Neutrinoless double beta decay nuclear matrix elements with energy density functional methods

Tomás R. Rodríguez

UNIVERSIDAD AUTONOMA DE MADRID

European Nuclear Physics Conference 2015

Groningen, August 31st, 2015

Acknowledgments

UNIVERSIDAD AUTONOMA DE MADRID

G. Martínez-Pinedo (TU-Darmstadt)

J. Menéndez (TU-Darmstadt/RIKEN)

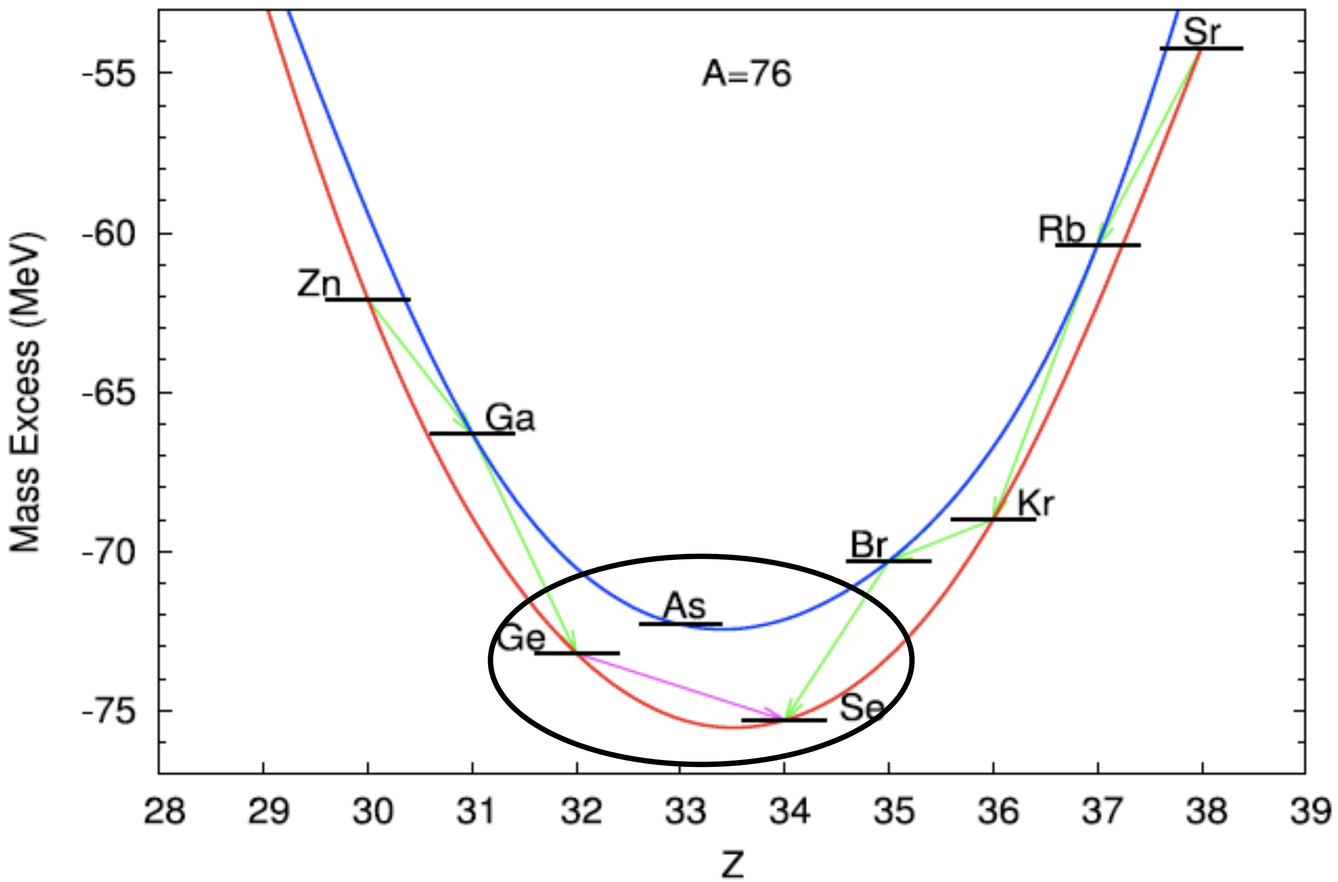
N. López-Vaquero (UAM-Madrid)

J. L. Egido (UAM-Madrid)

A. Poves (UAM-Madrid)

Neutrinoless double beta decay

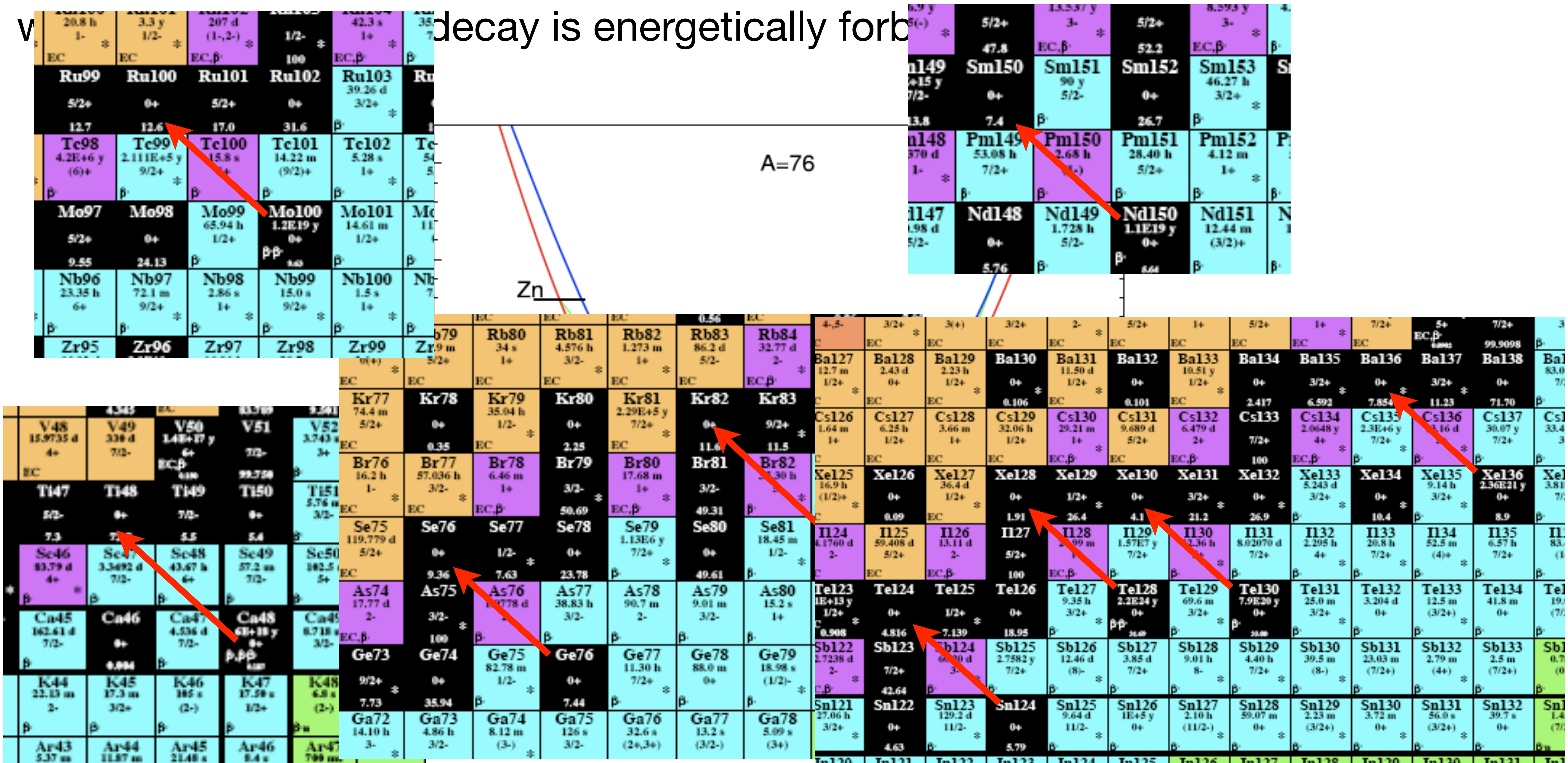
Process mediated by the weak interaction which occurs in those even-even nuclei where the single beta decay is energetically forbidden.



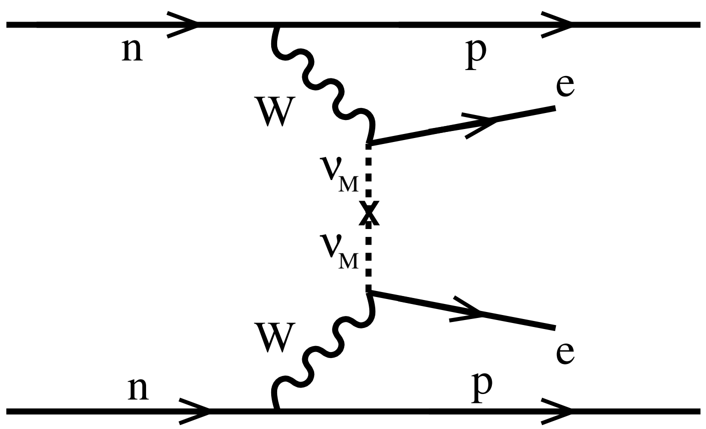
Neutrinoless double beta decay

UNIVERSIDAD AUTONOMA DE MADRID

Process mediated by the weak interaction which occurs in those even-even nuclei w decay is energetically forb



Neutrinoless double beta decay

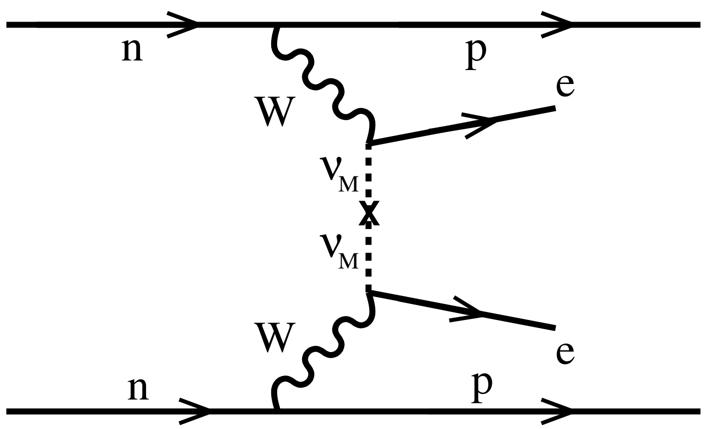


$$ {}^{A}_{Z}X_{N} \Rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} $$

- Violates the leptonic number conservation
- Neutrinos are massive Majorana particles
- Mass hierarchy of neutrinos
- Experimentally not observed ($T_{1/2} > 10^{25}$ y)
- Beyond the Standard Model
- Most plausible mechanism: exchange of light Majorana neutrinos

$$ \left(T^{0\nu\beta\beta}_{1/2}(0^{+} \rightarrow 0^{+})\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^{2}\left(\frac{\langle m_{\nu}\rangle}{m_{e}}\right)^{2} $$

Neutrinoless double beta decay



$$ {}^{A}_{Z}X_N \Rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^- $$

- Violates the leptonic number conservation
- Neutrinos are massive Majorana particles
- Mass hierarchy of neutrinos
- Experimentally not observed ($T_{1/2} > 10^{25}$ y)
- Beyond the Standard Model
- Most plausible mechanism: exchange of light Majorana neutrinos

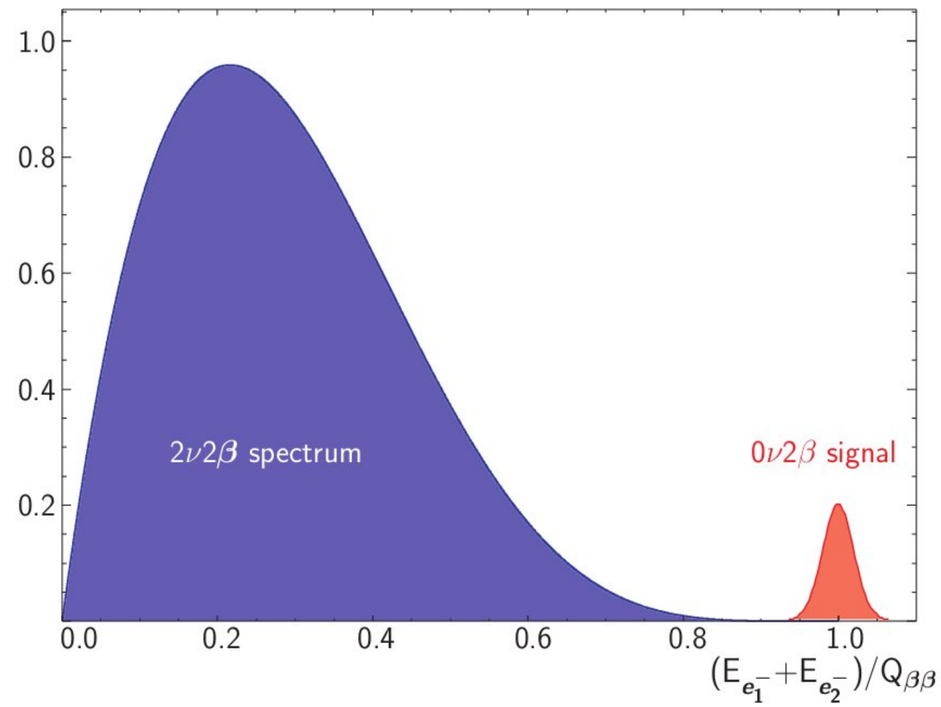
$$ \left(T^{0\nu\beta\beta}_{1/2}(0^+ \rightarrow 0^+)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2 $$

NME

$$ M^{0\nu\beta\beta}_{\xi} = \langle 0^+_f | \hat{O}^{0\nu\beta\beta}_{\xi} | 0^+_i \rangle $$

