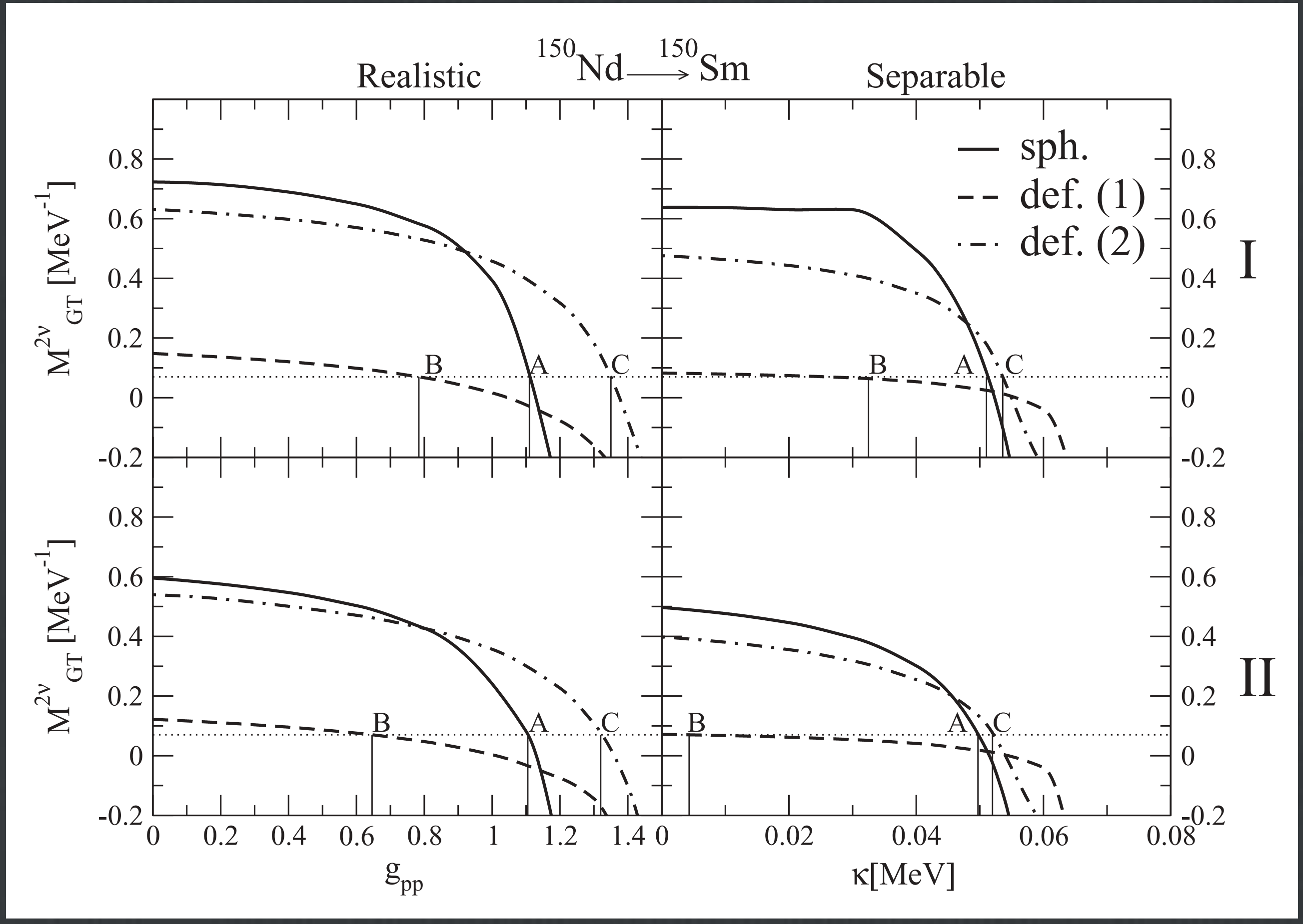
C. J. Guess et al. PRC83,064318(2011)



- ☐ Validation of the theory

Results

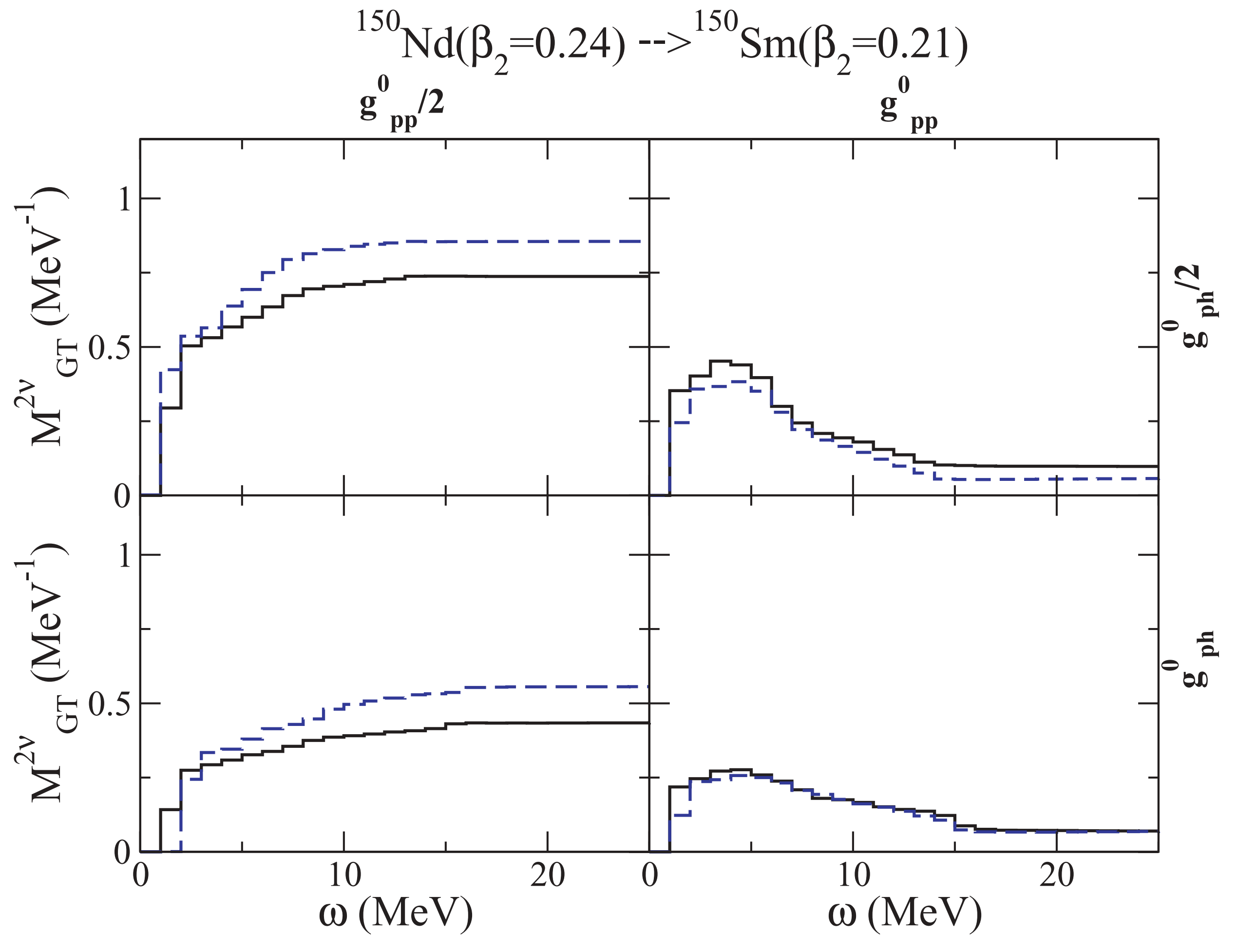
M.S.Yousef et. al. PRC79,014314(2009)



- Dependance of NME for 2νββ on residual interactions

Results

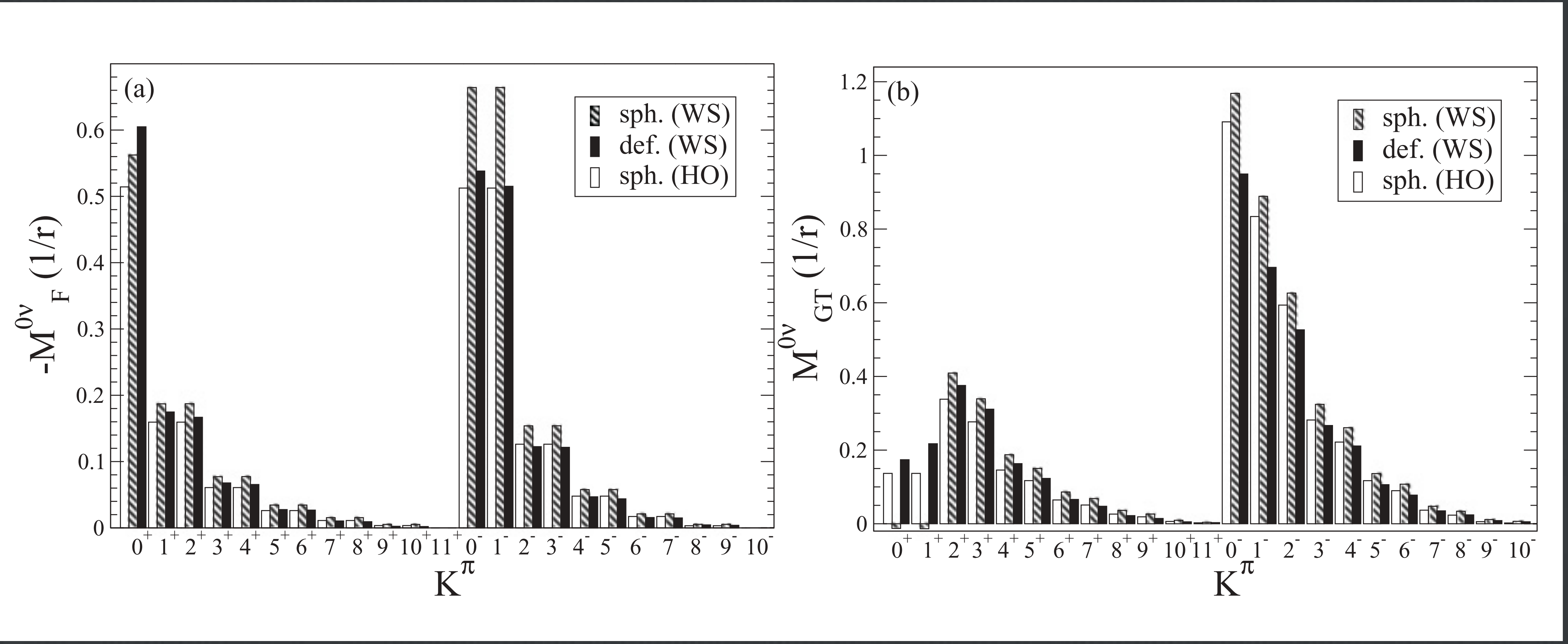
DLF et al. PRC81,037303(2010)



