JICFuS

Priority Issue 9
to be Tackled by Using Post K Computer
“Elucidation of the Fundamental Laws and
Evolution of the Universe”
KAKENHI grant 17K05433

“Nuclear *ab initio* Theories
and Neutrino Physics”
@ INT, Washington, 2018/03/07

Double Gamow-Teller transitions and its relation to neutrinoless $\beta\beta$ decay

東京大学
THE UNIVERSITY OF TOKYO

CENTER *for*
NUCLEAR STUDY

Noritaka Shimizu (CNS, U. Tokyo)

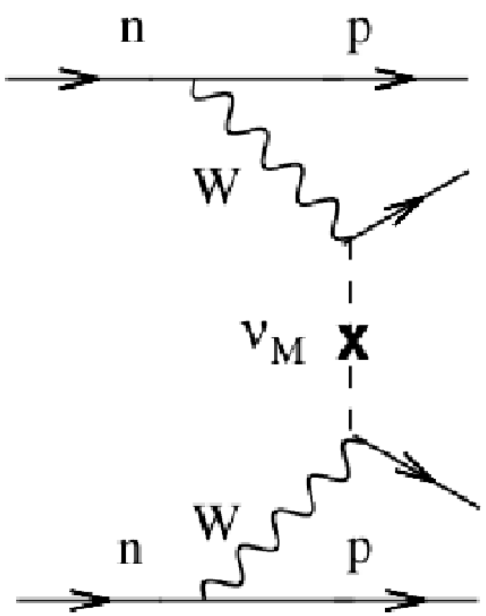
N. Shimizu, J. Menendez, and K. Yako,
Phys. Rev. Lett. accepted, arXiv:1709.01088 [nucl-th]

Outline

- Large scale shell model calculations of neutrinoless double beta decay nuclear matrix element ($0\nu\beta\beta$ NME) of ^{48}Ca
- Double Gamow Teller Resonance and its relation to $0\nu\beta\beta$ NME of ^{48}Ca
- Relation between double Gamow Teller transition and $0\nu\beta\beta$ NME, systematic study

Nuclear Matrix Element (NME) of neutrinoless double-beta decay

Majorana particle or not?
neutrinoless double beta decay



lepton number violation
(beyond the standard model)

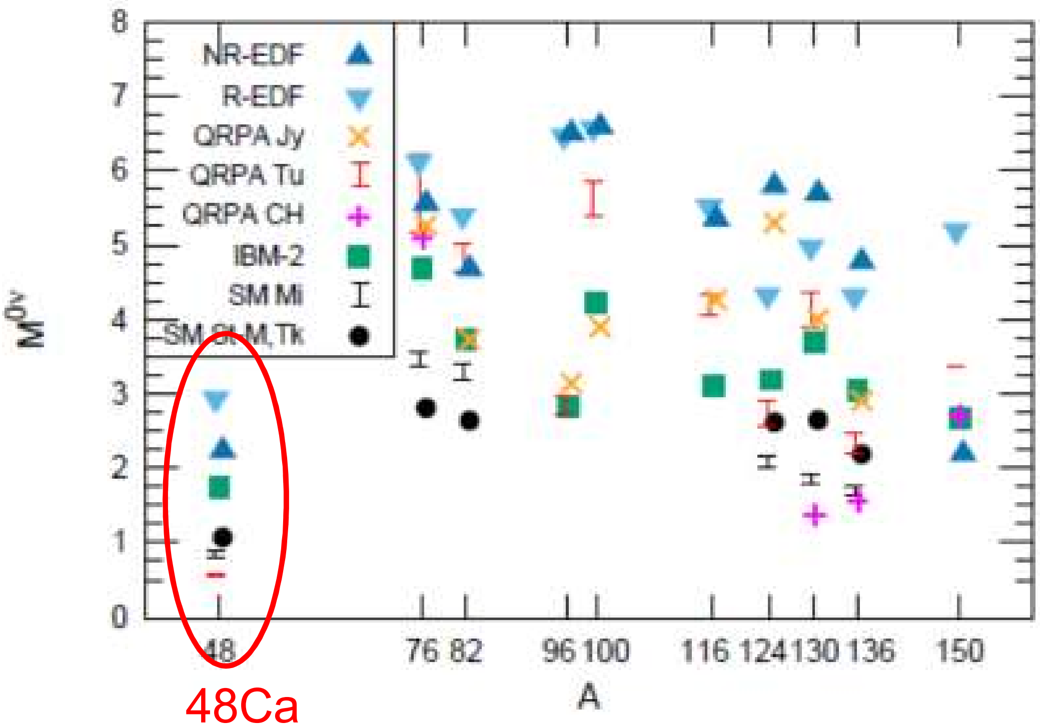
Theoretical prediction on the *0νββ* NME varies depending on theoretical models.