Current experimental status

UAM UNIVERSIDAD AUTONOMA DE MADRID

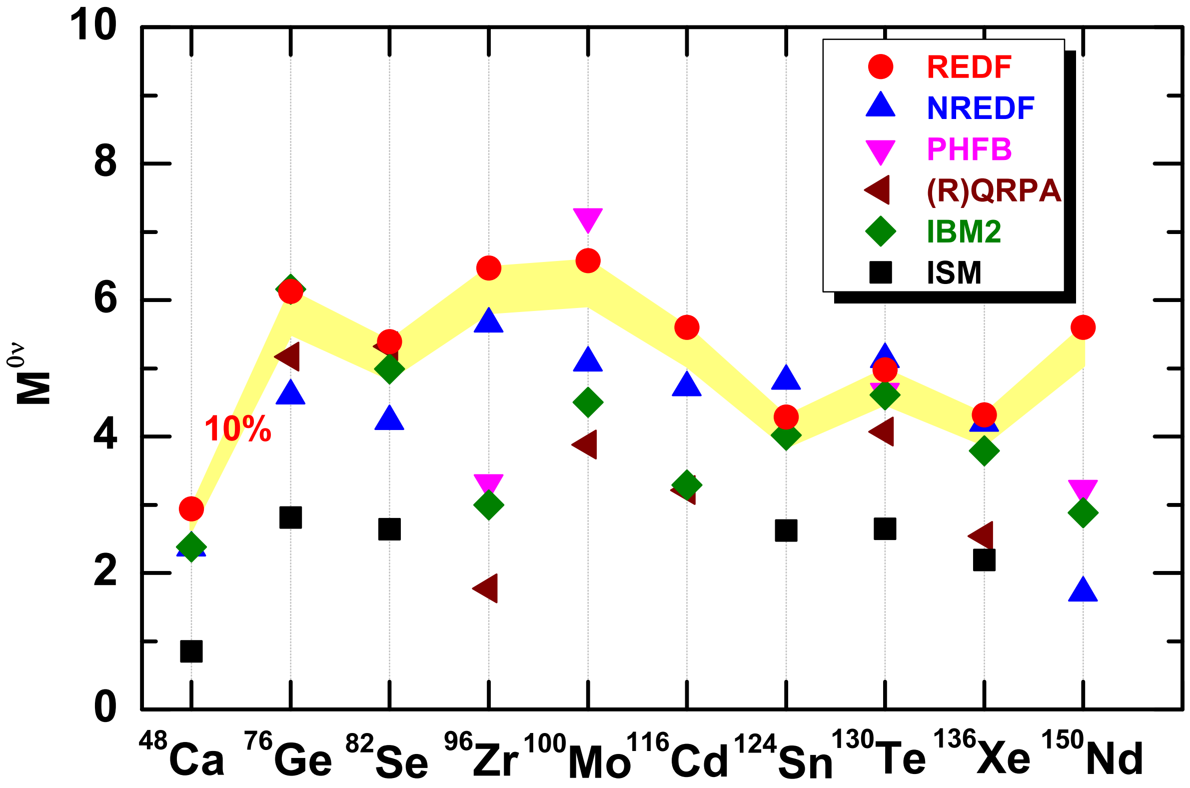


Only lower limits to the half-lives have been measured so far

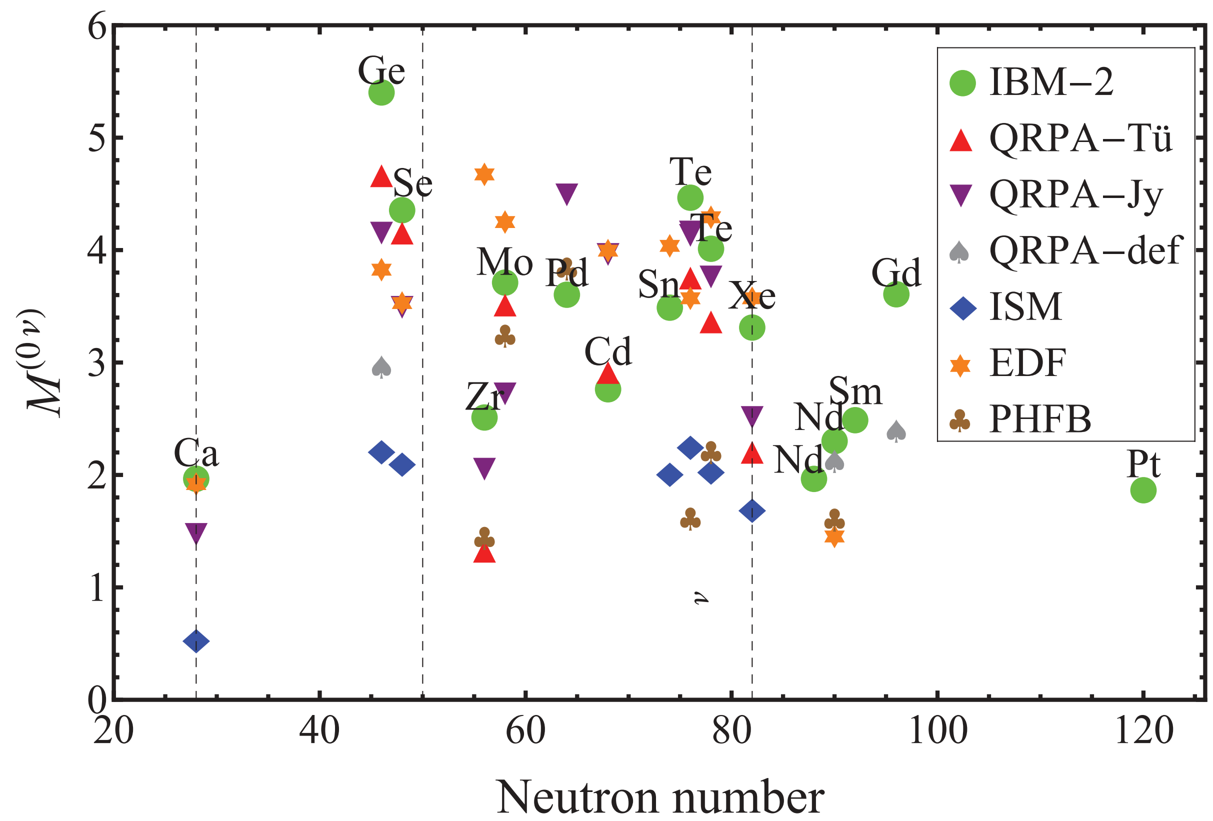
Experiment	Decay	Present limit $T_{1/2}$	Forecast limit $T_{1/2}$	Ref.
GERDA	^{76}Ge	> 2.1×10^{25} yr	~2×10^{26} yr	PRL. 111, 122503 (2013)
Majorana	^{76}Ge	— —	~4×10^{27} yr	arXiv:nucl-ex/ 0311013
EXO-200	^{136}Xe	> 1.1×10^{25} yr	~1.3×10^{28} yr	Nature 510, 229 (2014)
KamLAND-Zen	^{136}Xe	> 1.9×10^{25} yr	~4×10^{26} yr	PRL 110, 062502 (2013)
NEXT	^{136}Xe	— —	~10^{26} yr	JINST 7, C11007 (2012)
(S)NEMO3	^{82}Se	> 3.6×10^{23} yr	~1.2×10^{26} yr	PRL 95, 182302 (2005)
CUORICINO (CUORE)	^{130}Te	> 3×10^{24} yr	~2×10^{26} yr	PRC 78, 035502 (2008)
(S)NEMO3	^{150}Nd	> 1.8×10^{22} yr	~5×10^{25} yr	PRC 80, 032501 (2009)
SNO+	^{150}Nd	— —	> 1.6×10^{25} yr	J. Phys. Conf. Ser. 447, 012065 (2013)

Current theoretical status

Different methods give different values of NME's with a factor ~3 difference



J. M. Yao et al., arXiv:1410.6326

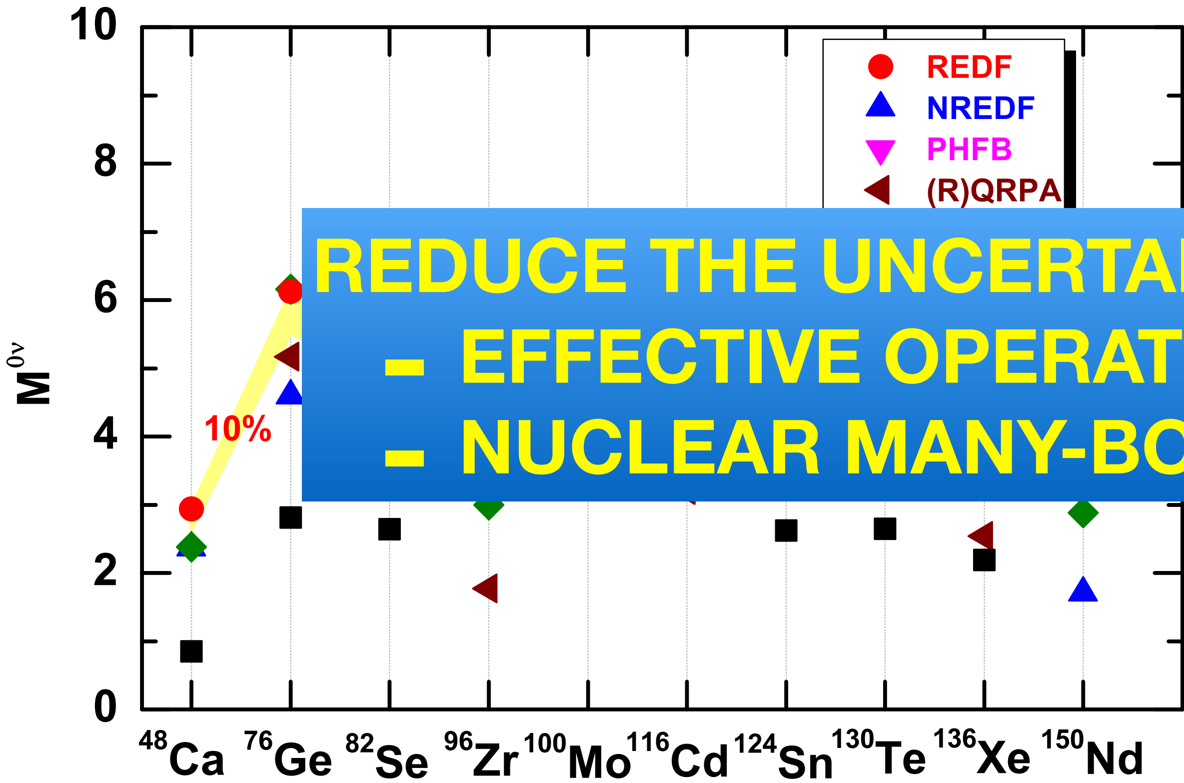


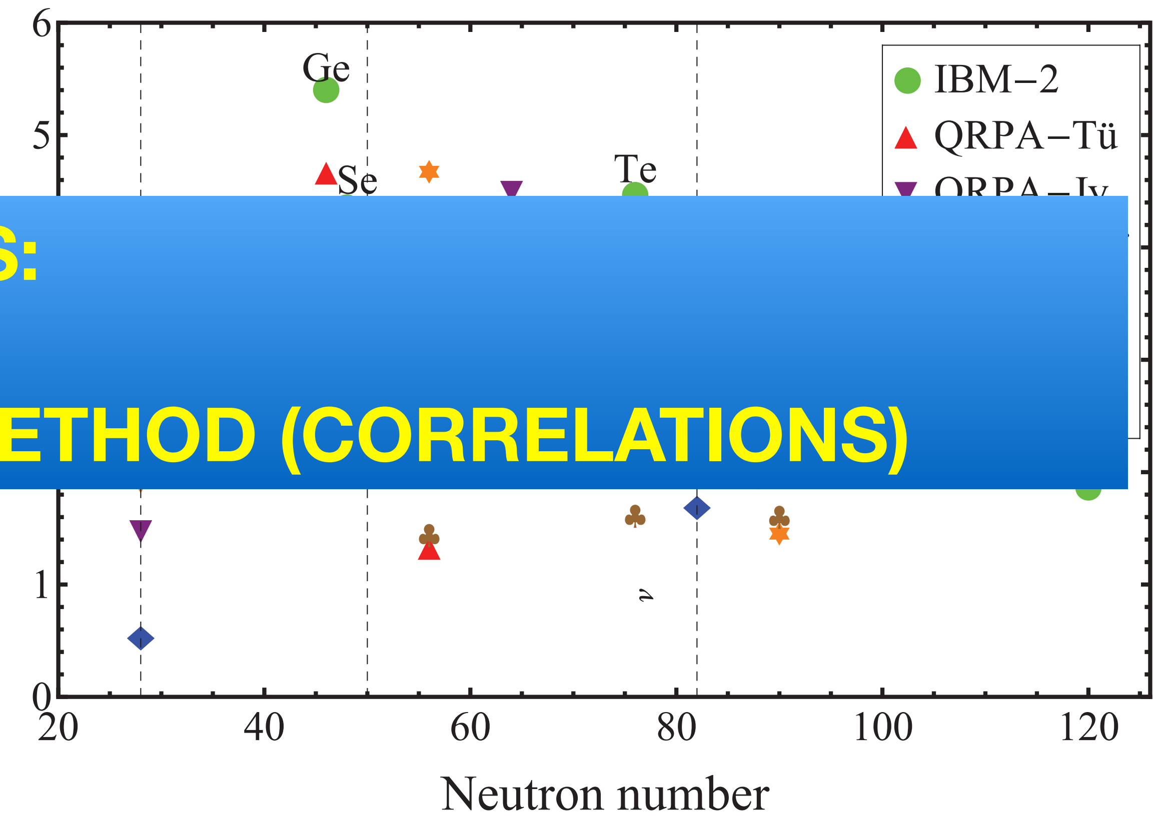
J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 87, 014315 (2013)

Current theoretical status

UNIVERSIDAD AUTONOMA DE MADRID

Different methods give different values of NME's with a factor ~3 difference





REDUCE THE UNCERTAINTIES:
- **EFFECTIVE OPERATOR**
- **NUCLEAR MANY-BODY METHOD (CORRELATIONS)**

J. M. Yao et al., arXiv:1410.6326

J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 87, 014315 (2013)

$$M_{\xi}^{0\nu\beta\beta} = \langle 0_f^+ | \hat{O}_{\xi}^{0\nu\beta\beta} | 0_i^+ \rangle$$

NME: Nuclear structure aspects

We want to study the role of

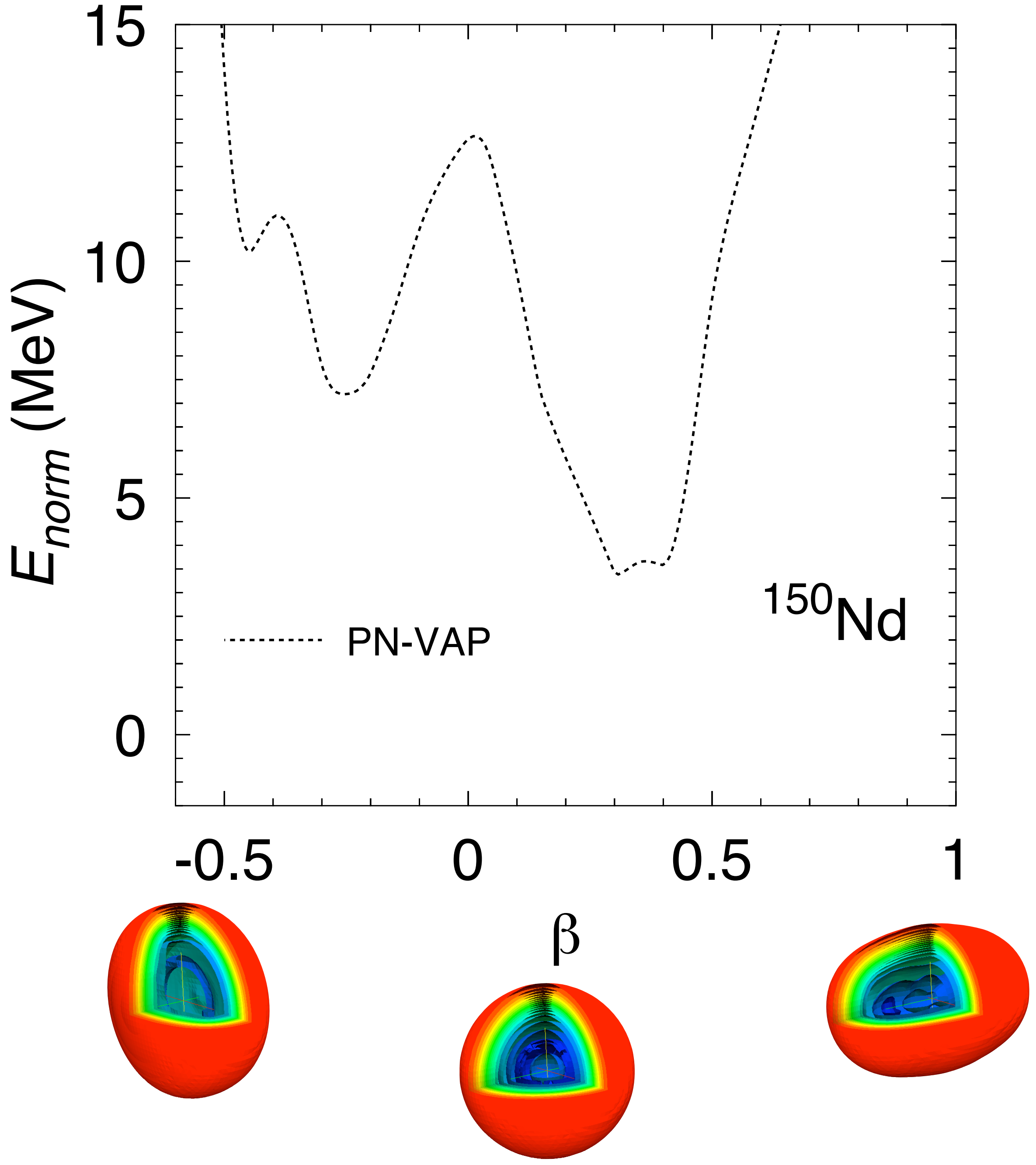
- Deformation and shape mixing.
- Pairing pp/nn/pn correlations.
- Shell effects.
- Isospin conservation.
- Pair breaking (seniority).
- Occupation numbers.
- Size of the valence space.