- Lowlying states dominance

Results

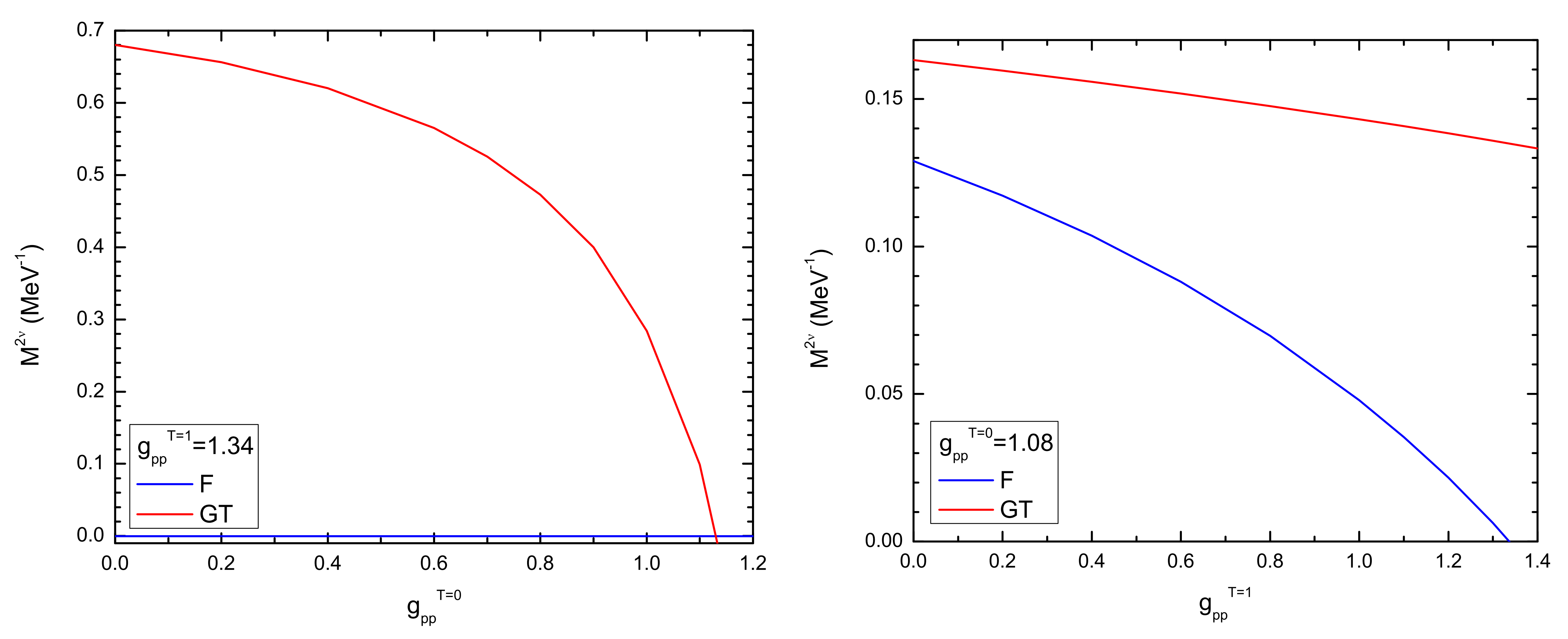
DLF et al. PRC83,034320(2011)



- Comparison of results from different wave functions

Results

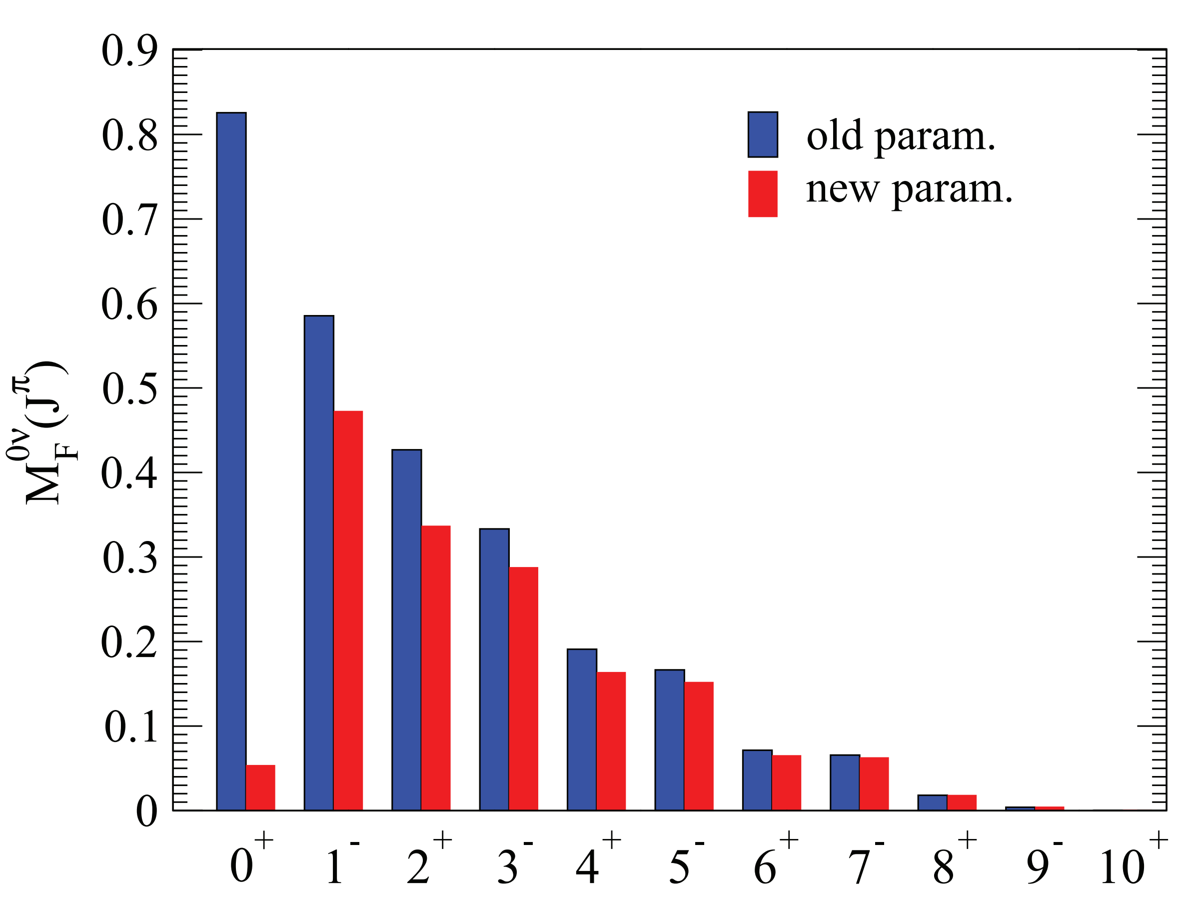
V. Rodin and A. Faessler PRC84,014322(2011)