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}_1 \boxed{|M^{0\nu}|^2} \left(\frac{<m_{\beta\beta}>}{m_e}\right)^2$$

Half life
(exp.)

NME

effective
neutrino mass



48Ca

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

SM calc. for nuclear matrix element (NME) of ^{48}Ca $0\nu\beta\beta$ decay

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}_{1}\boxed{|M^{0\nu}|^2}\left(\frac{<m_{\beta\beta}>}{m_e}\right)^2$$

Half life (exp.)

NME

effective neutrino mass

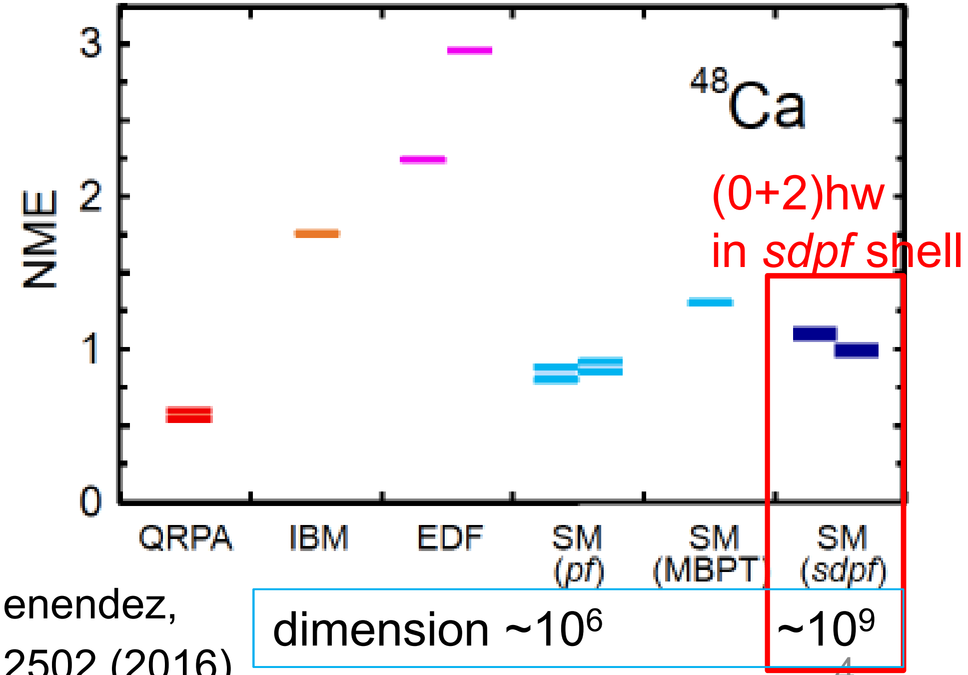
$2\nu\beta\beta$ decay

$$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti} + 2e^- + 2\overline{\nu}_e$$

$0\nu\beta\beta$ decay

$$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti} + 2e^-$$

Large scale shell model calculation including 2hw excitation from *sd* shell with closure approximation