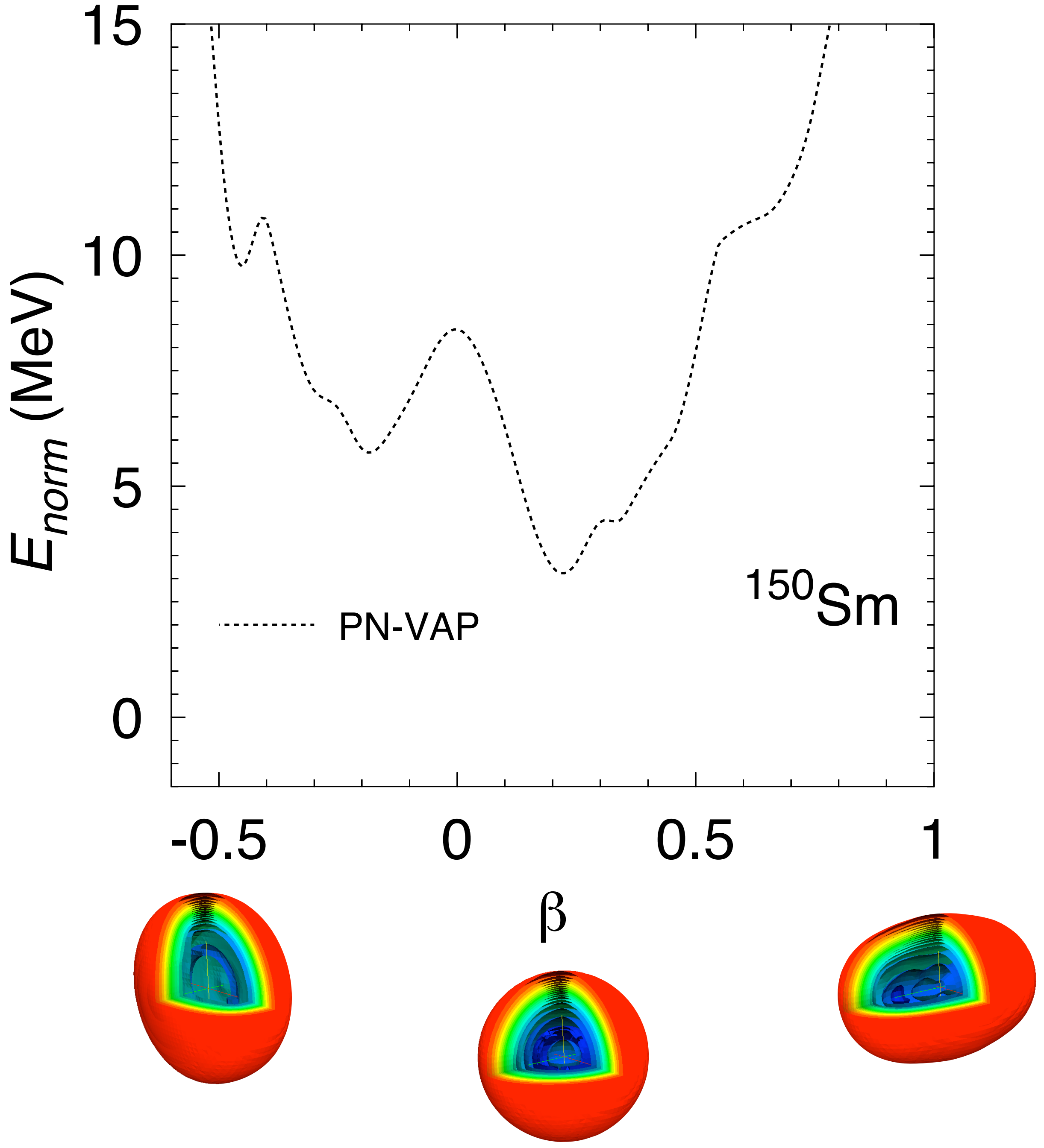
$$M_{\xi}^{0\nu\beta\beta}=\langle 0_f^+|\hat{O}_{\xi}^{0\nu\beta\beta}|0_i^+\rangle$$

in the nuclear matrix elements using a standard prescription for the transition operator.

Particle number projection

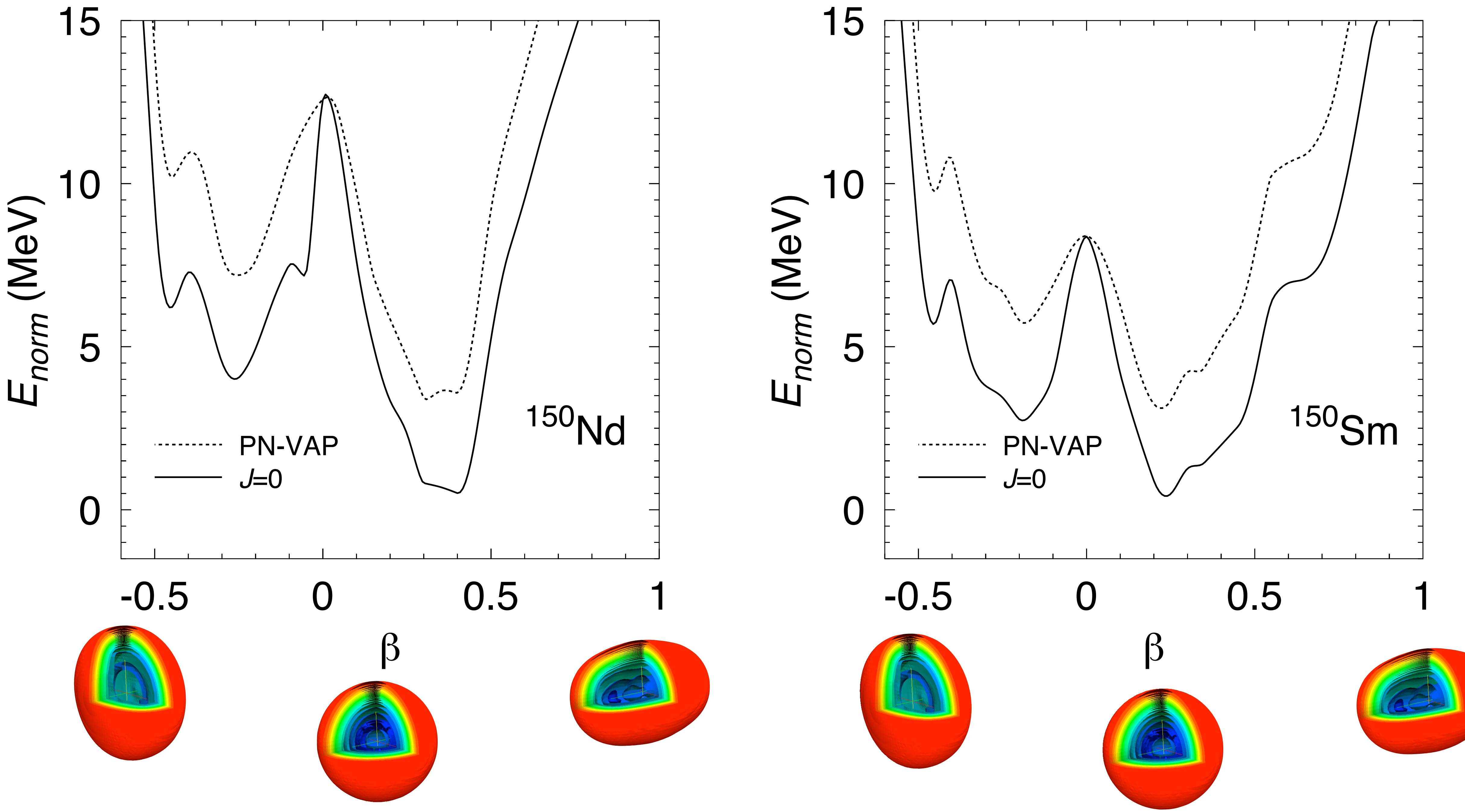
Determination of initial and final states (I) (Gogny D1S)





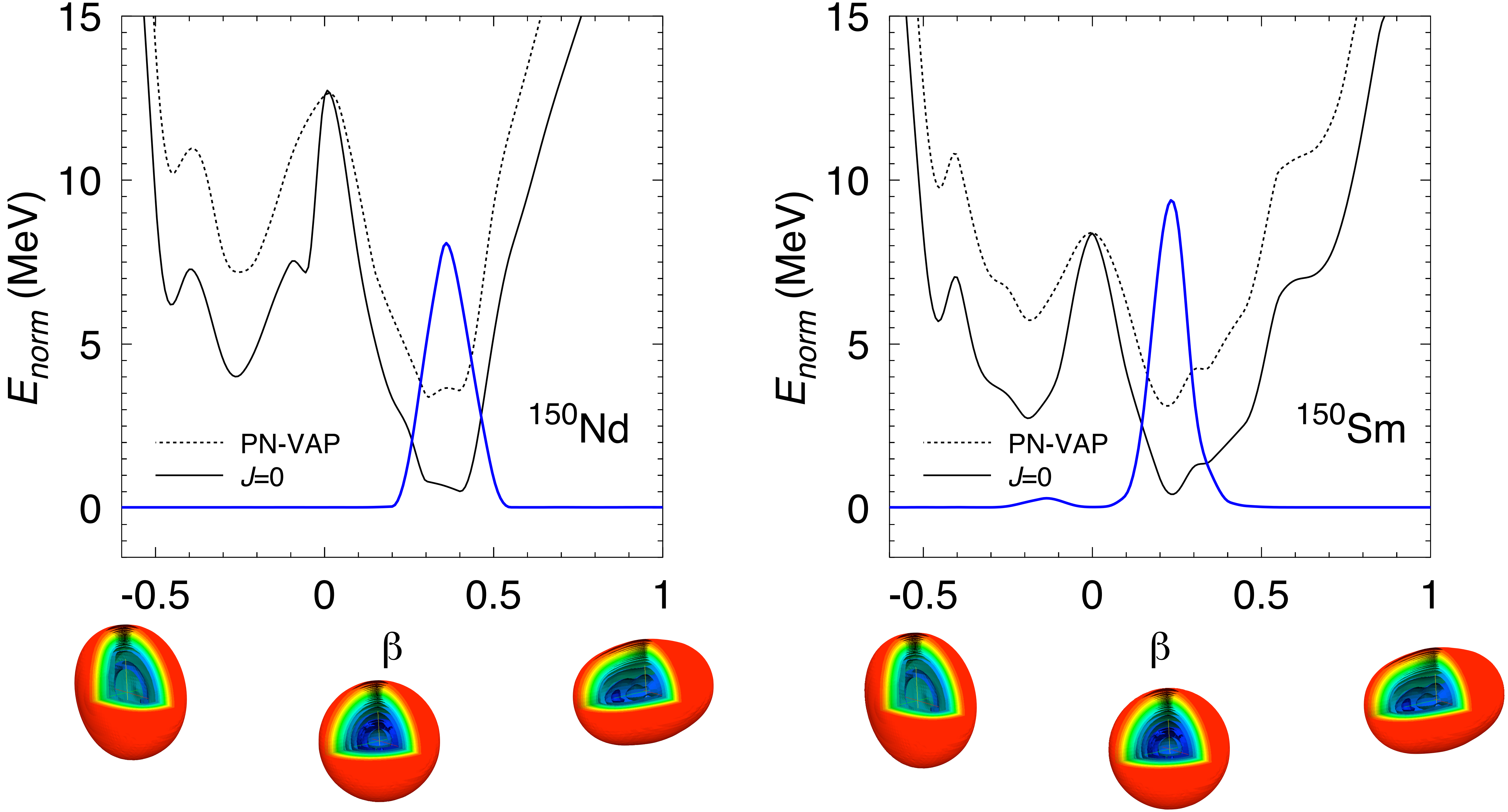
Particle number and angular momentum projection

Determination of initial and final states (II) (Gogny D1S)



Configuration (shape) mixing

Determination of initial and final states (& III) (Gogny D1S)

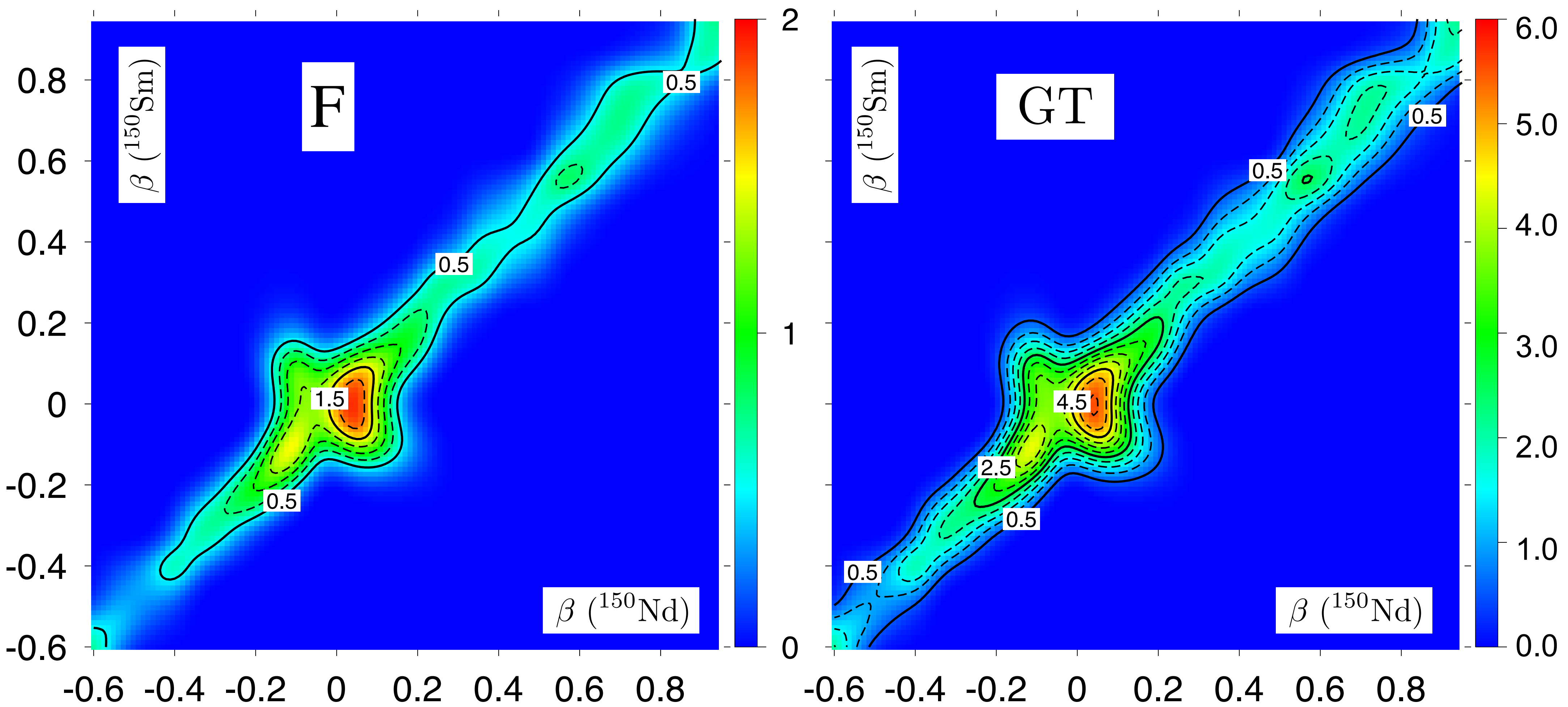


NME: deformation and mixing

$$\frac{\langle 0; N_f Z_f; q_f | \hat{O}_\xi^{0\nu\beta\beta} | 0; N_i Z_i; q_i\rangle}{\sqrt{\langle 0; N_f Z_f; q_f | 0; N_f Z_f; q_f\rangle \langle 0; N_i Z_i; q_i | 0; N_i Z_i; q_i\rangle}}$$