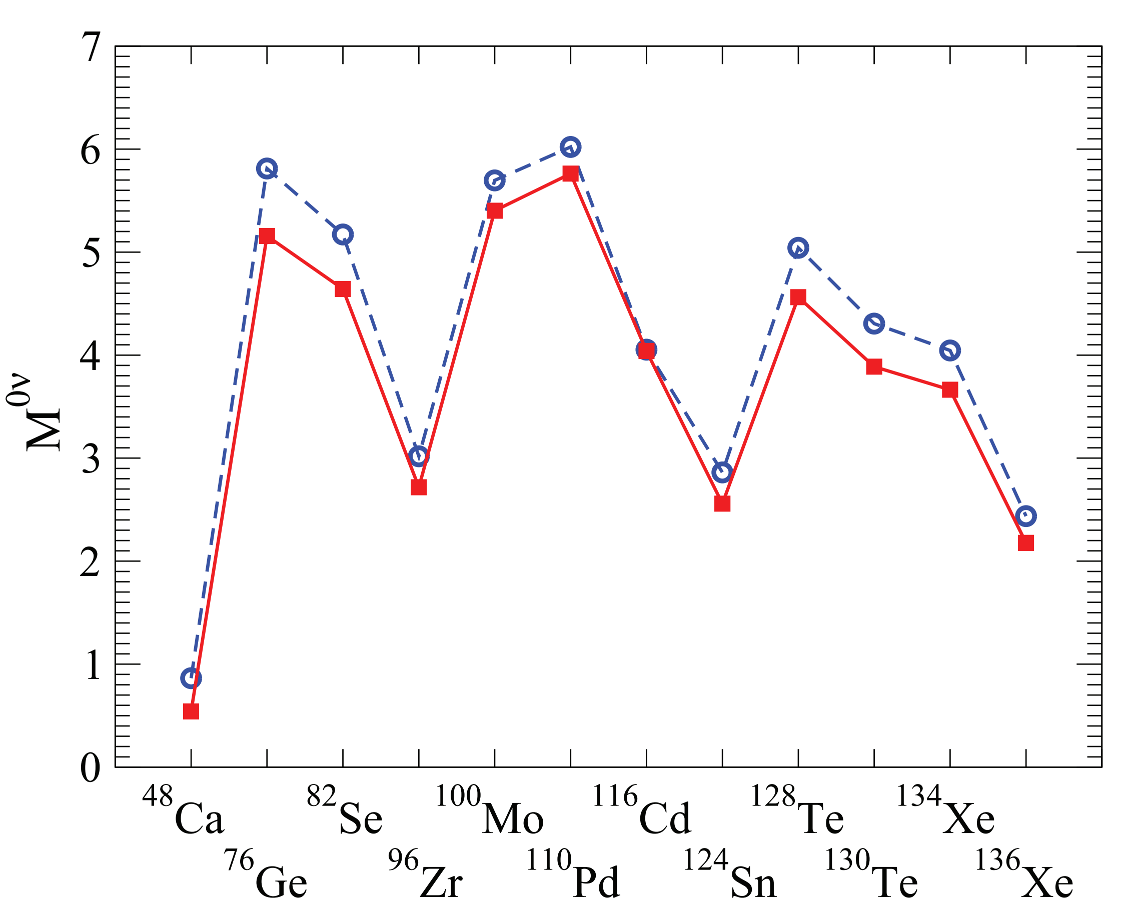


- Restoration of isospin symmetry $M_F^{2\nu}=0$

Results

F. Simkovic et al. PRC87,045501(2013)

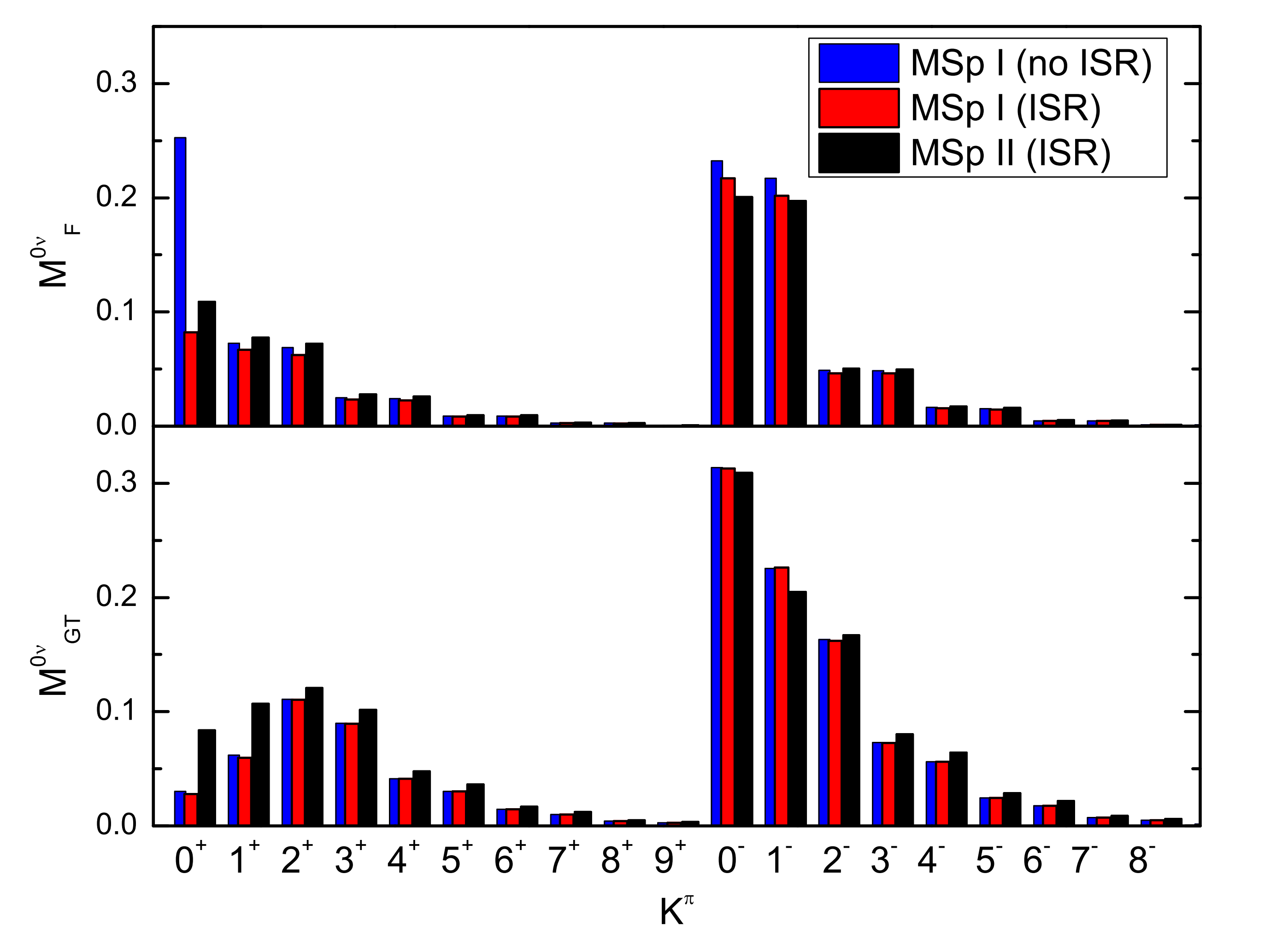




- ☐ Impact of Isospin restoration on $0\nu\beta\beta$

Results

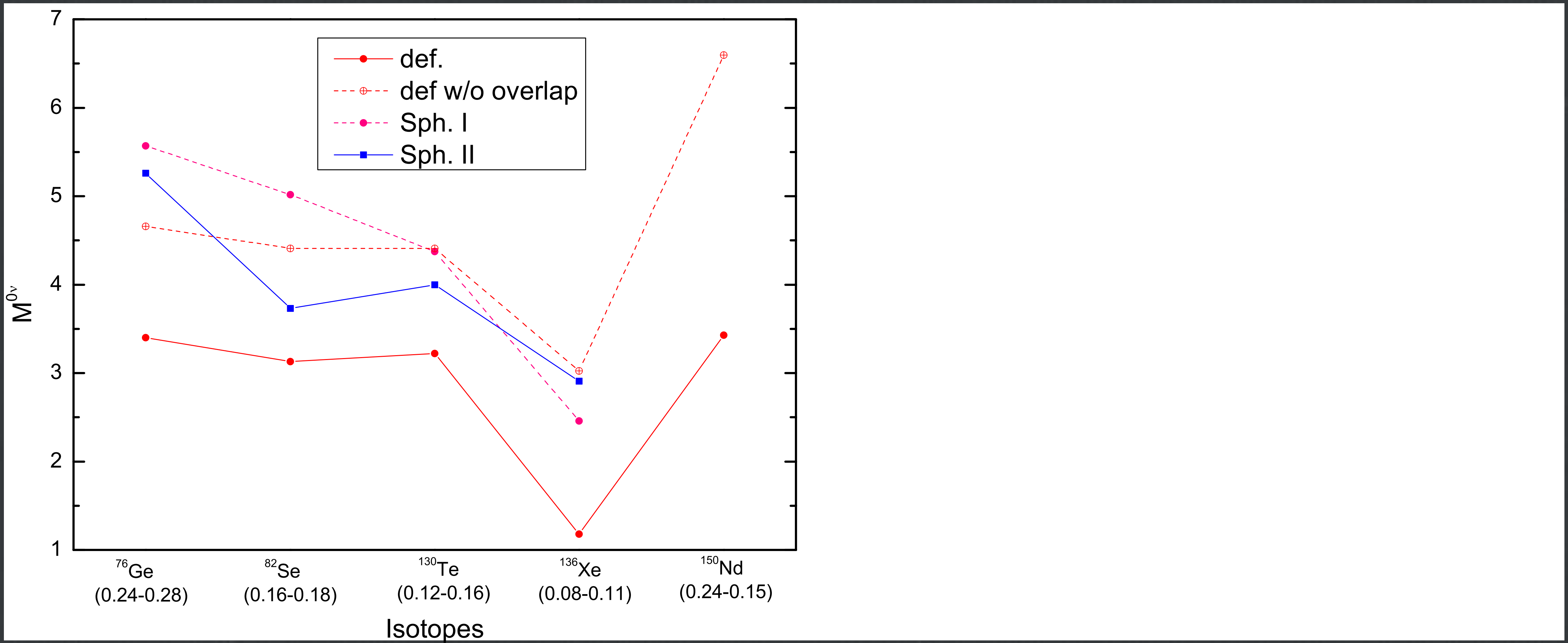
DLF et al. PRC92,044301(2015)



- $0\nu\beta\beta$ matrix elements with isospin symmetry restoration

Results

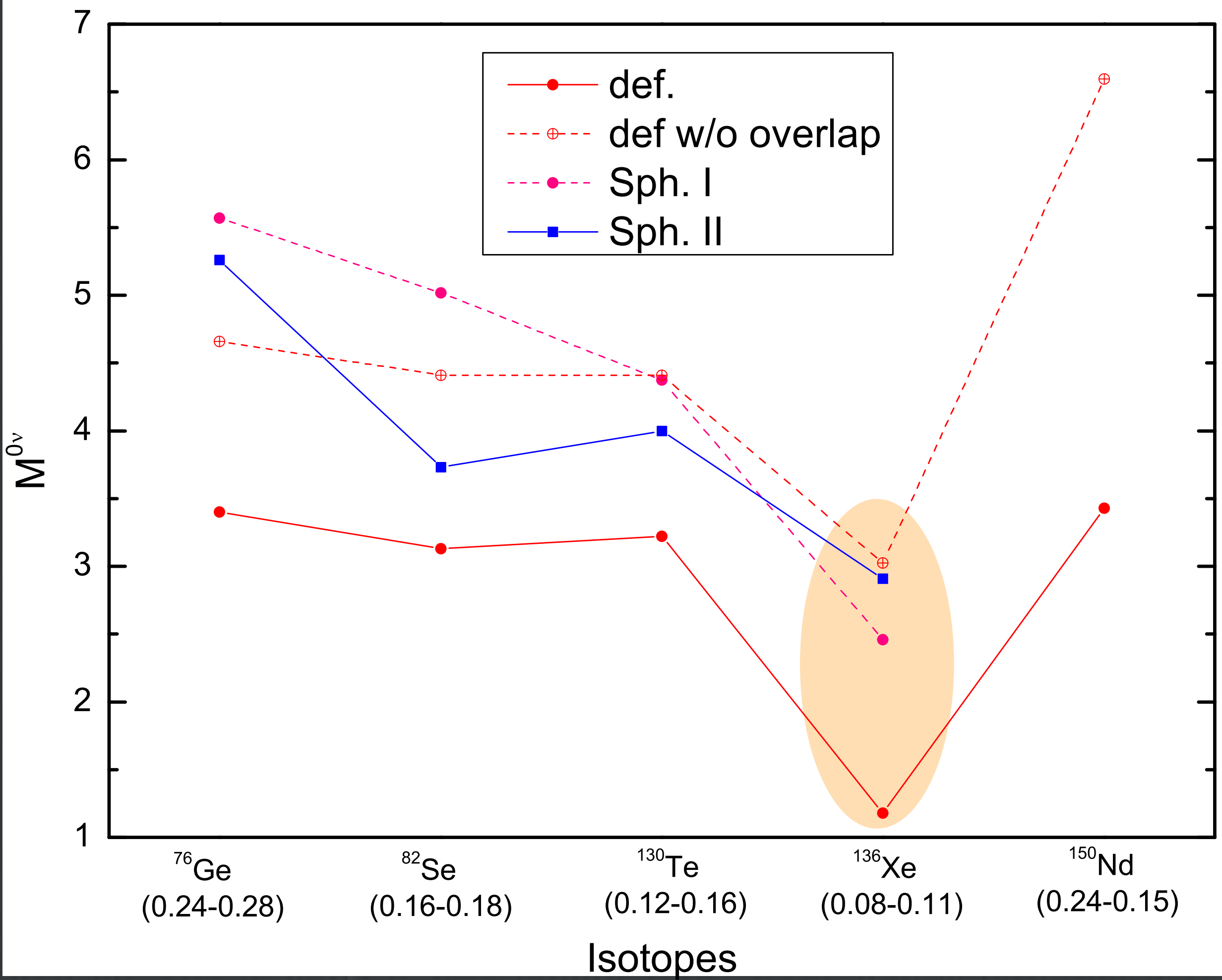
DLF et al. PRC97,045503(2018)



- NME of double beta decay and role of deformation and overlap factors (is ^{136}Xe reasonable?)