A=150

T.R.R., Martínez-Pinedo, PRL 105, 252503 (2010)

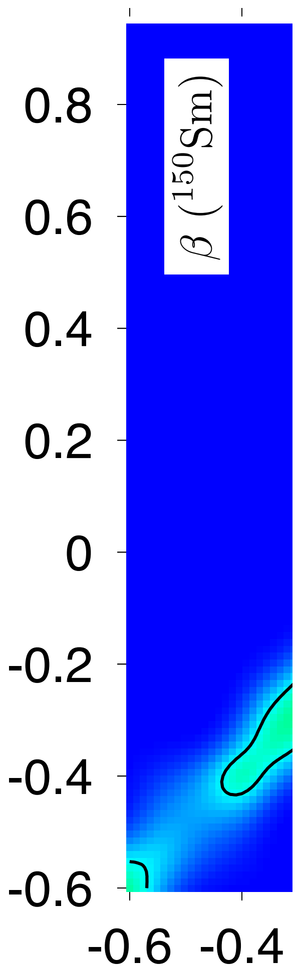


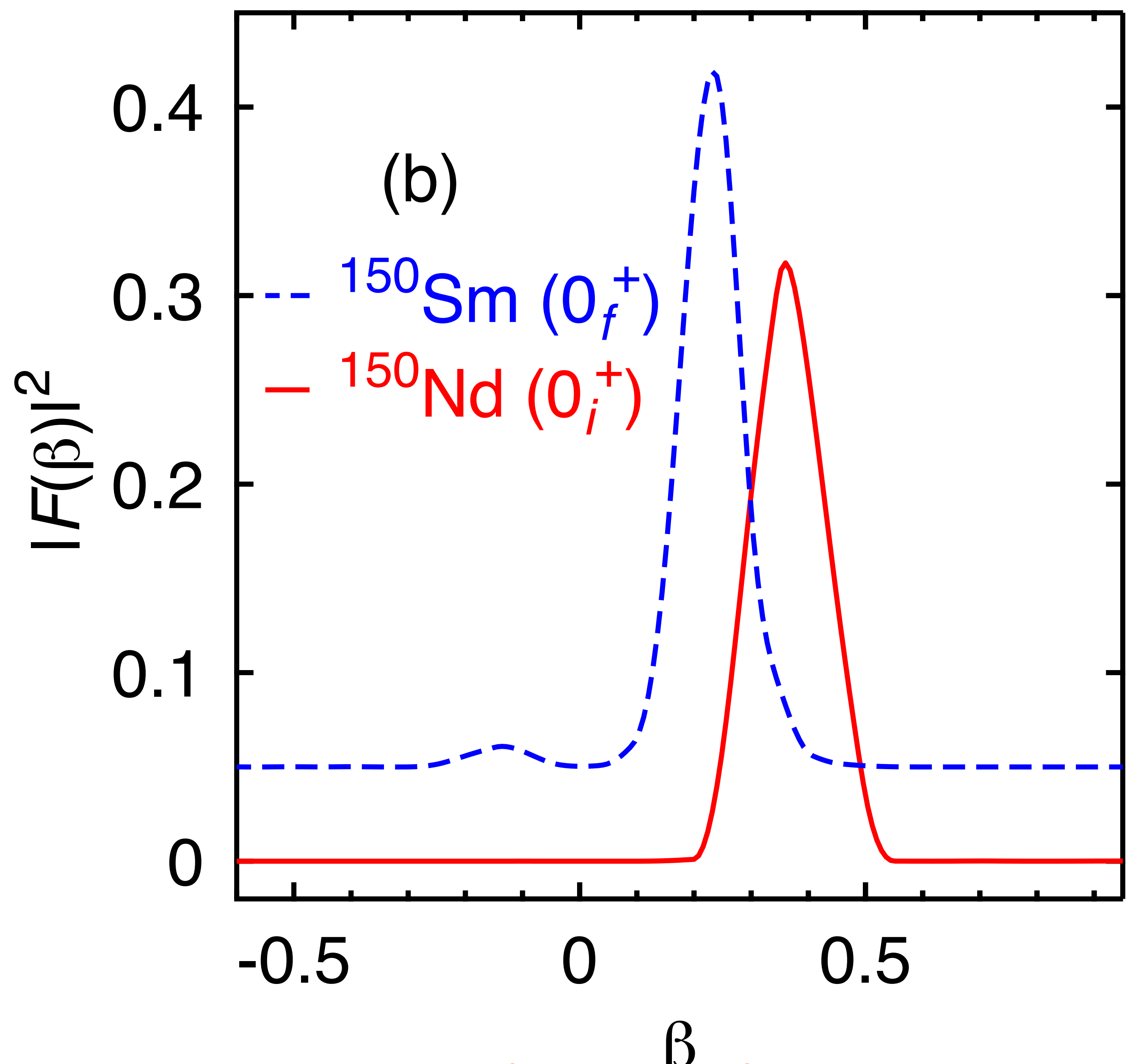
- GT strength greater than Fermi.
- Similar deformation between mother and granddaughter is favored by the transition operators
- Maxima are found close to sphericity although some other local maxima are found

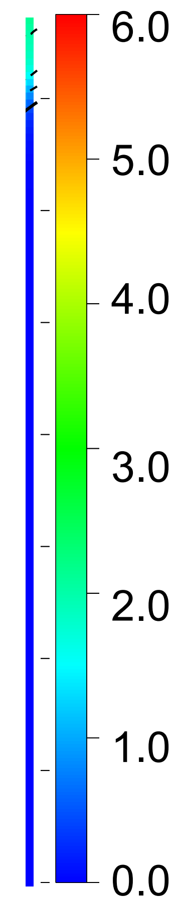
NME: deformation and mixing

T.R.R., Martínez-Pinedo, PRL 105, 252503 (2010)

$$\frac{\langle 0; N_f Z_f; q_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i; q_i \rangle}{\sqrt{\langle 0; N_f Z_f; q_f | 0; N_f Z_f; q_f \rangle \langle 0; N_i Z_i; q_i | 0; N_i Z_i; q_i \rangle}}$$





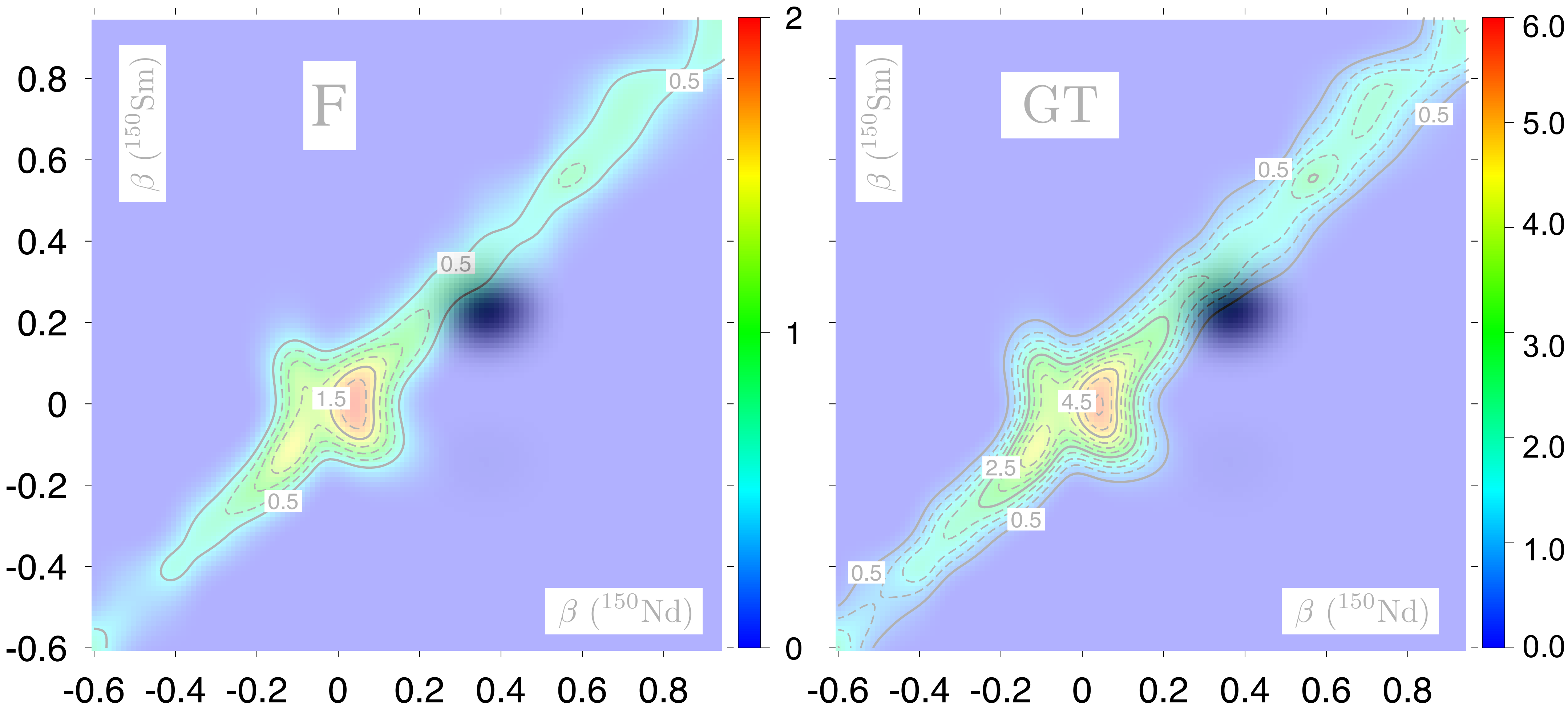


- GT streng
- Similar de
- Maxima a
- Final result depends on the distribution of probability of the corresponding initial and final collective states within this plot

$$\frac{\langle 0; N_f Z_f; q_f | \hat{O}^{0\nu\beta\beta}_{\xi} | 0; N_i Z_i; q_i \rangle}{\sqrt{\langle 0; N_f Z_f; q_f | 0; N_f Z_f; q_f \rangle \langle 0; N_i Z_i; q_i | 0; N_i Z_i; q_i \rangle}}$$

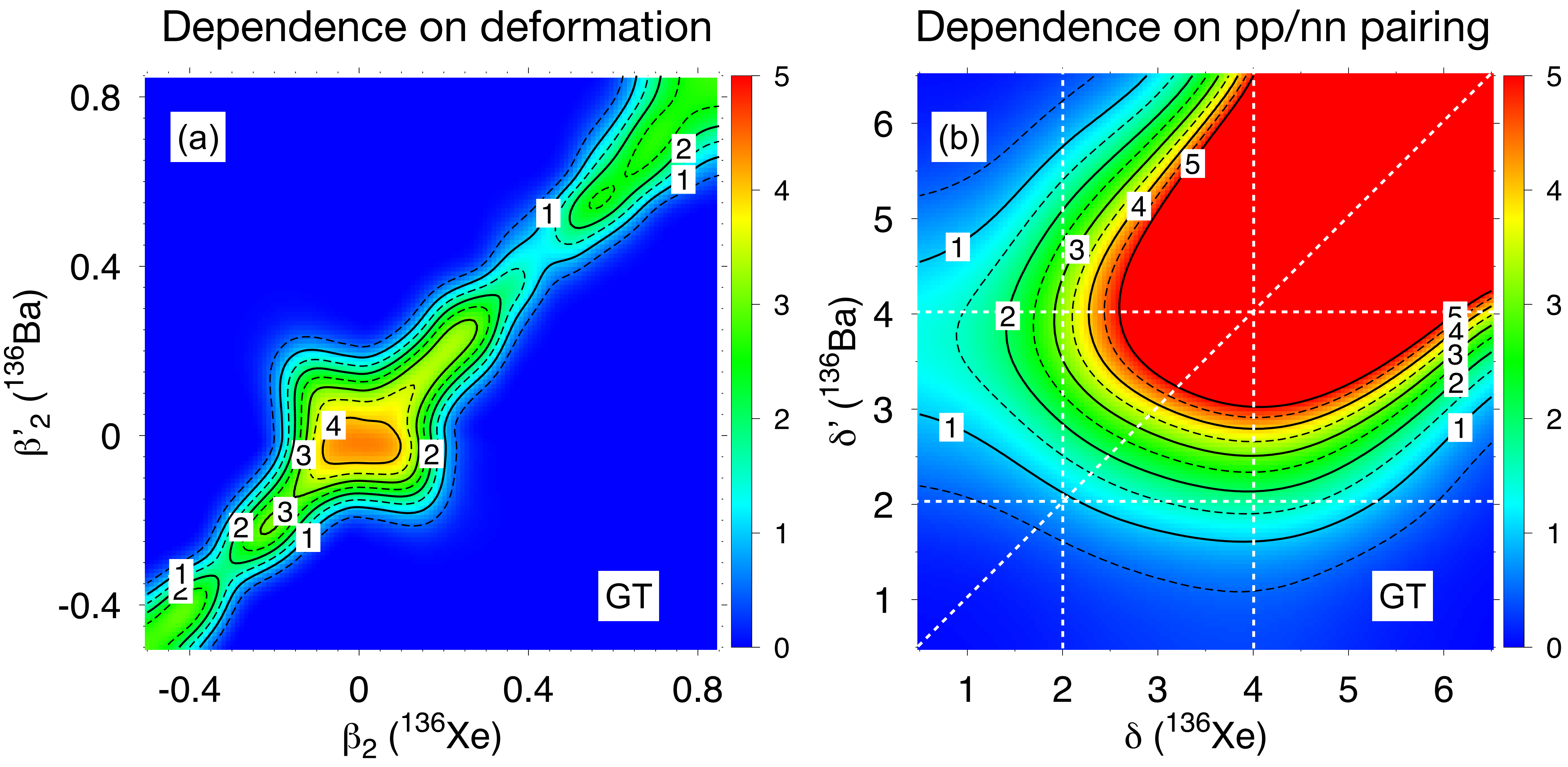
A=150

T.R.R., Martínez-Pinedo, PRL 105, 252503 (2010)



- GT strength greater than Fermi.
- Similar deformation between mother and granddaughter is favored by the transition operators
- Maxima are found close to sphericity although some other local maxima are found
- Final result depends on the distribution of probability of the corresponding initial and final collective states within this plot

Shape and pp/nn pairing fluctuations



N. López-Vaquero, T.R.R., J.L. Egido, PRL 111, 142501 (2013)

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

where h_0 contains spherical single particle energies, Q_{2K} are the components of a quadrupole operator defined in Ref. [15], and

$$S_\mu^\dagger = \frac{1}{\sqrt{2}}\sum_l \hat{l}[c_l^\dagger c_l^\dagger]^{001}_{00\mu}\,, \quad P_\mu^\dagger = \frac{1}{\sqrt{2}}\sum_l \hat{l}[c_l^\dagger c_l^\dagger]^{010}_{0\mu 0}\,,$$
$$F_\nu^\mu = \frac{1}{2}\sum_i \sigma_i^\mu \tau_i^\nu = \sum_l \hat{l}[c_l^\dagger \bar{c}_l]^{011}_{0\mu\nu}\,. \qquad (3)$$

$$H' = H - \lambda_Z N_Z - \lambda_N N_N - \lambda_Q Q_{20} - \frac{\lambda_P}{2}\left(P_0 + P_0^\dagger\right)\,, \quad (6)$$

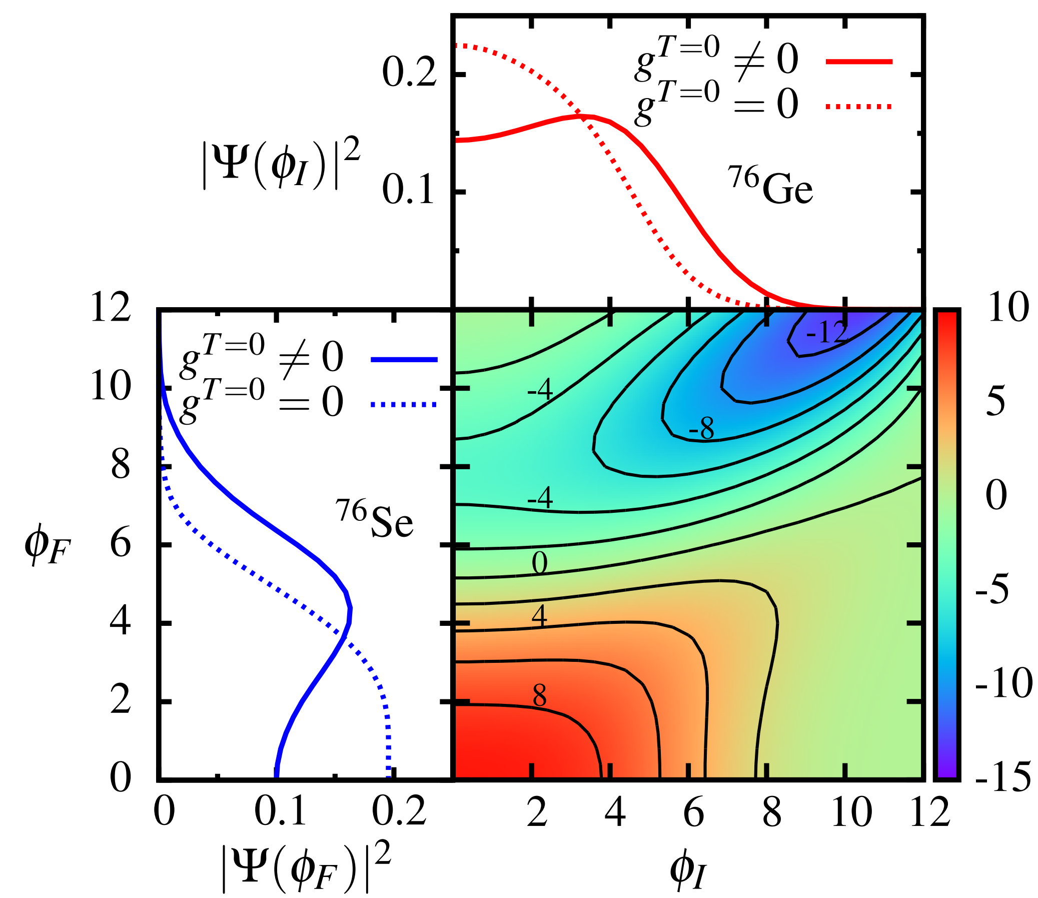


FIG. 3. (Color online.) **Bottom right:** $\mathcal{N}_{\phi_I}\mathcal{N}_{\phi_F}\langle\phi_F|\mathcal{P}_F\hat{M}_{0\nu}\mathcal{P}_I|\phi_I\rangle$ for projected quasiparticle vacua with different values of the initial and final isoscalar pairing amplitudes ϕ_I and ϕ_F, from the SkO′-based interaction (see text). **Top and bottom left:** Square of collective wave functions in ^{76}Ge and ^{76}Se.

N. Hinohara and J. Engel, PRC 031031(R) (2014)

pn pairing fluctuations

UNIVERSIDAD AUTONOMA DE MADRID

$$H = h_0 - \sum_{\mu=-1}^{1} g_\mu^{T=1}\, S_\mu^\dagger S_\mu - \frac{\chi}{2}\sum_{K=-2}^{2} Q_{2K}^\dagger Q_{2K}$$

$$- g^{T=0}\sum_{\nu=-1}^{1} P_\nu^\dagger P_\nu + \ldots$$

where h_0 contains spherical ... are the components of a qu... Ref. [15], and

$$S_\mu^\dagger = \frac{1}{\sqrt{2}}\sum_l \hat{l}[c_l^\dagger c_l^\dagger]^{001}_{00\mu}\,, \ldots$$

$$F_\nu^\mu = \frac{1}{2}\sum_i \sigma_i^\mu \tau_i^\nu = \sum_l \hat{l}[c_l^\dagger \bar{c}_l]^{011}_{0\mu\nu}\,. \quad (3)$$

$$H' = H - \lambda_Z N_Z - \lambda_N N_N - \lambda_Q Q_{20} - \frac{\lambda_P}{2}\left(P_0 + P_0^\dagger\right)\,, \quad (6)$$

Exploring explicitly pp/nn and pn pairing could produce cancellations

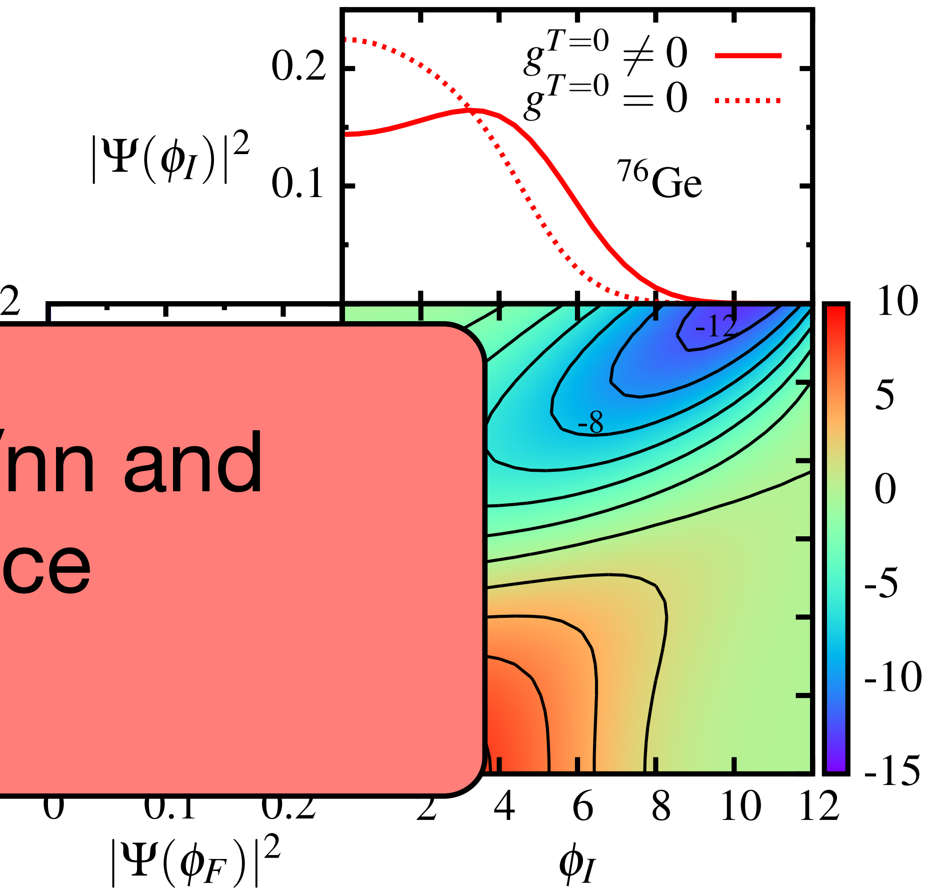


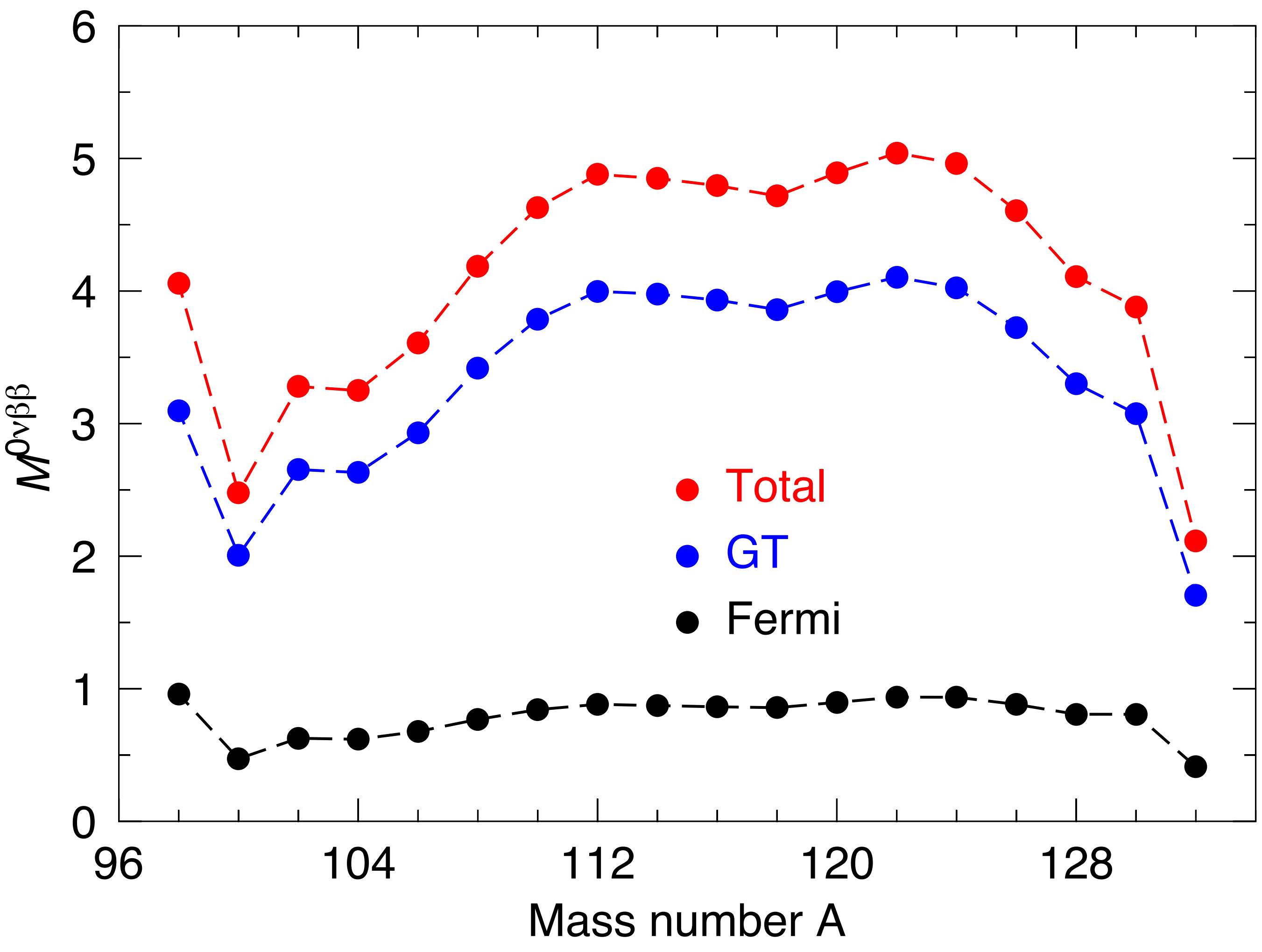
FIG. 3. (Color online.) **Bottom right:** $\mathcal{N}_{\phi_I}\mathcal{N}_{\phi_F}\langle\phi_F|\mathcal{P}_F\hat{M}_{0\nu}\mathcal{P}_I|\phi_I\rangle$ for projected quasiparticle vacua with different values of the initial and final isoscalar pairing amplitudes ϕ_I and ϕ_F, from the SkO′-based interaction (see text). **Top and bottom left:** Square of collective wave functions in ^{76}Ge and ^{76}Se.