Results

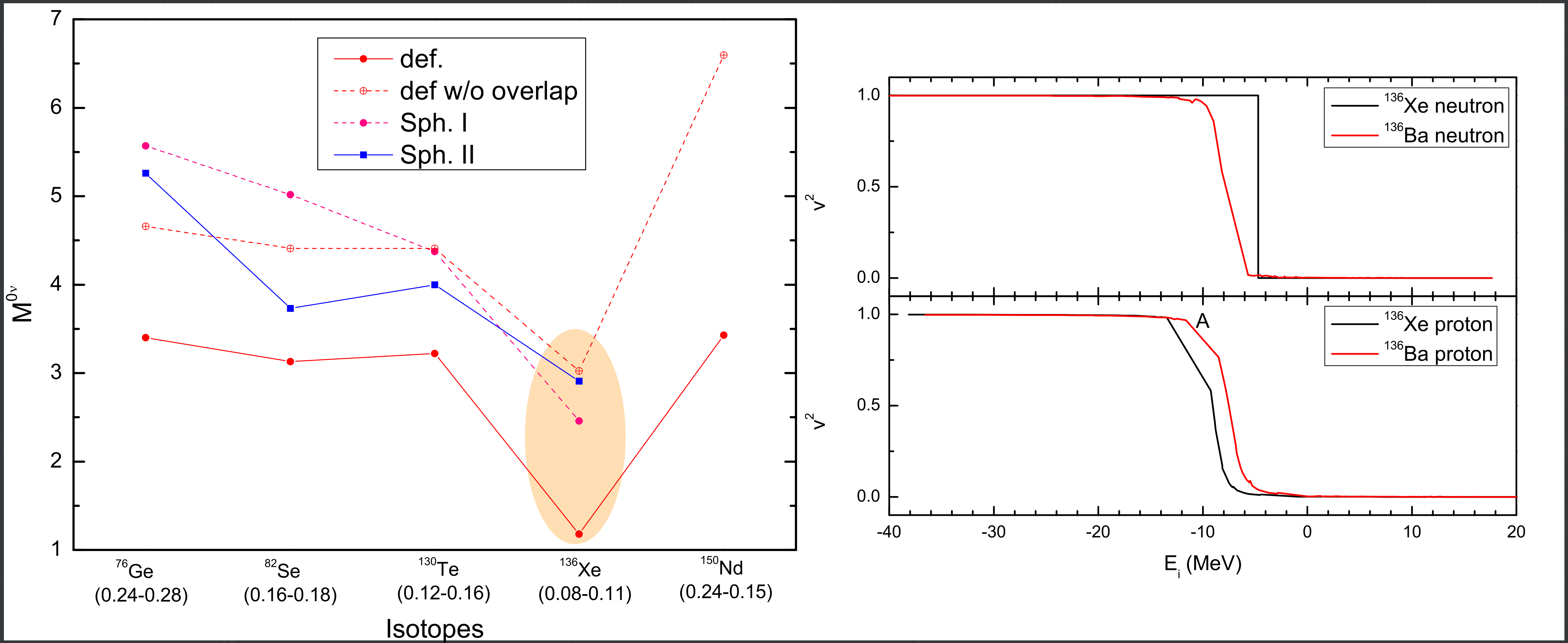
DLF et al. PRC97,045503(2018)



- NME of double beta decay and role of deformation and overlap factors (is ^{136}Xe reasonable?)

Results

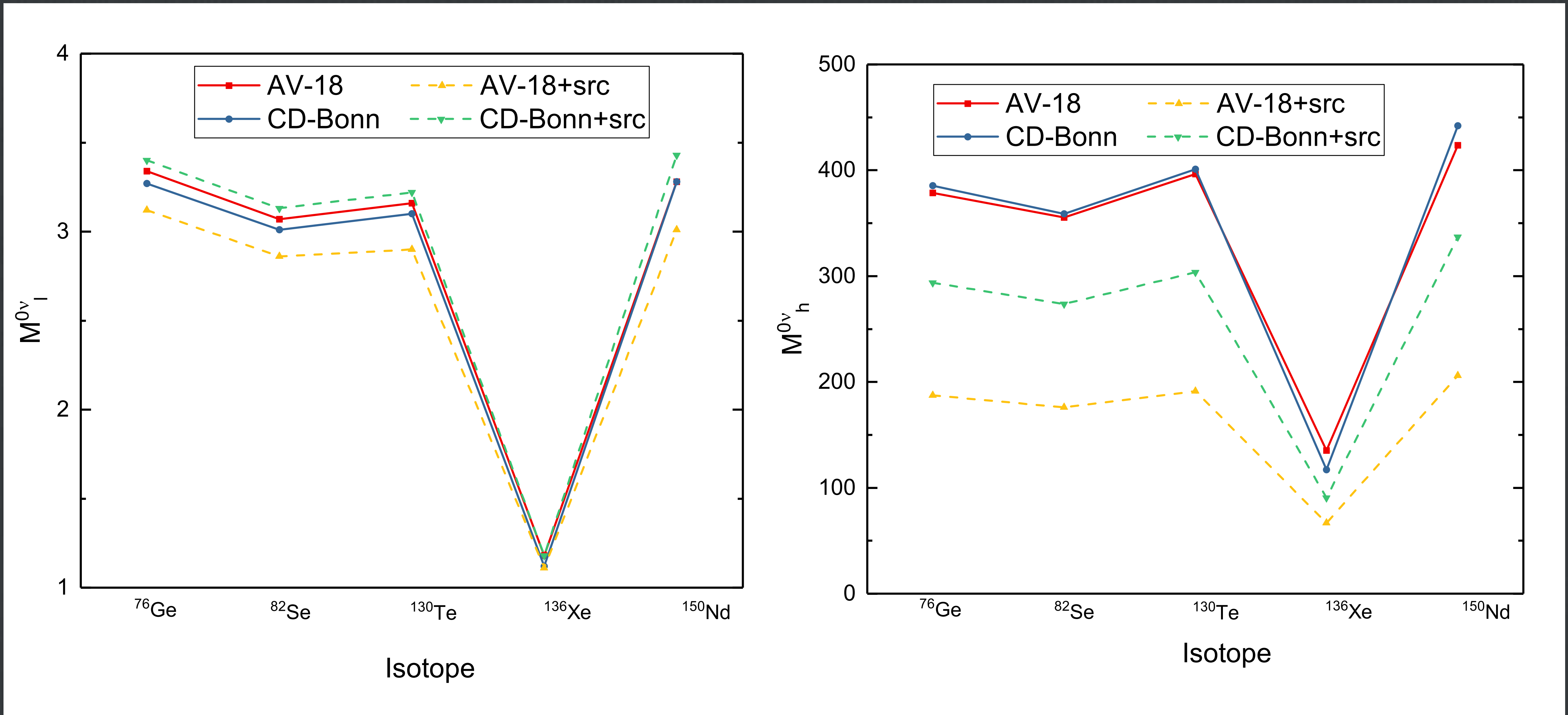
DLF et al. PRC97,045503(2018)



- NME of double beta decay and role of deformation and overlap factors (is ^{136}Xe reasonable?)

Results

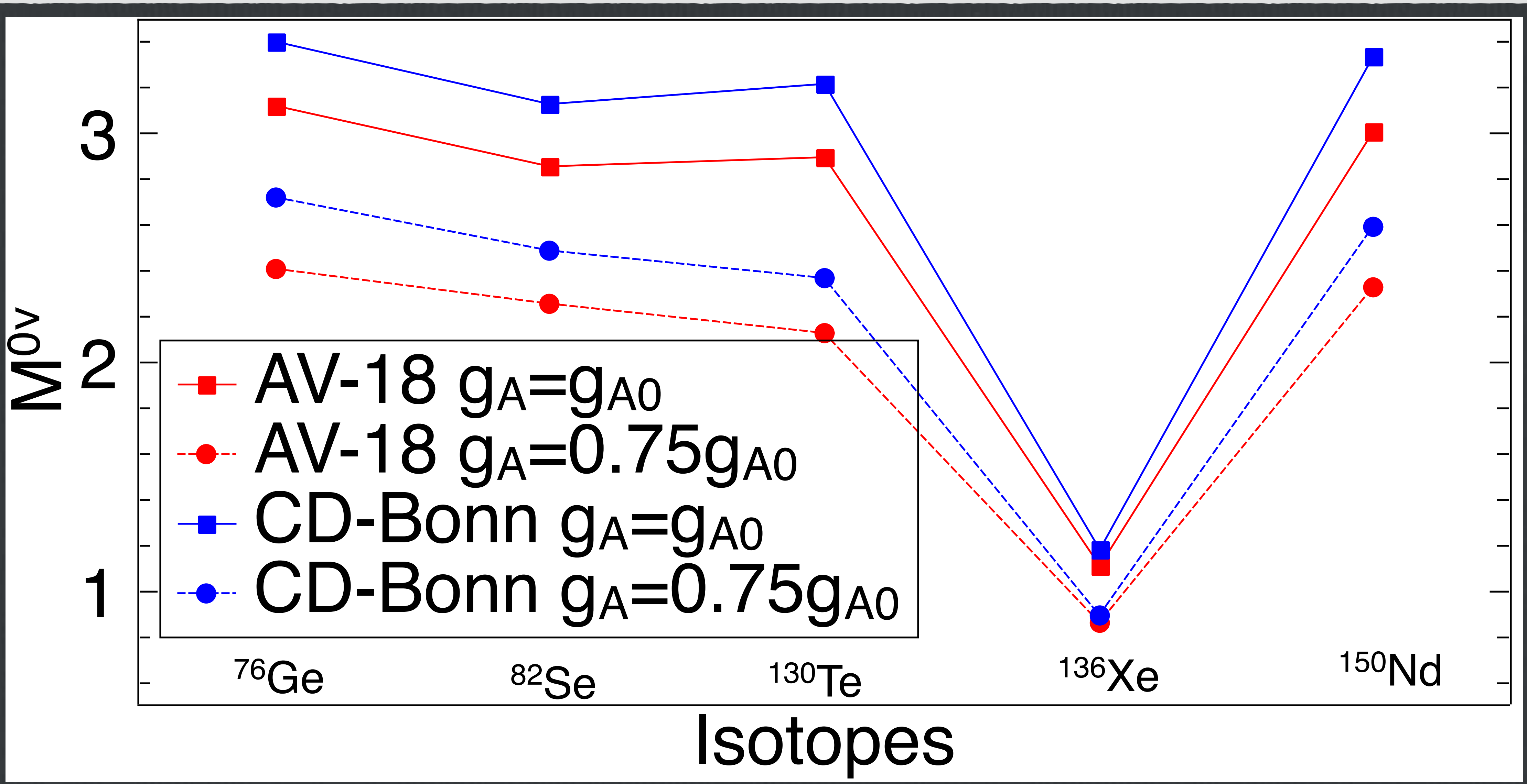
DLF et al. PRC97,045503(2018)