N. Hinohara and J. Engel, PRC 031031(R) (2014)

NME: $^{A}Cd \rightarrow {}^{A}Sn$ Shell Effects

UAM UNIVERSIDAD AUTONOMA DE MADRID

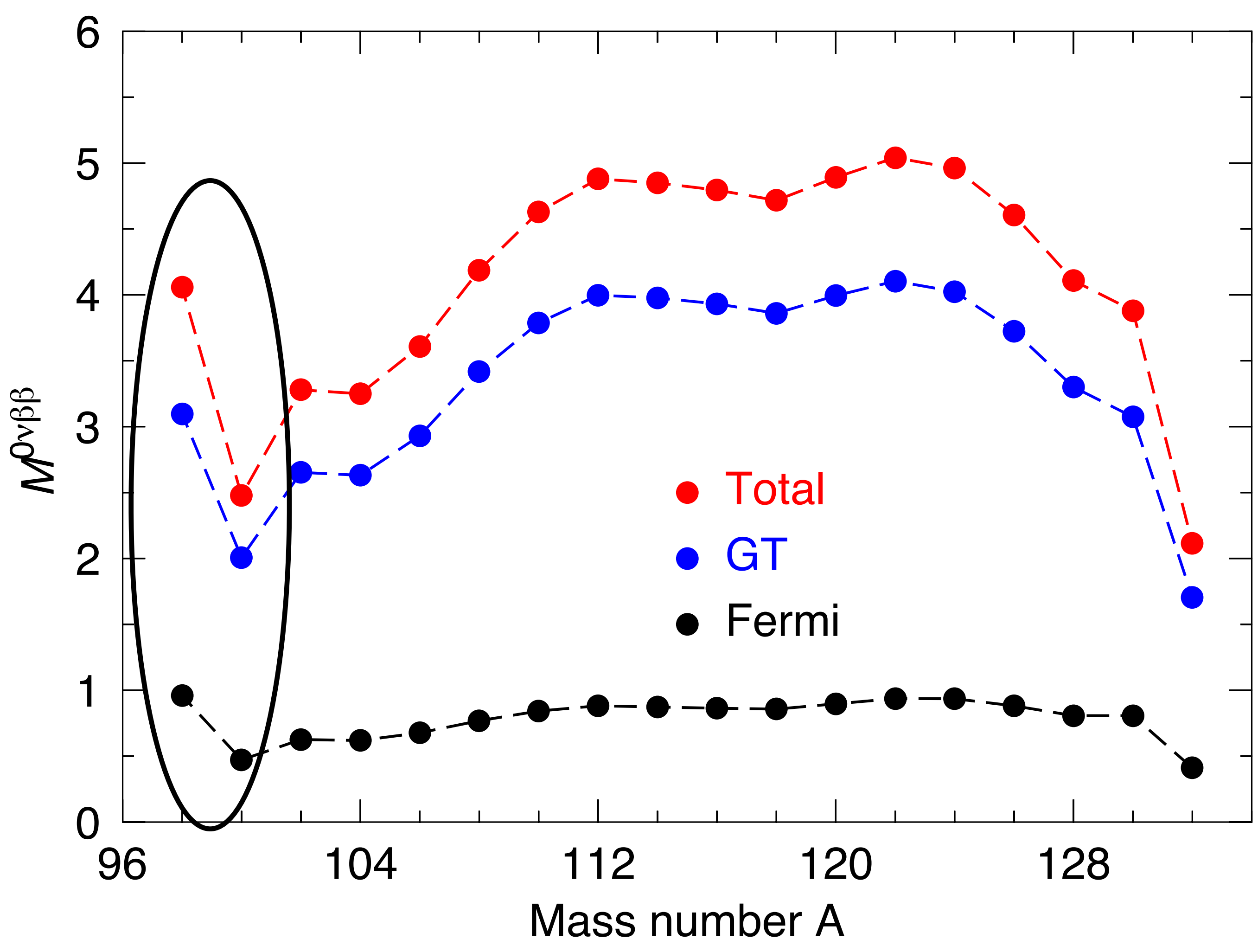
- GT component is always larger than Fermi.



T.R.R., Martínez-Pinedo, PLB 719, 174 (2013)

NME: $^{A}Cd \rightarrow {}^{A}Sn$ Shell Effects

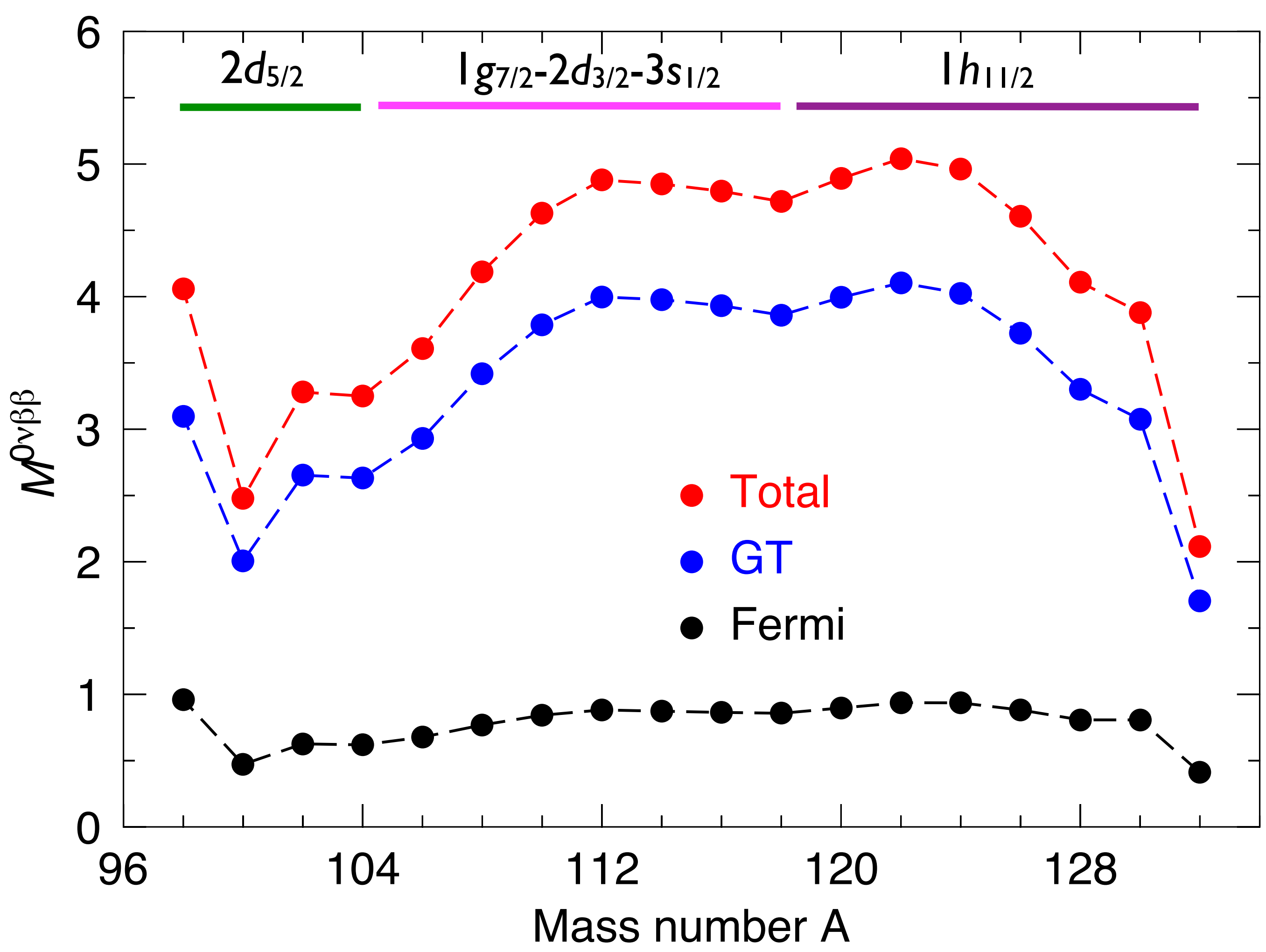
UNIVERSIDAD AUTONOMA DE MADRID



- GT component is always larger than Fermi.
- Large enhancement of the NME for the mirror decay A=98.

T.R.R., Martínez-Pinedo, PLB 719, 174 (2013)

NME: ^{A}Cd→^{A}Sn Shell Effects

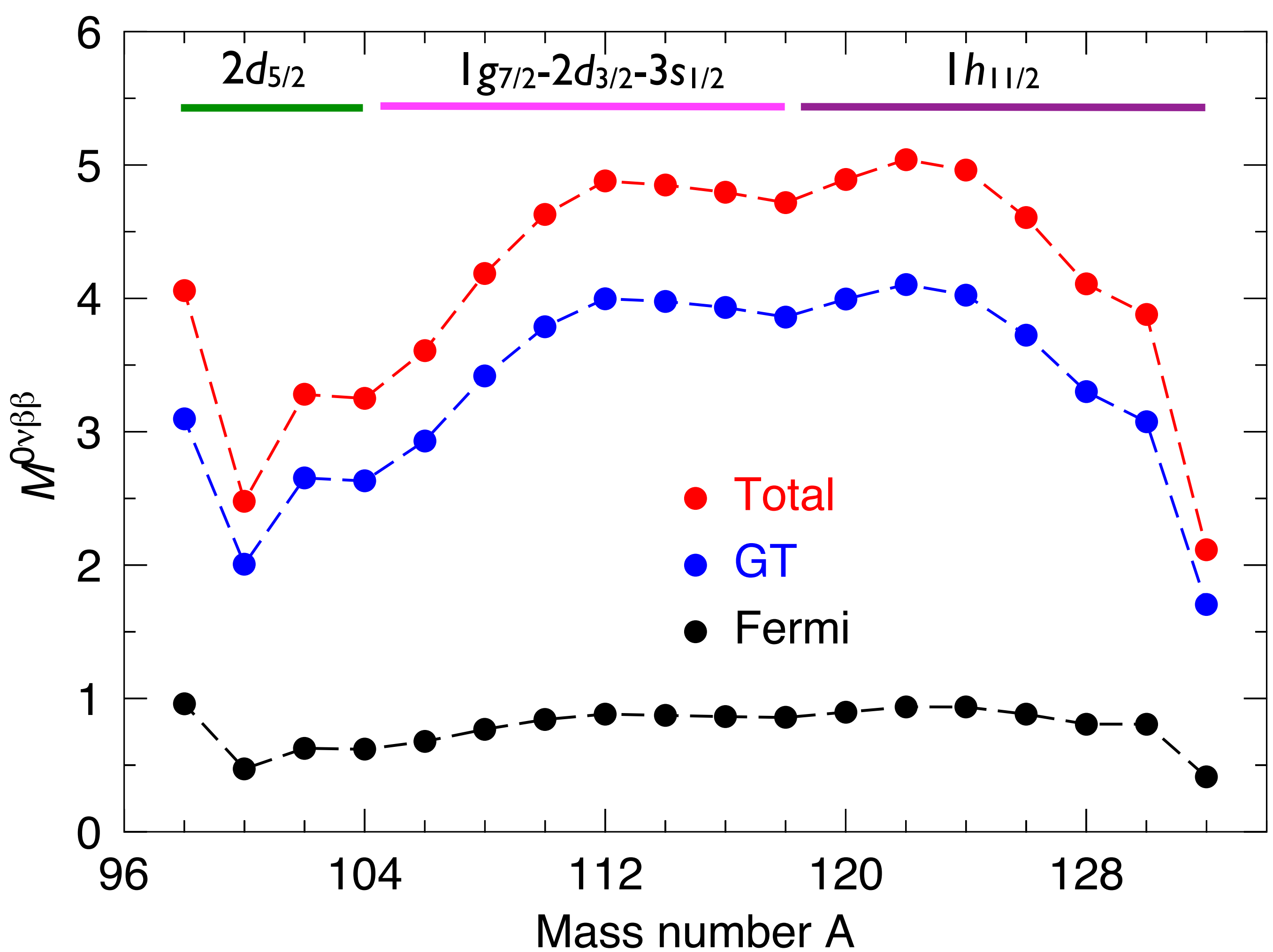


- GT component is always larger than Fermi.
- Large enhancement of the NME for the mirror decay *A*=98.
- Shell effects associated to the filling of neutrons in the corresponding sub-shells. Consistent with seniority model.

T.R.R., Martínez-Pinedo, PLB 719, 174 (2013)

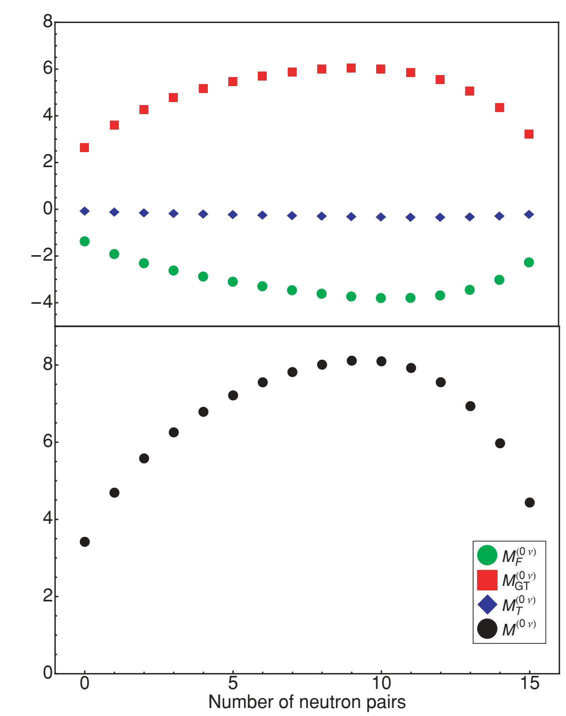
NME: $^{A}Cd \rightarrow ^{A}Sn$ Shell Effects

UNIVERSIDAD AUTONOMA DE MADRID



T.R.R., Martínez-Pinedo, PLB 719, 174 (2013)

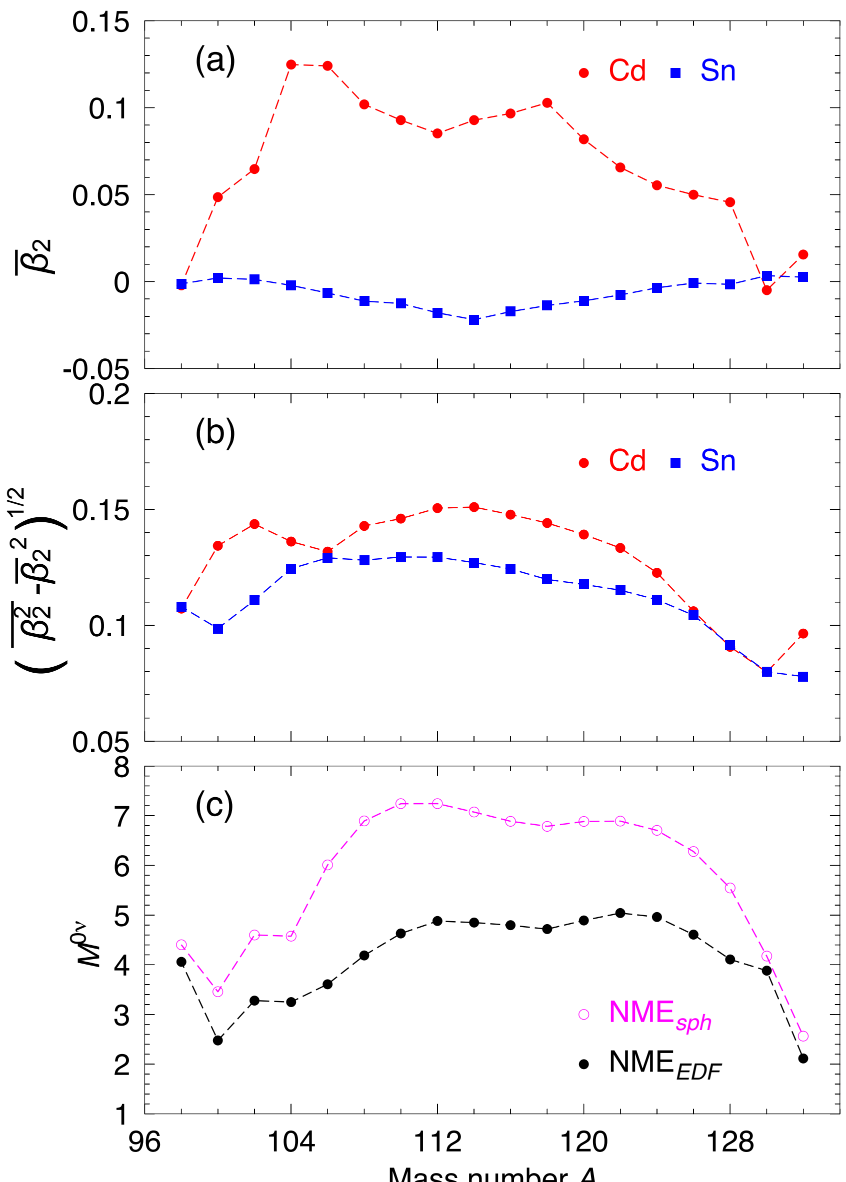
- GT component is always larger than Fermi.
- Large enhancement of the NME for the mirror decay A=98.
- Shell effects associated to the filling of neutrons in the corresponding sub-shells. Consistent with seniority model.