- Impact from Short-Range Correlation

Results

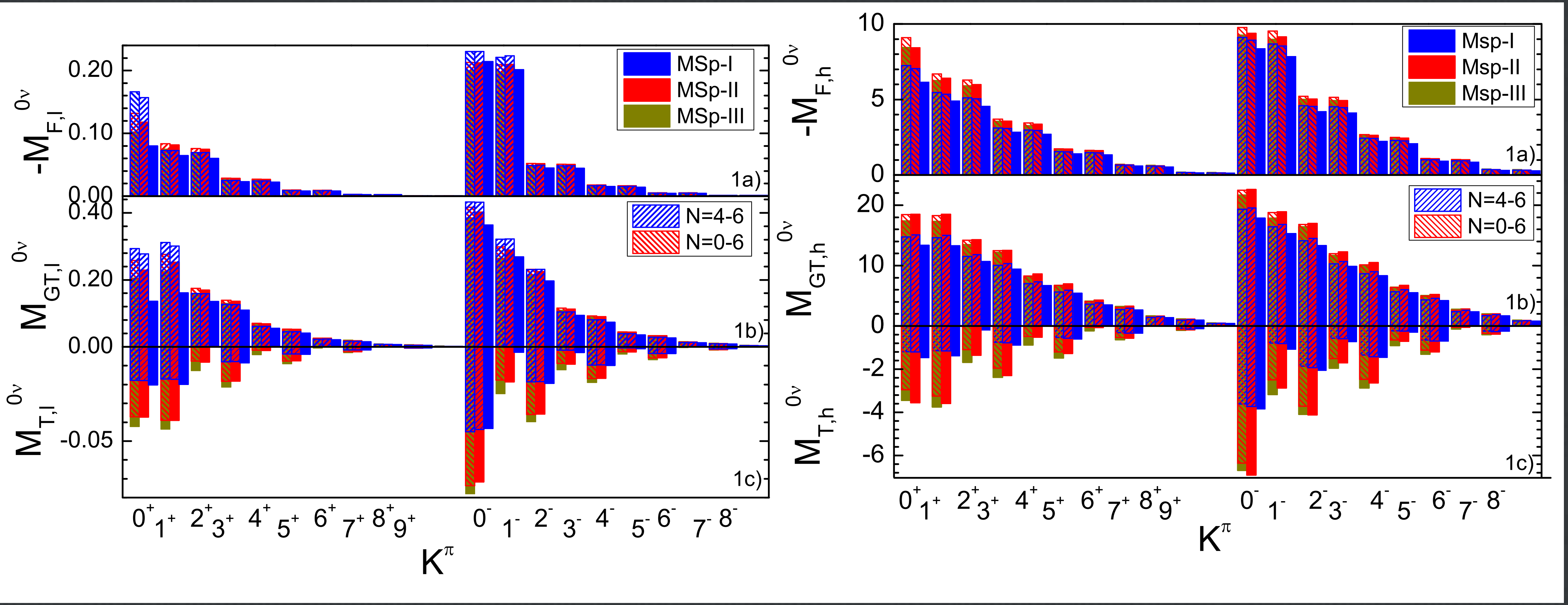
DLF et al. PRC97,045503(2018)



- ☐ The quenching of g_A

Results

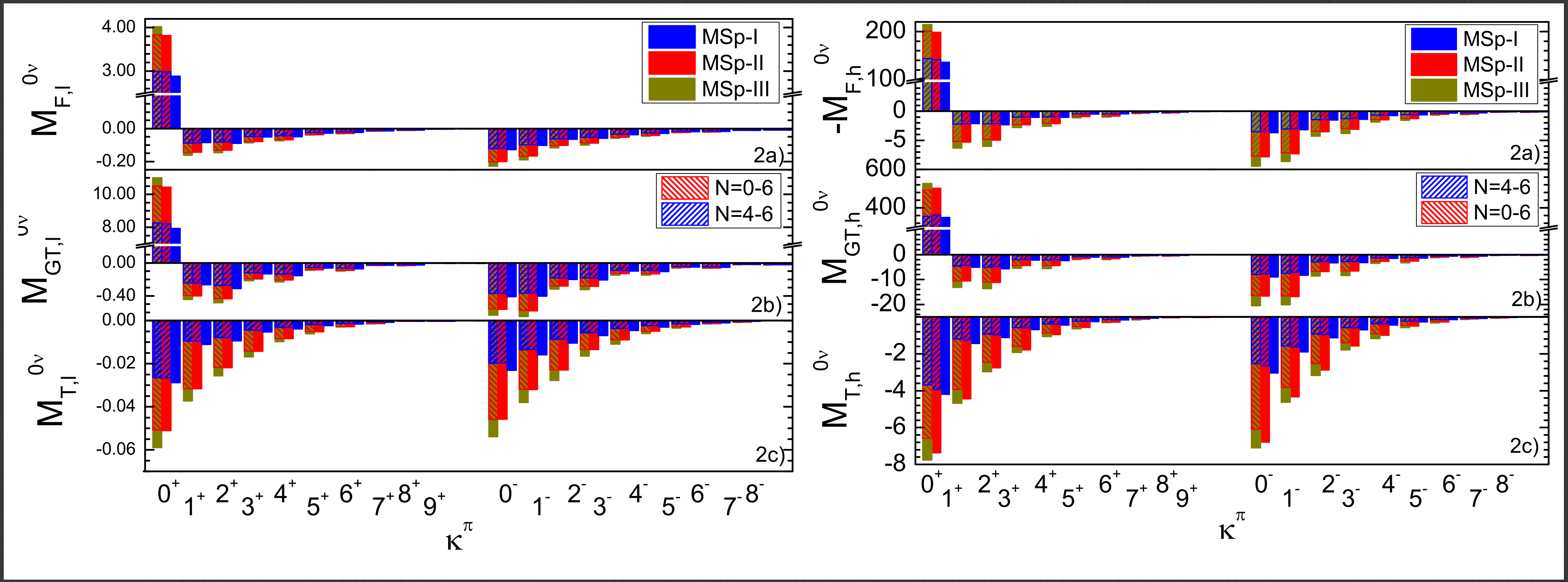
DLF et al. PRC97,045503(2018)



- ☐ Contribution from different intermediate states
- ☐ Different dependence on model space

Results

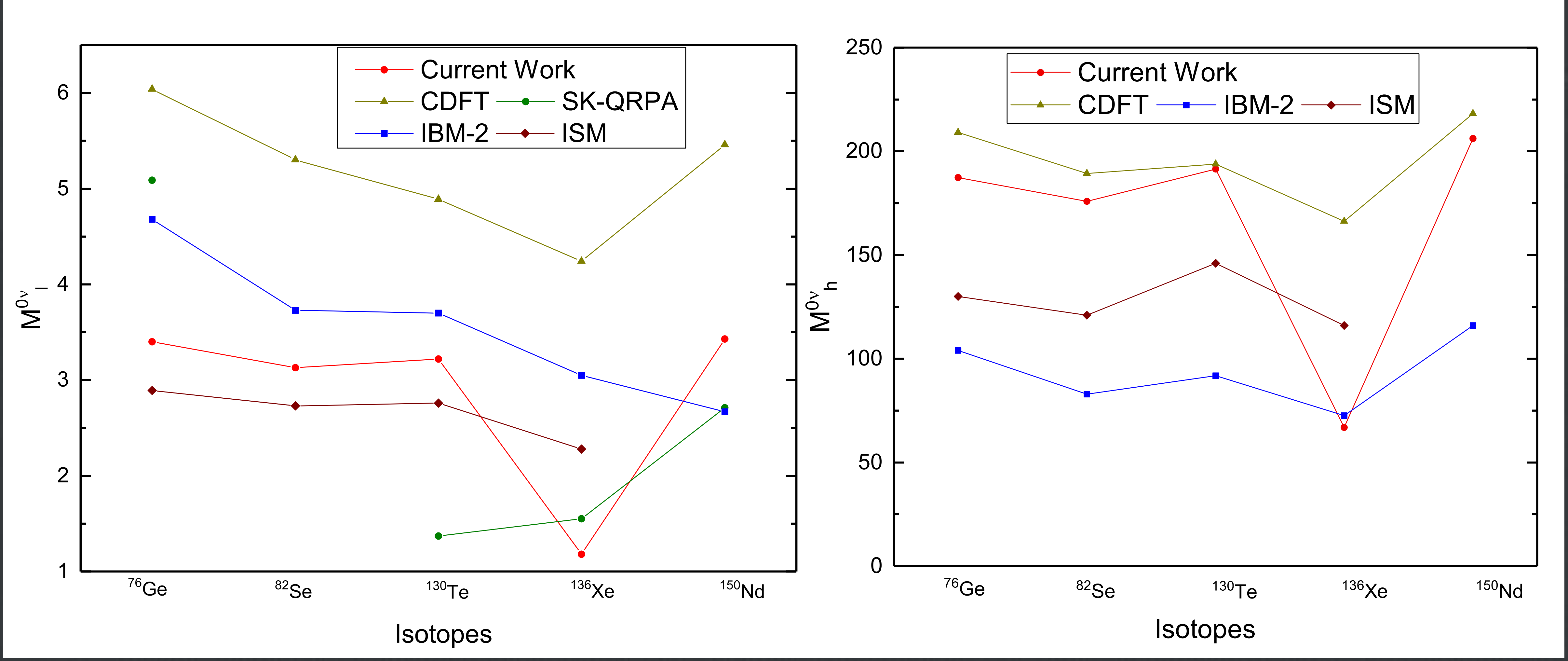
DLF et al. PRC97,045503(2018)



- Contribution from different nucleon pairs
- 0+ dominance

Results

DLF et al. PRC97,045503(2018)