J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009)

NME: $^{A}Cd \rightarrow {}^{A}Sn$

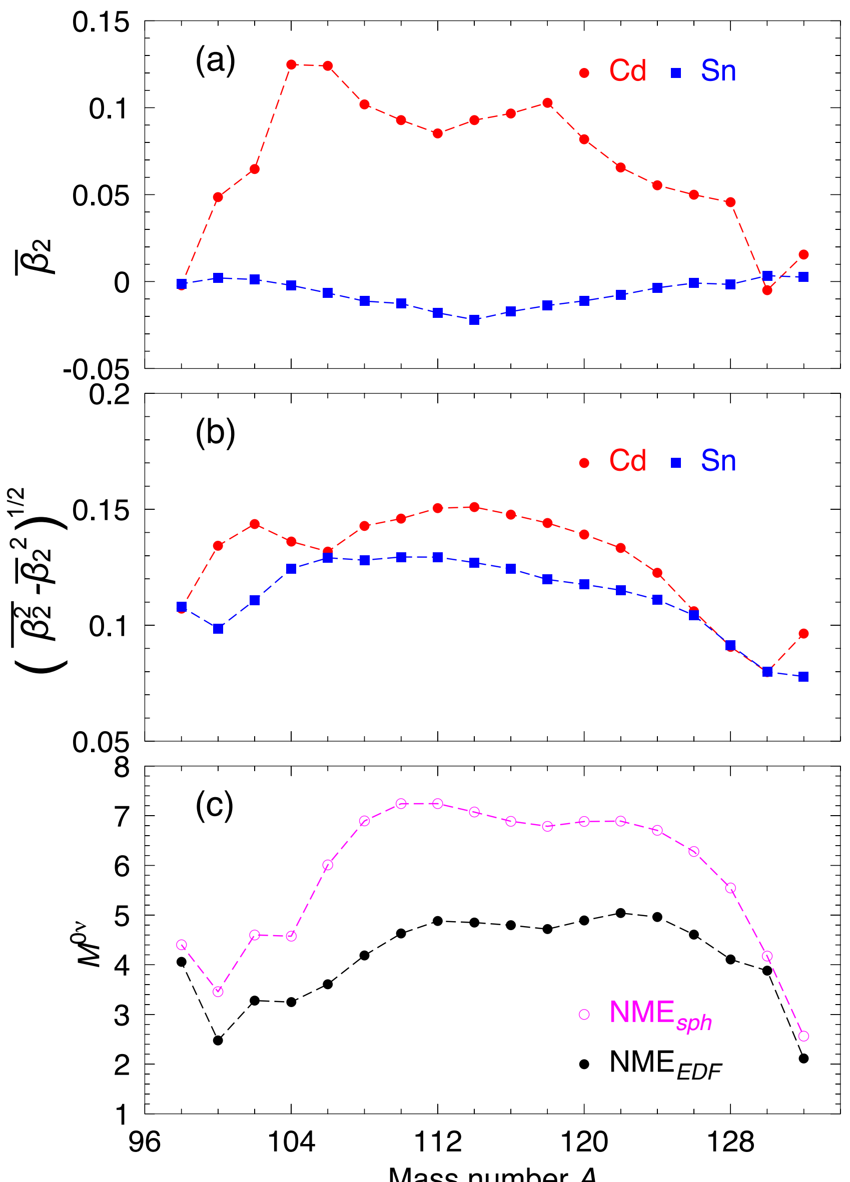
- Reduction of the NME with respect to the spherical value when shape mixing is included
- Larger reduction when the difference in deformation is larger



T.R.R., Martínez-Pinedo, PLB 719, 174 (2013)

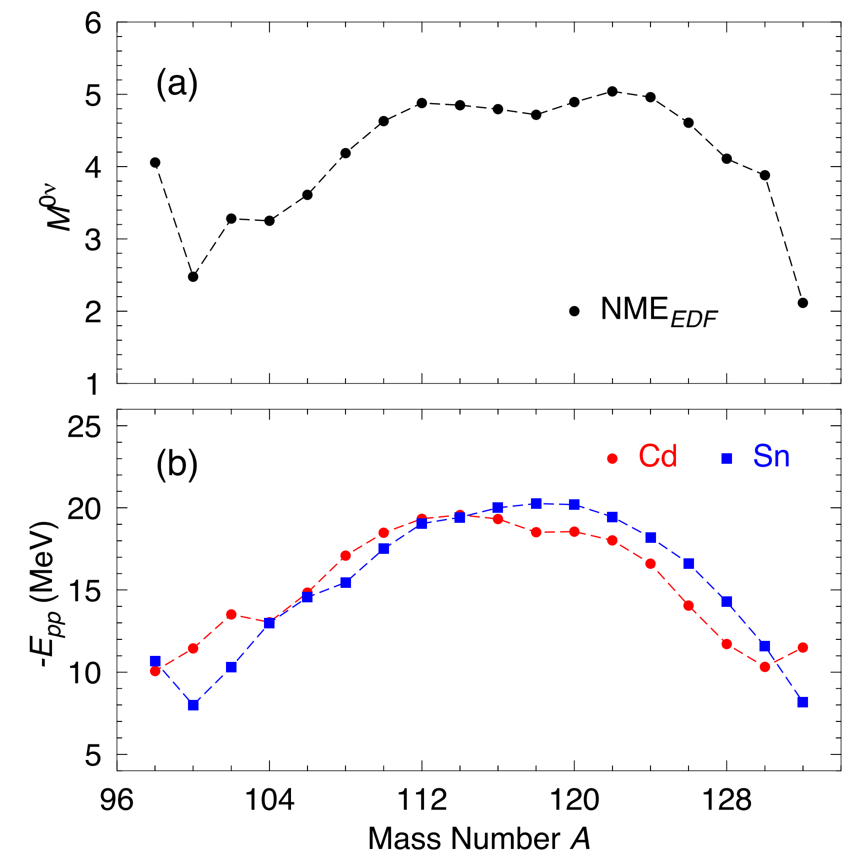
NME: $^{A}Cd \rightarrow ^{A}Sn$

- Reduction of the NME with respect to the spherical value when shape mixing is included
- Larger reduction when the difference in deformation is larger



- Larger pairing correlations in mother/daughter nuclei produces larger NMEs.

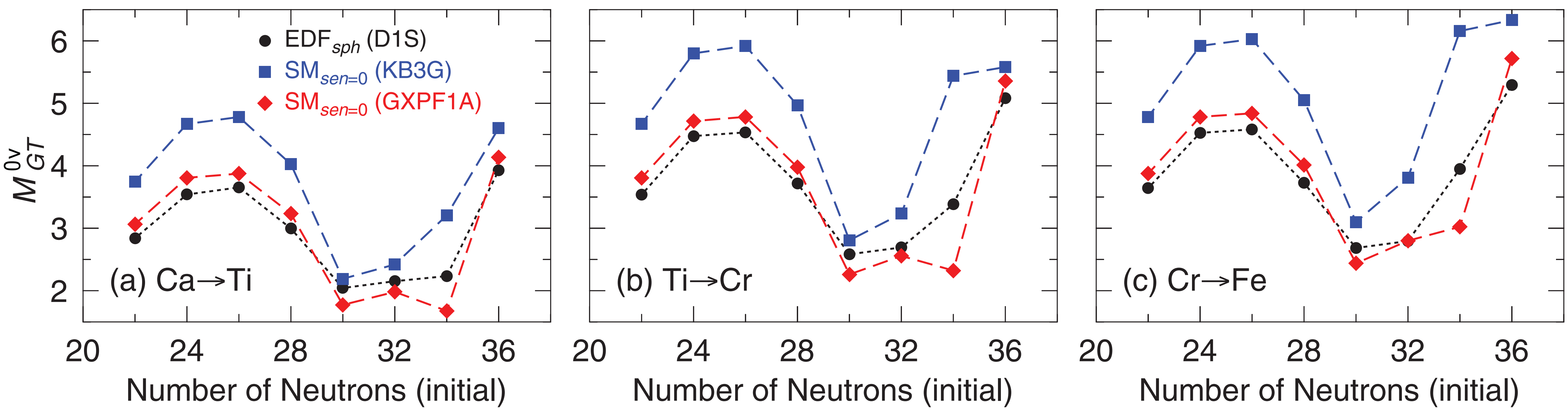
- Closely related to shell effects



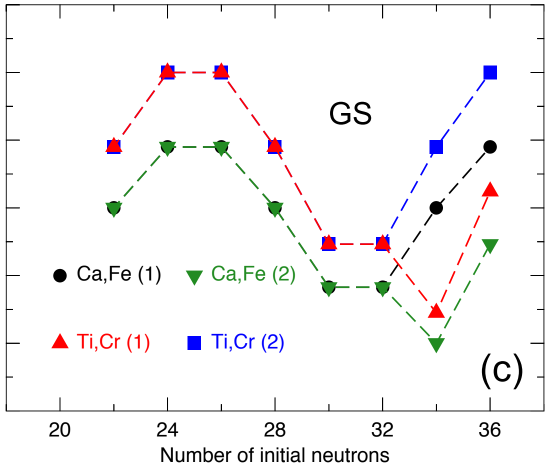
T.R.R., Martínez-Pinedo, PLB 719, 174 (2013)

NME: *pf*-shell

Where do the differences come from?

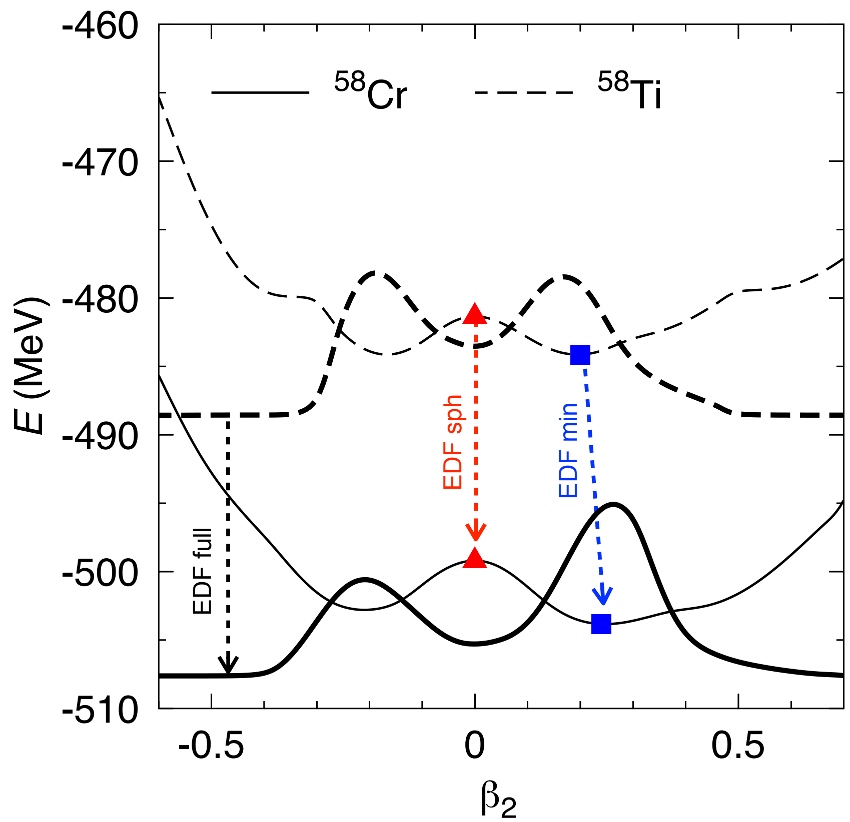


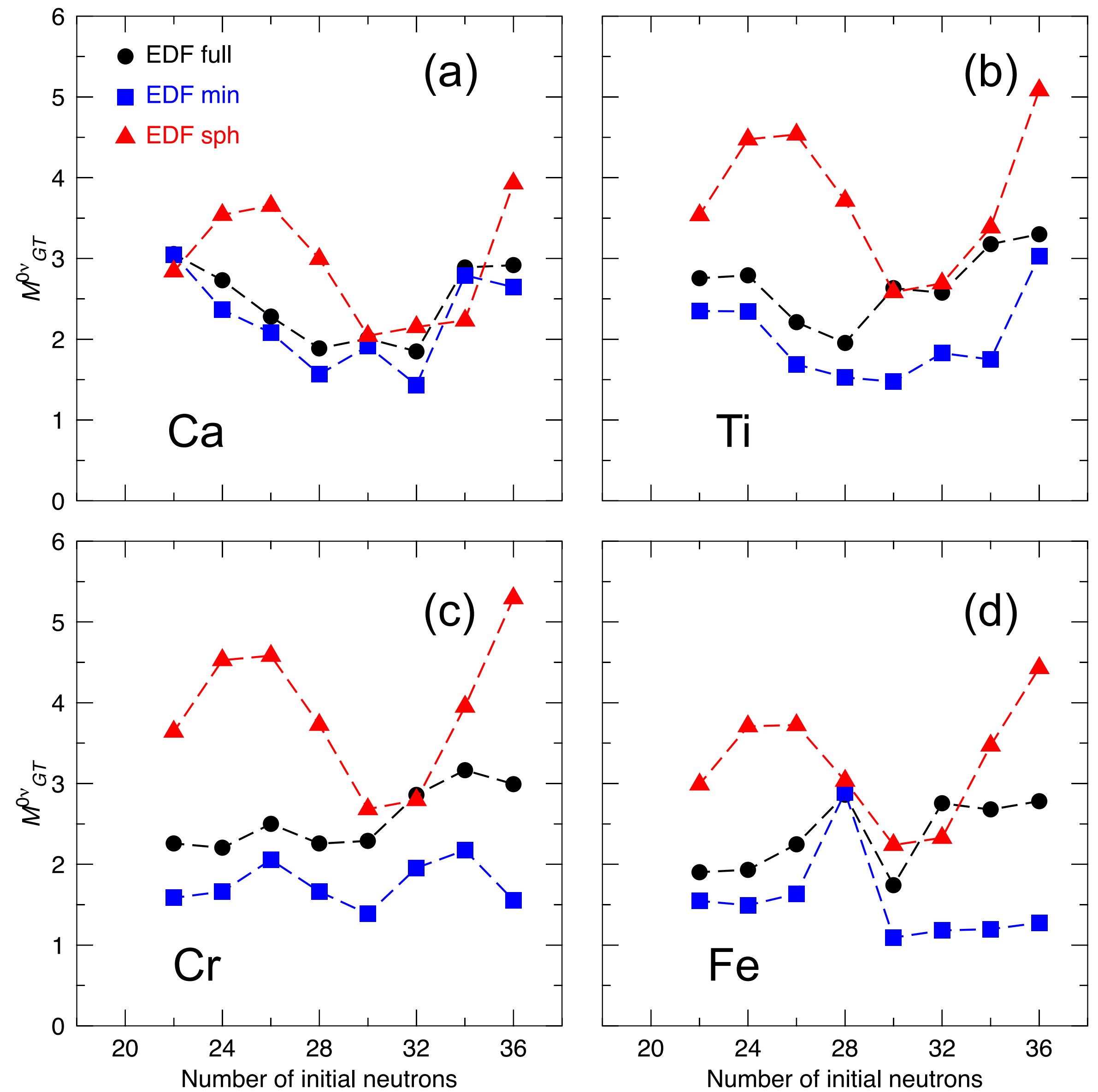
- Same pattern in spherical EDF, seniority 0 Shell Model, and Generalized Seniority model (overall scale?)
- What is the effect of including more **correlations**?