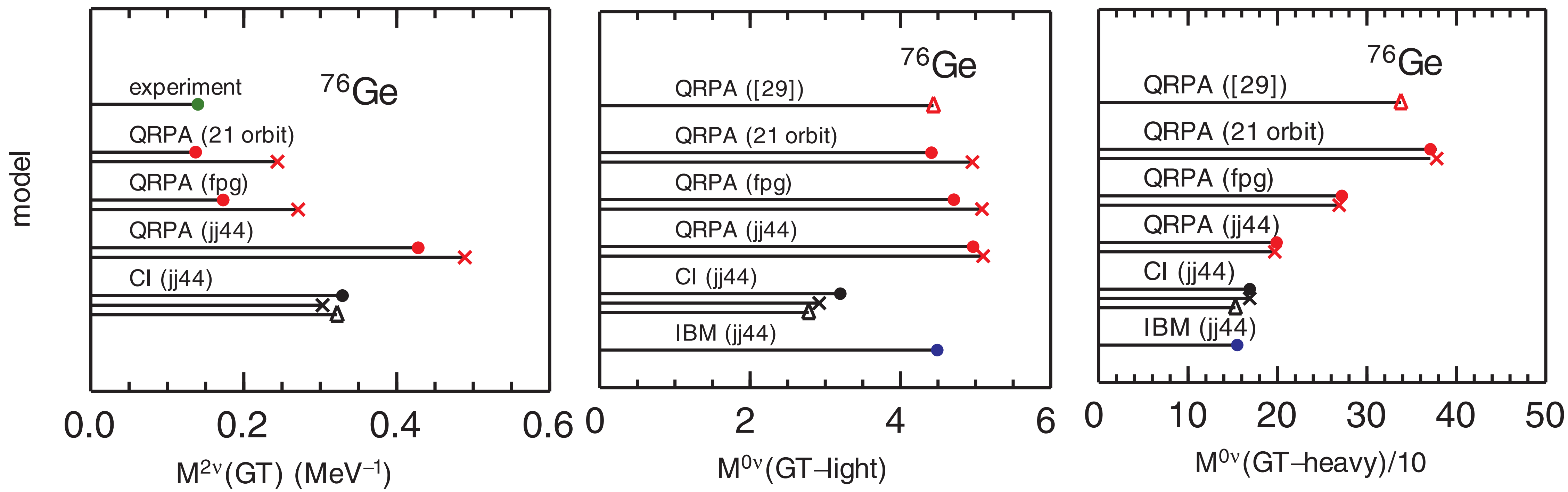
- Results from different models

Error Analysis

- To compare different many-body approaches, we need some assumptions:
  - Different approaches have something in common
  - The some approximation plays similar role
    - For example: inclusion of pp force will reduce the $2\nu\beta\beta$ NME
- Narrow the deviations brought by the method itself

Error Analysis

B.A. Brown et. al. PRC92,041301(2015)



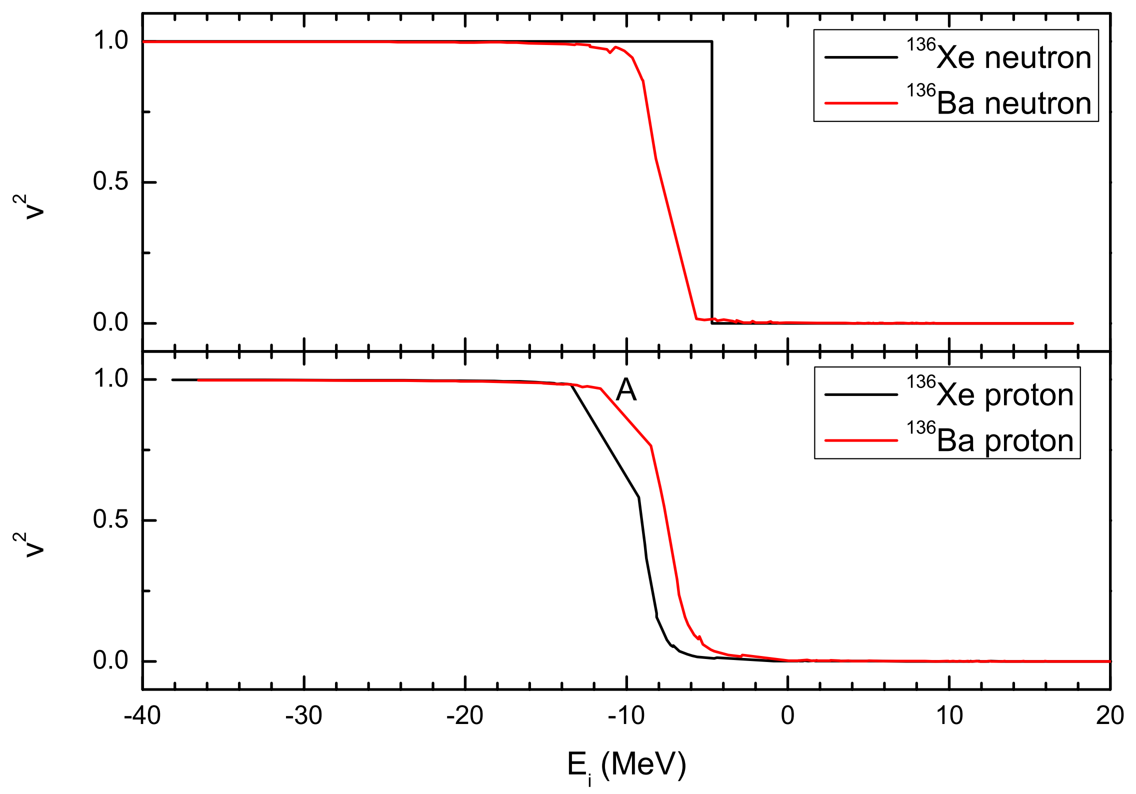
$M^{2\nu} = 0.140(5) = [0.31(3)][0.45][1][1]$ $M^{0\nu} = [3.0(3)][1.2(2)][0.97(3)][1.12(7)] = 3.9(8)$

$M = [M_{\mathrm{GT}}(\mathrm{CI})][R_V][R_S][R_{\mathrm{GT}}]$ $M^{0N} = [155(10)][1.65(25)][0.80(20)][1.13(13)] = 232(80)$

- The roles of model space

Error Analysis

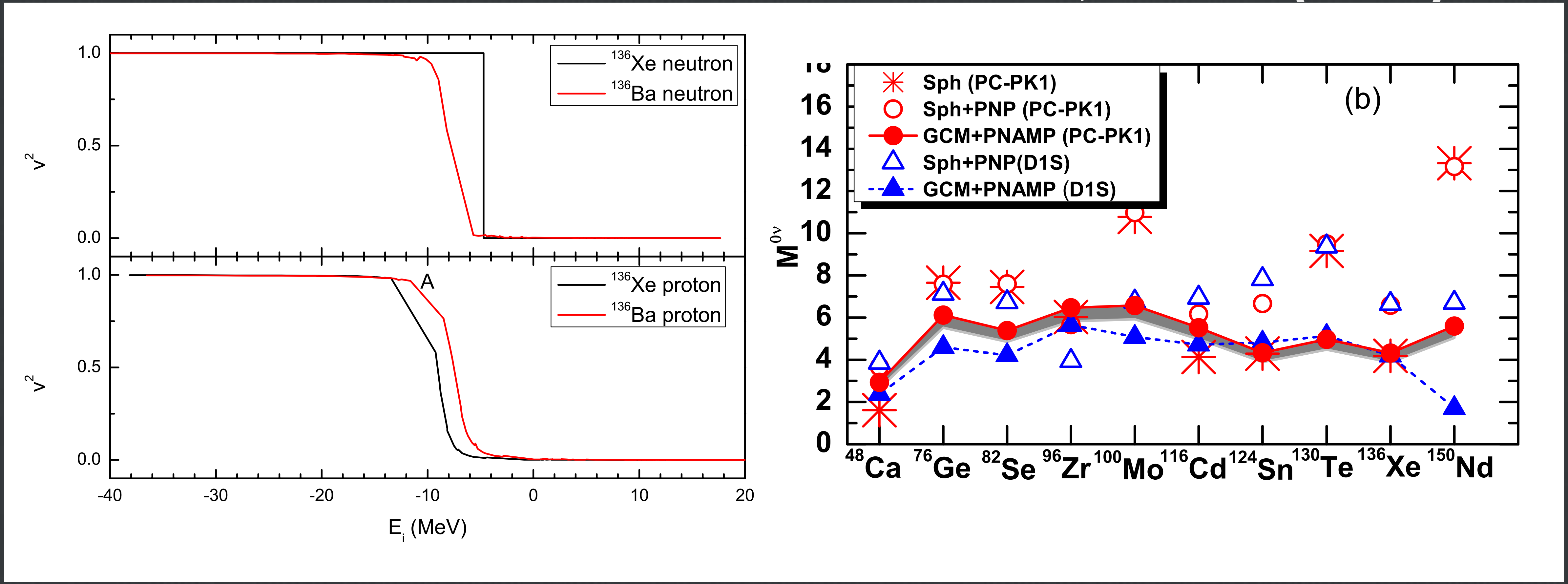
J. M. Yao et. al. PRC91,024306(2015)



- Is small values of NME for ^{136}Xe reasonable?

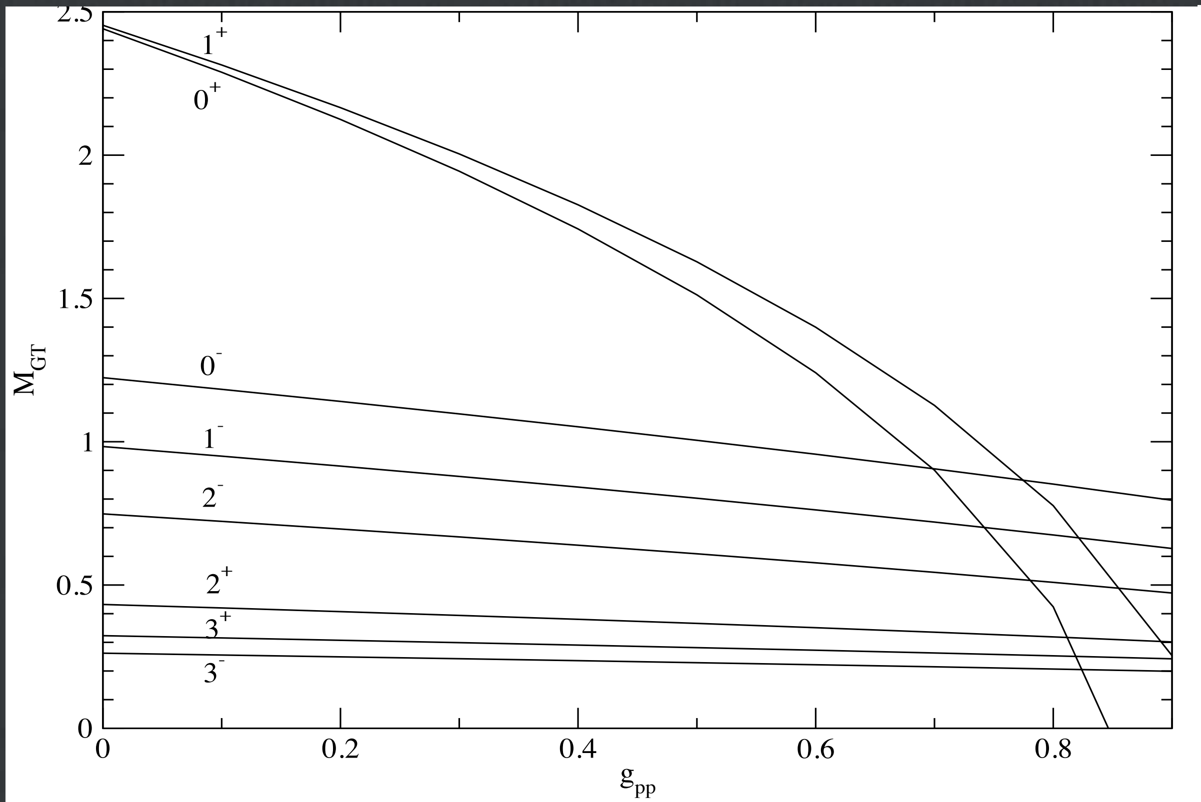
Error Analysis

J. M. Yao et. al. PRC91,024306(2015)



- ☐ Is small values of NME for ^{136}Xe reasonable?

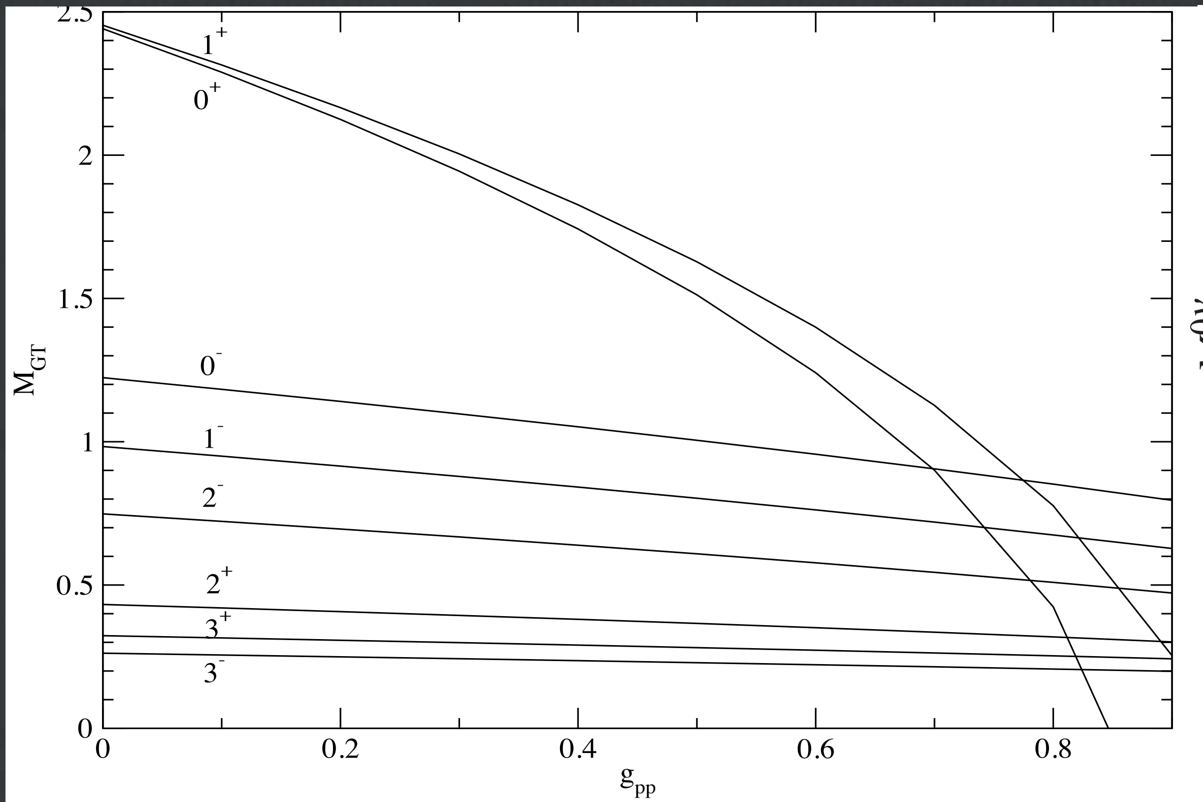
Error Analysis

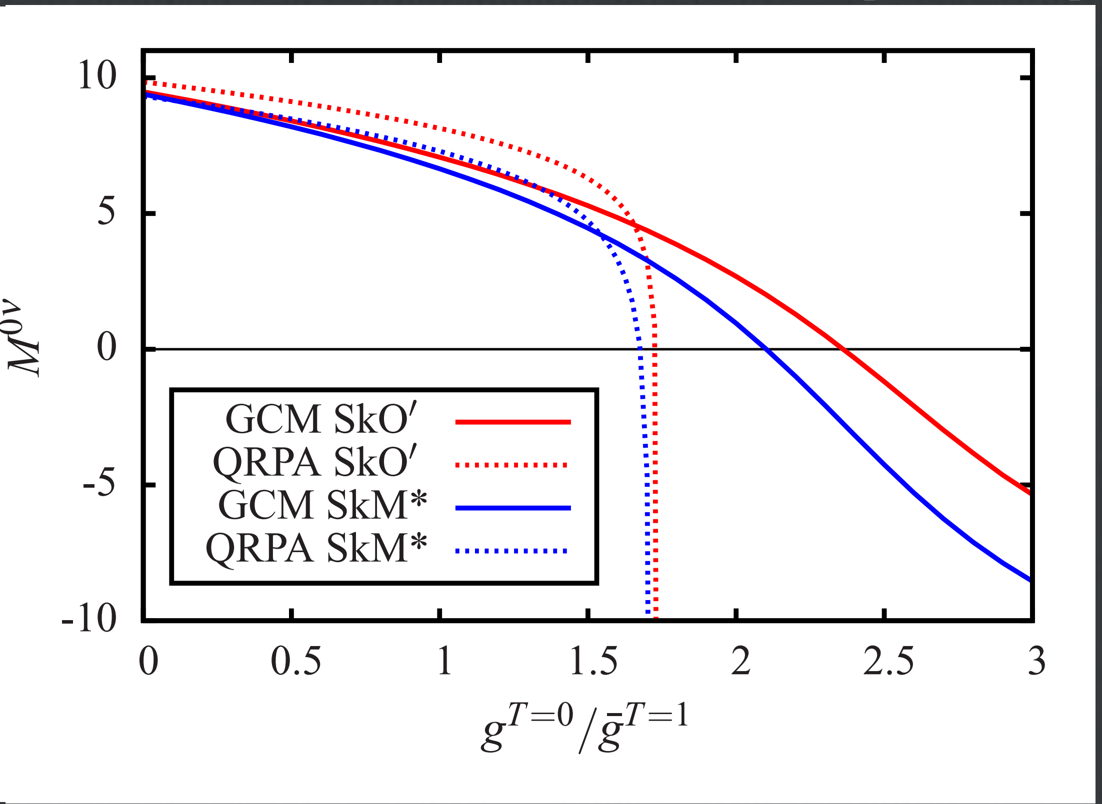


- Proton-neutron particle-particle interactions(or protons-neutron pairing) play important role
- Is this the reason for deviations?

Error Analysis

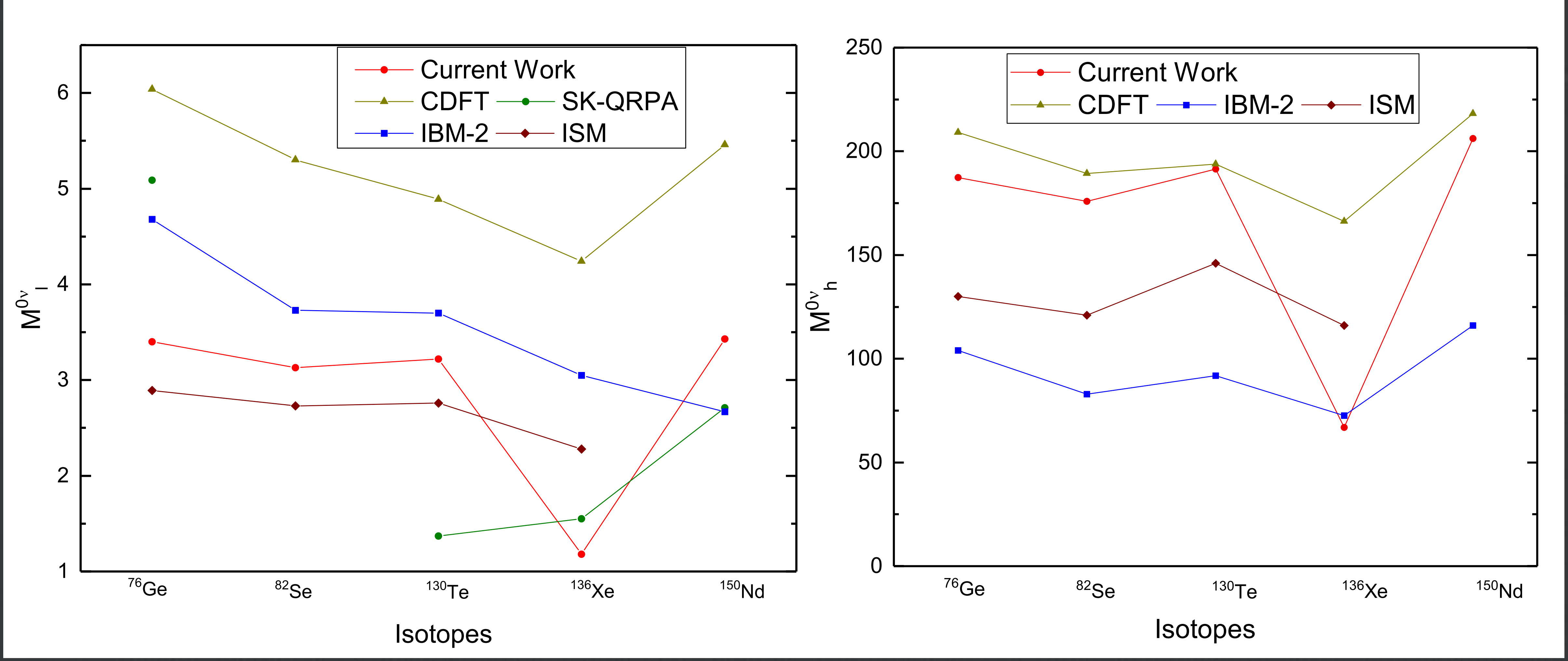
N. Hinohara et. al. PRC90,031301(2014)