J. Menéndez, T. R. R., A. Poves, G. Martínez-Pinedo, PRC 90, 024311 (2014).

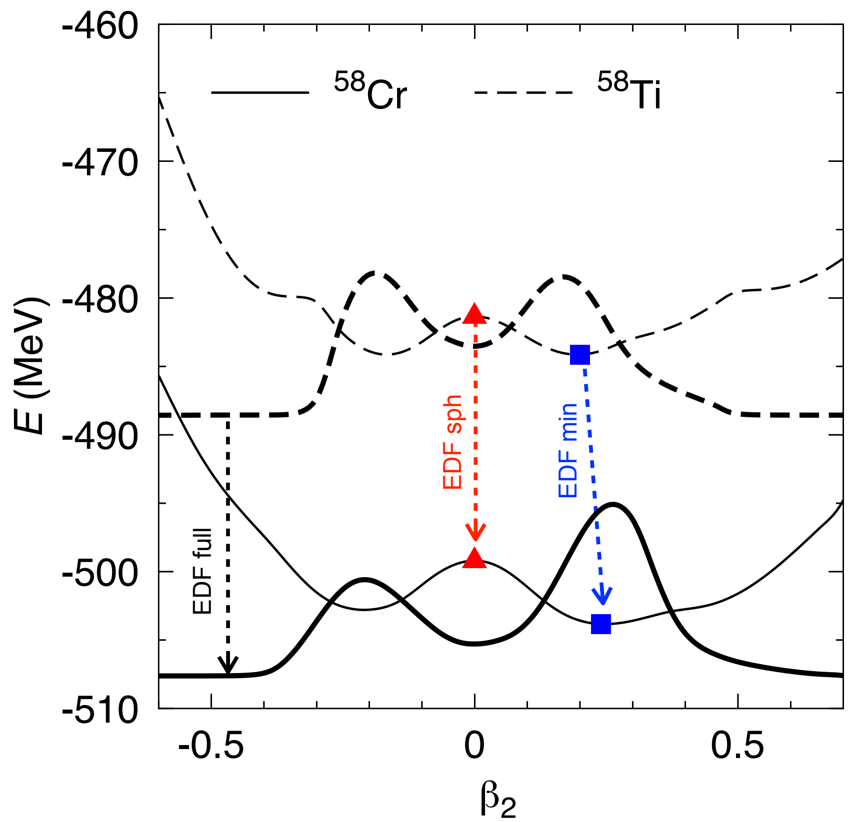
NME: *pf*-shell

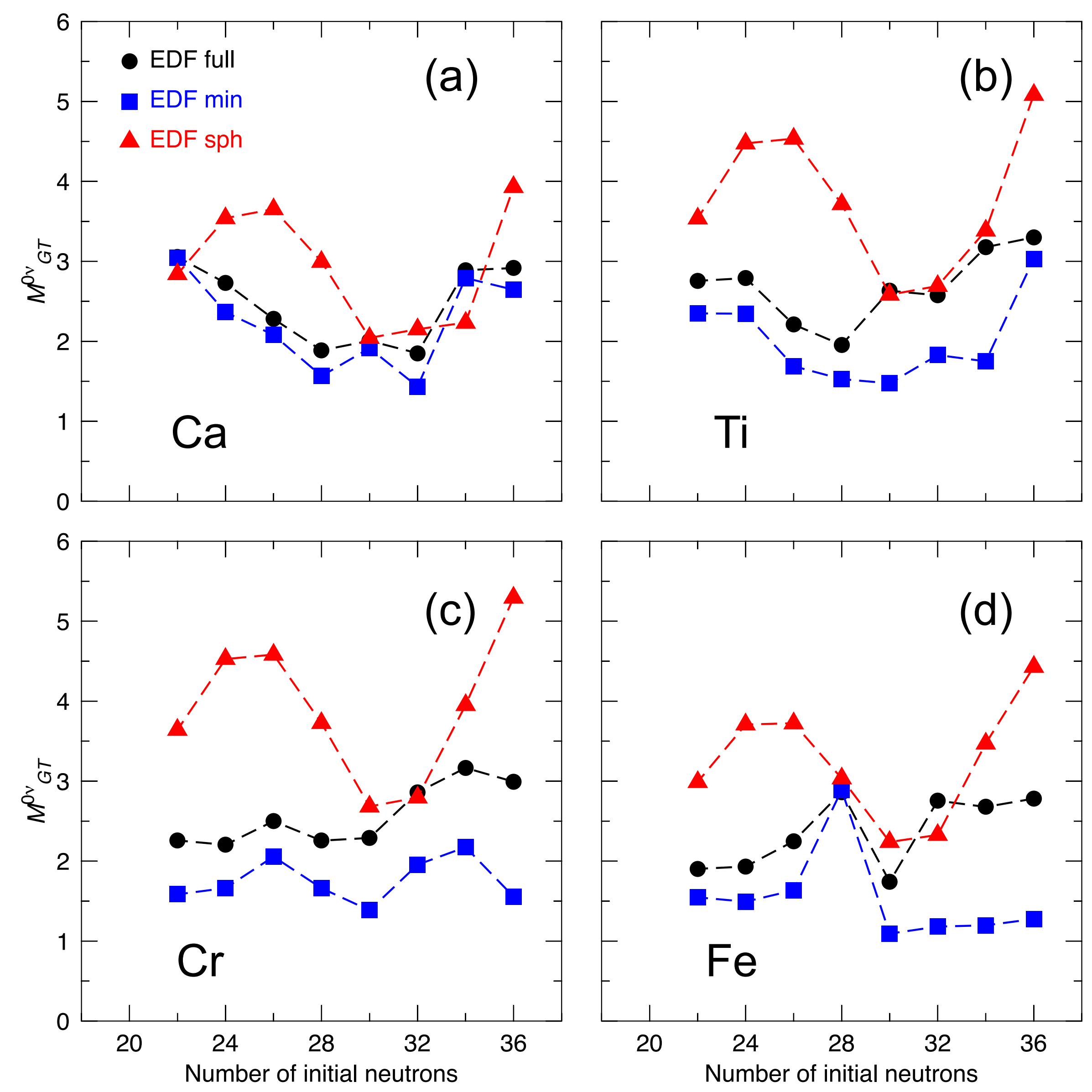




J. Menéndez, T. R. R., A. Poves, G. Martínez-Pinedo, PRC 90, 024311 (2014).

NME: *pf*-shell





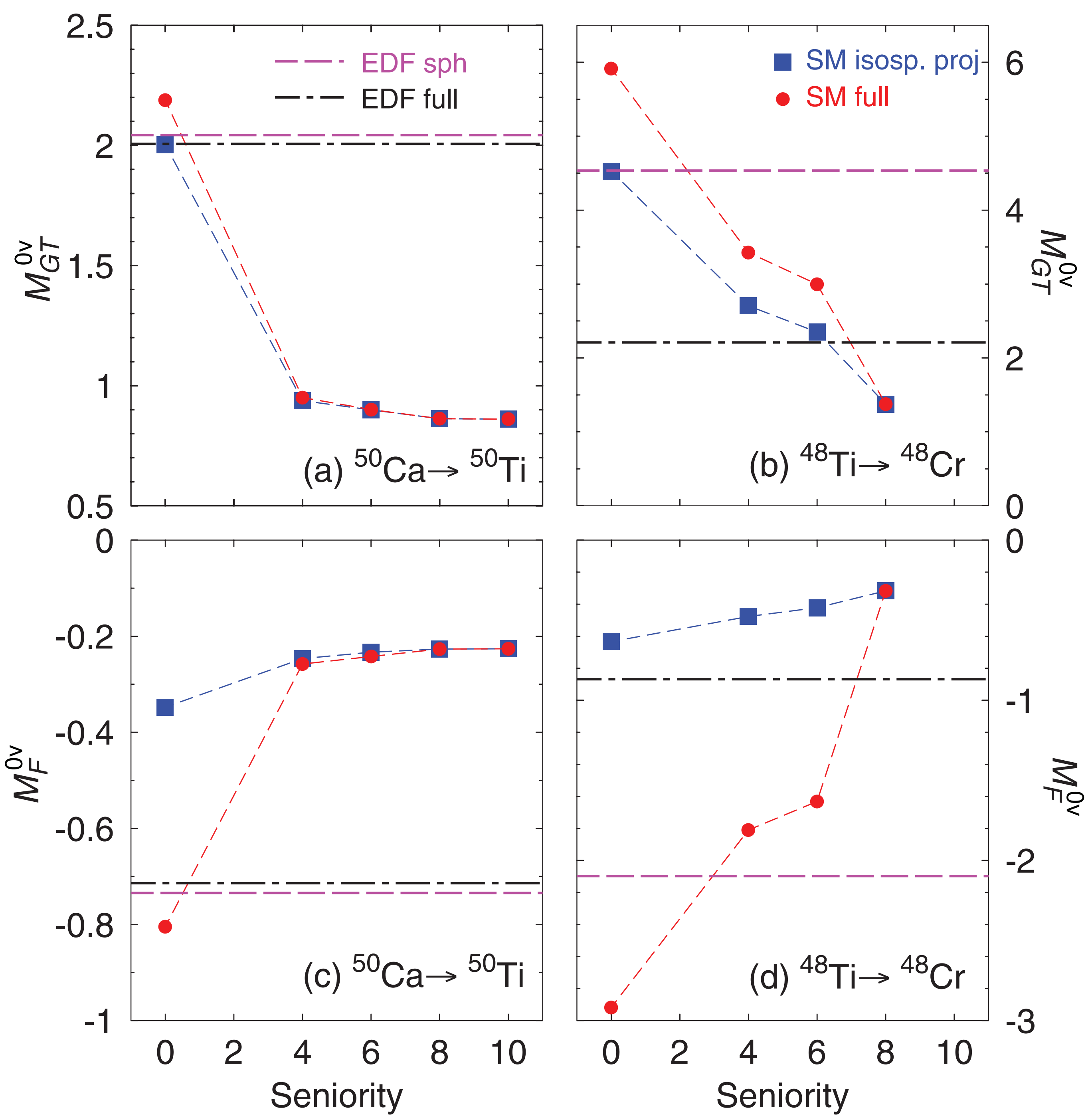
- NMEs are reduced with respect to the spherical value when correlations are included.

- The biggest reduction is produced by angular momentum restoration and configuration mixing produces an increase of the NME.

- Cross-check nuclei: ^{42}Ca, ^{50}Ca, ^{56}Fe

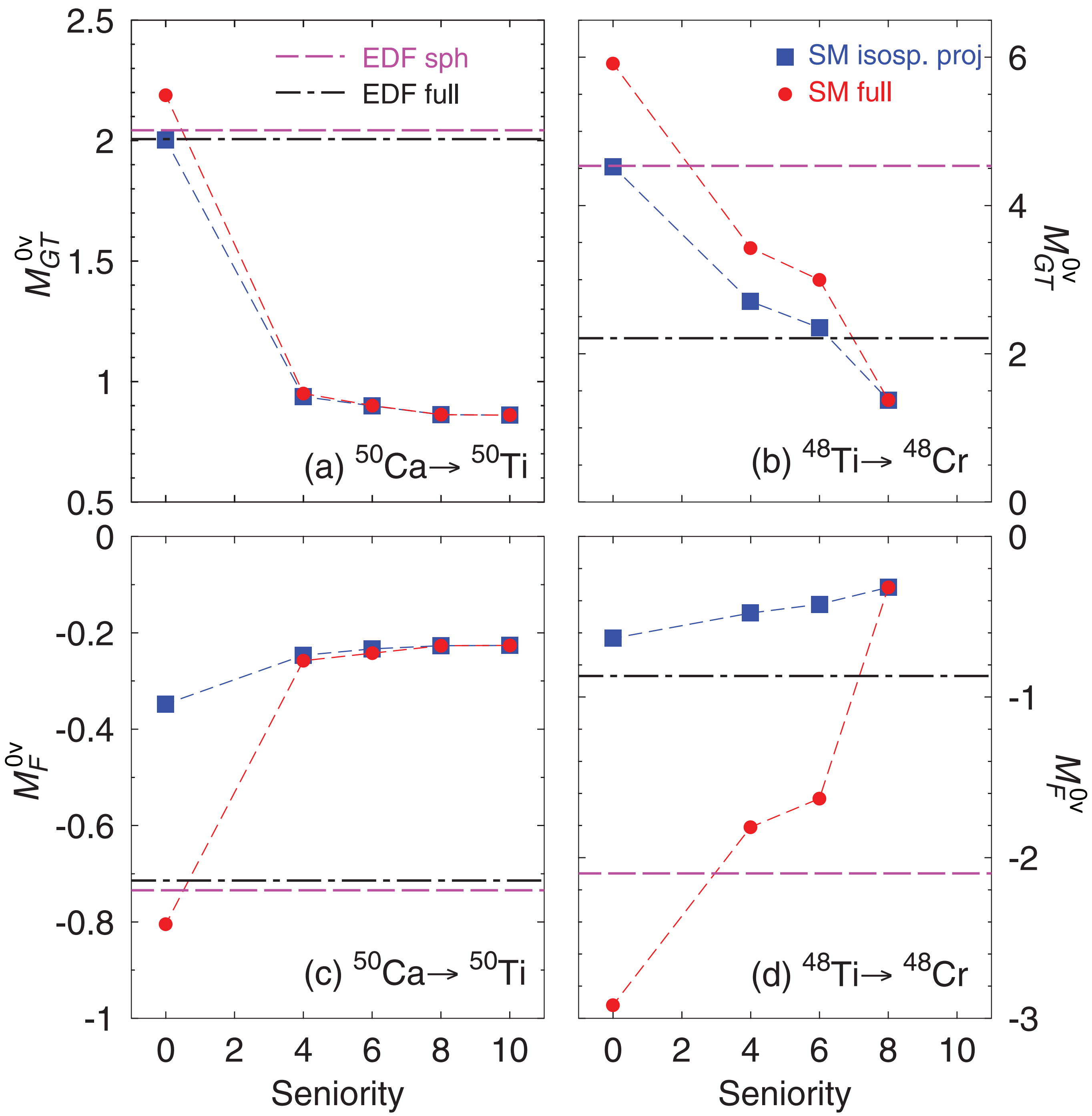
J. Menéndez, T. R. R., A. Poves, G. Martínez-Pinedo, PRC 90, 024311 (2014).

NME: *pf*-shell



J. Menéndez, T. R. R., A. Poves, G. Martínez-Pinedo, PRC 90, 024311 (2014).

NME: *pf*-shell



- The biggest reduction (in Shell model calculations) is produced by including higher seniority components in the nuclear wave functions.
- Isospin projection is relevant for the Fermi part of the NME and less important for the Gamow-Teller part.
- Isospin projection tends to reduce the NME.
- EDF does not include properly those higher seniority components, specially in spherical nuclei.
- p-n pairing effects could also be important in the reduction of the NME.

J. Menéndez, T. R. R., A. Poves, G. Martínez-Pinedo, PRC 90, 024311 (2014).

Summary

- Experimental data are already able to constrain very long lower limit half-lives (we cross fingers for a positive signal soon!).
- NMEs differ a factor of three between the different methods but we need to understand which are the pros/cons of each method to provide reliable numbers (precision vs. accuracy).
- Nuclear physics aspects like deformation, pairing, shell effects, isospin restoration, etc. are understood similarly within different approaches.
- Systematic comparisons between ISM/EDF methods have been performed.