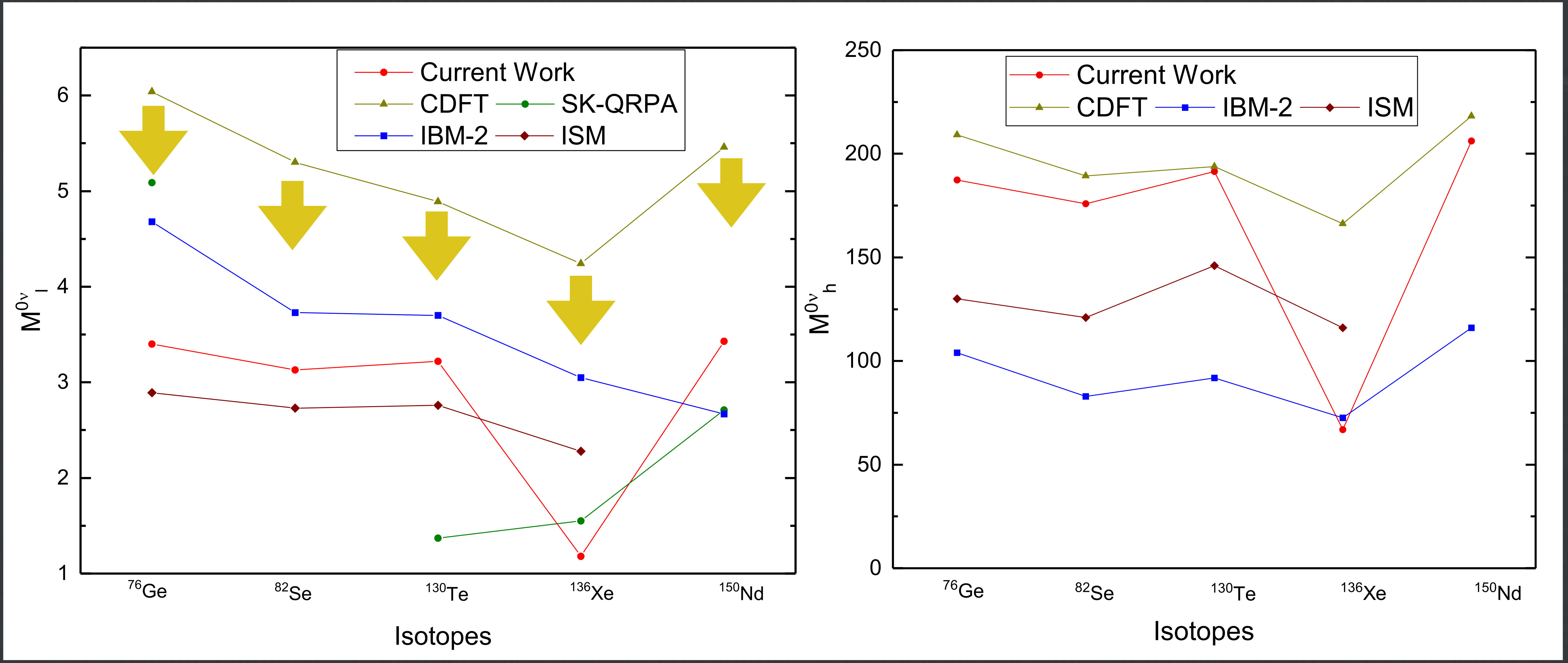
- Proton-neutron particle-particle interactions(or protons-neutron pairing) play important role
- Is this the reason for deviations?

Error Analysis



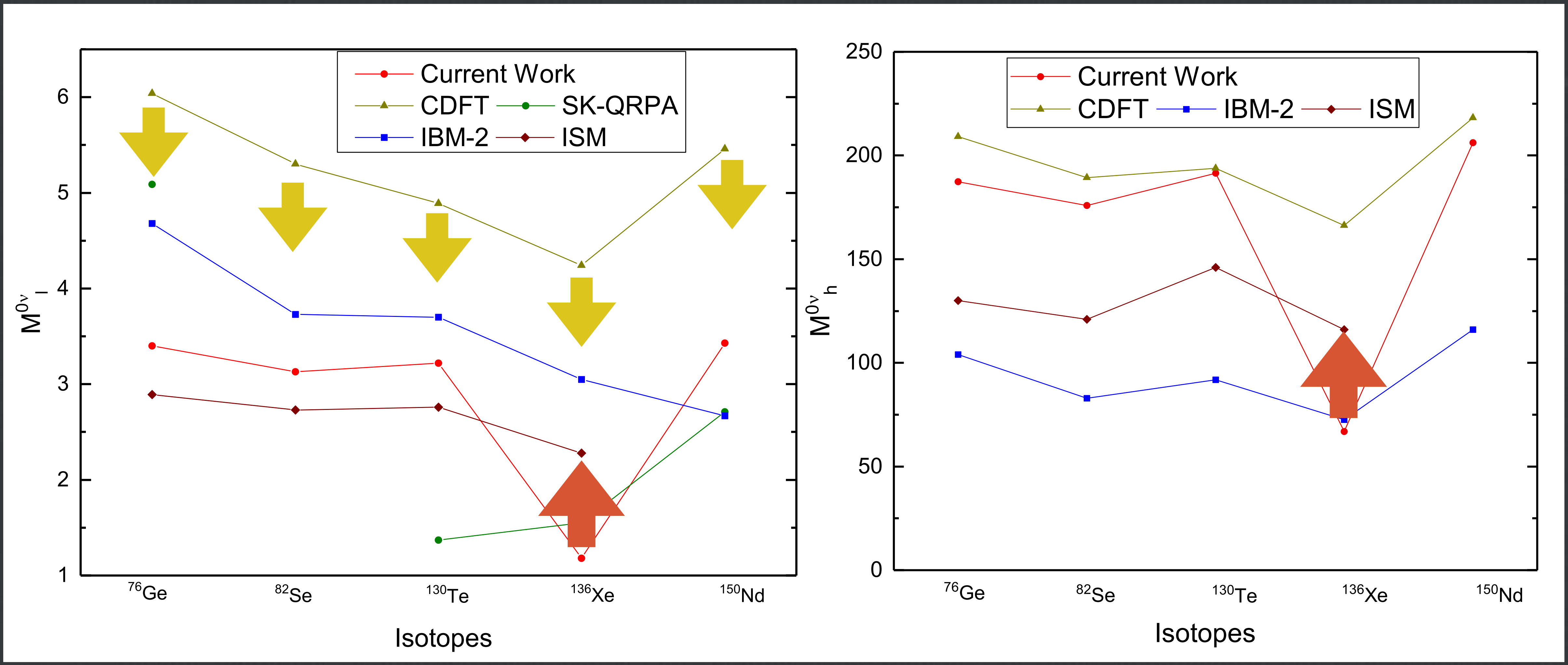
- [ ] Results from different models converge?

Error Analysis



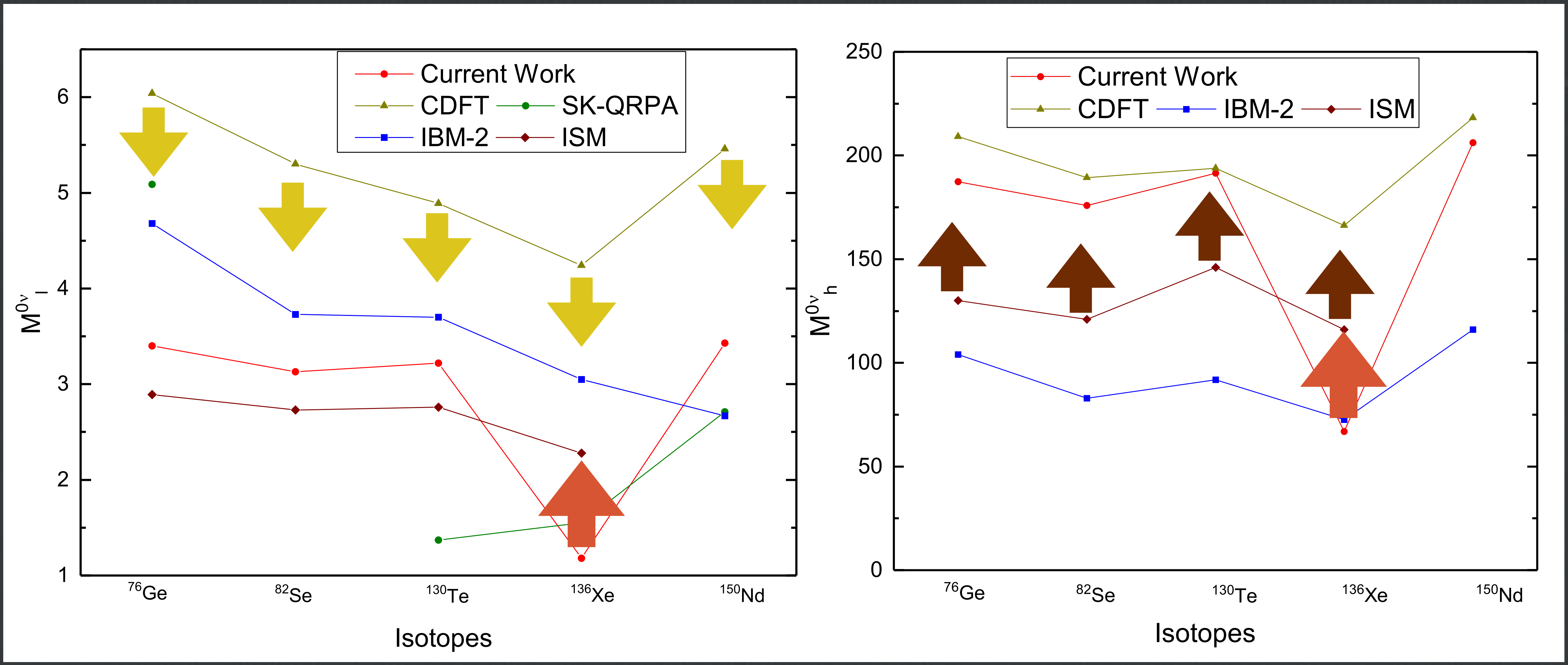
- [ ] **Results from different models converge?**

Error Analysis



- Results from different models converge?

Error Analysis



- Results from different models converge?

Open Questions

- Inputs needed by many-body approaches:
- Beyond "impulse approximation"— the chiral two body currents?
- The g_A quenching problem—is it originated from the choice of hadron current
- More degrees of freedom for hard neutrino?

Conclusion

- We adopted deformed QRPA method with realistic force for the calculation of nuclear matrix elements for double beta decay
- The major effects of deformation comes from the BCS overlaps
- Possible errors are analyzed

Thanks