(0+2)hw in *sdpf* shell

dimension ~10^6

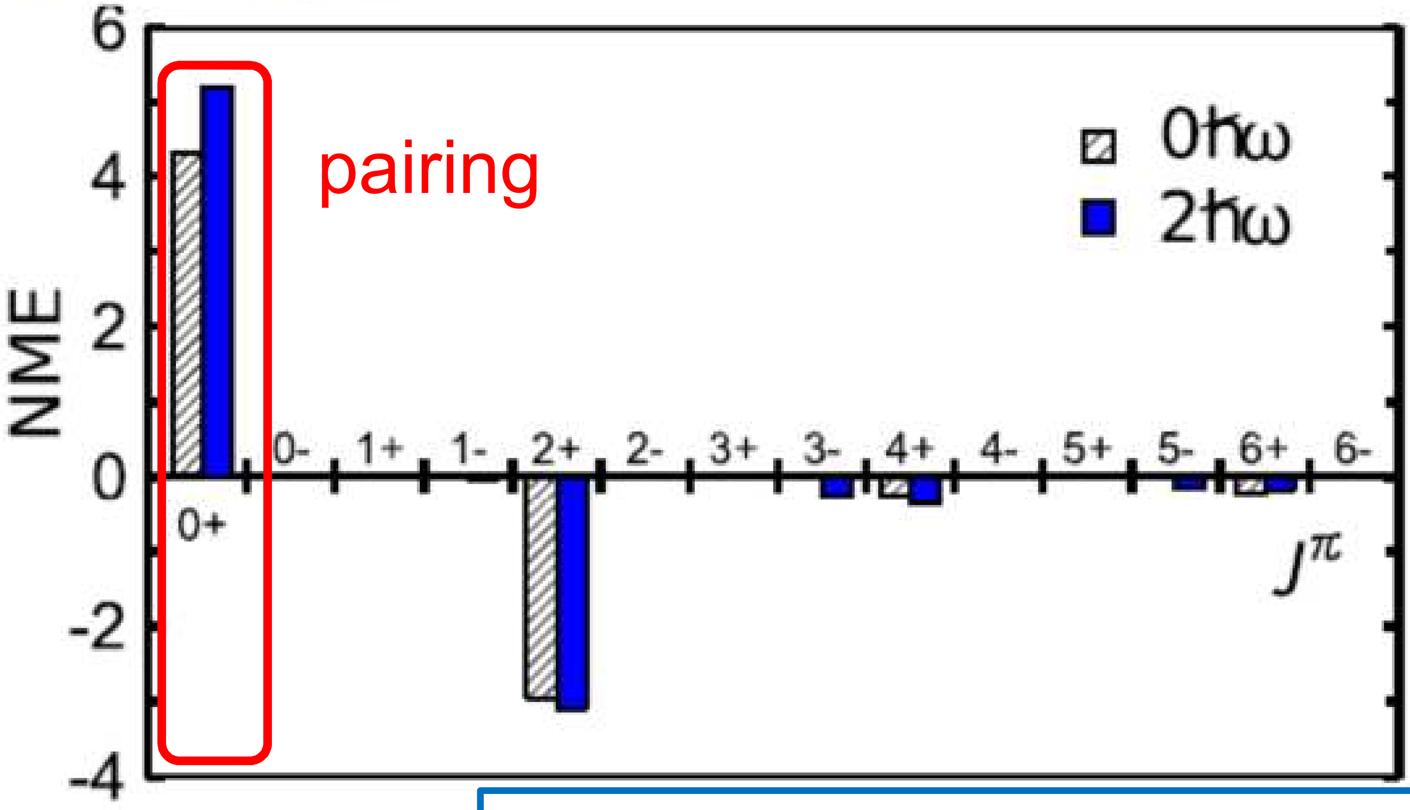
~10^9

Y. Iwata, N. Shimizu, T. Otsuka, Y. Utsuno, J. Menendez, M. Honma and T. Abe, Phys. Rev. Lett. **116**, 112502 (2016)

Why does the NME increases by extending the model space?

decompose this sum

$$M^{0\nu} = \sum_{J} \langle 0_f^+ | \sum_{i\le j,k\le l} M^J_{ij,kl}[(\hat{a}_i^\dagger \hat{a}_j^\dagger)^J (\hat{a}_k \hat{a}_l)^J]^0 | 0_i^+ \rangle$$



⇒ Talk by T. Otsuka, tomorrow

$0\nu\beta\beta$-decay NME and double Gamow-Teller (DGT) transition

- $0\nu\beta\beta$-decay nuclear matrix element (NME) with closure approximation

$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F + M^{0\nu}_T$$

$$\mathcal{O}_{GT} = \tau_{1-}\tau_{2-}\,(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\,H_{GT}(r, E_\kappa),$$

$$\mathcal{O}_F = \tau_{1-}\tau_{2-}\,H_F(r, E_\kappa),$$

$$\mathcal{O}_T = \tau_{1-}\tau_{2-}\,S_{12}\,H_T(r, E_\kappa),$$

neutrino potential

$$H_\alpha(r, E_\kappa) = \frac{2R}{\pi}\int_0^\infty \frac{f_\alpha(qr)h_\alpha(q^2)q\,dq}{q + E_\kappa - (E_i + E_f)/2}$$

N.B. GT-type NME is dominant

- DGT transition

$$\mathcal{O}^{\pm} = [\sigma t^{\pm} \otimes \sigma t^{\pm}]^{(\lambda)} \quad \lambda = 0, 2$$

Double Gamow-Teller transition

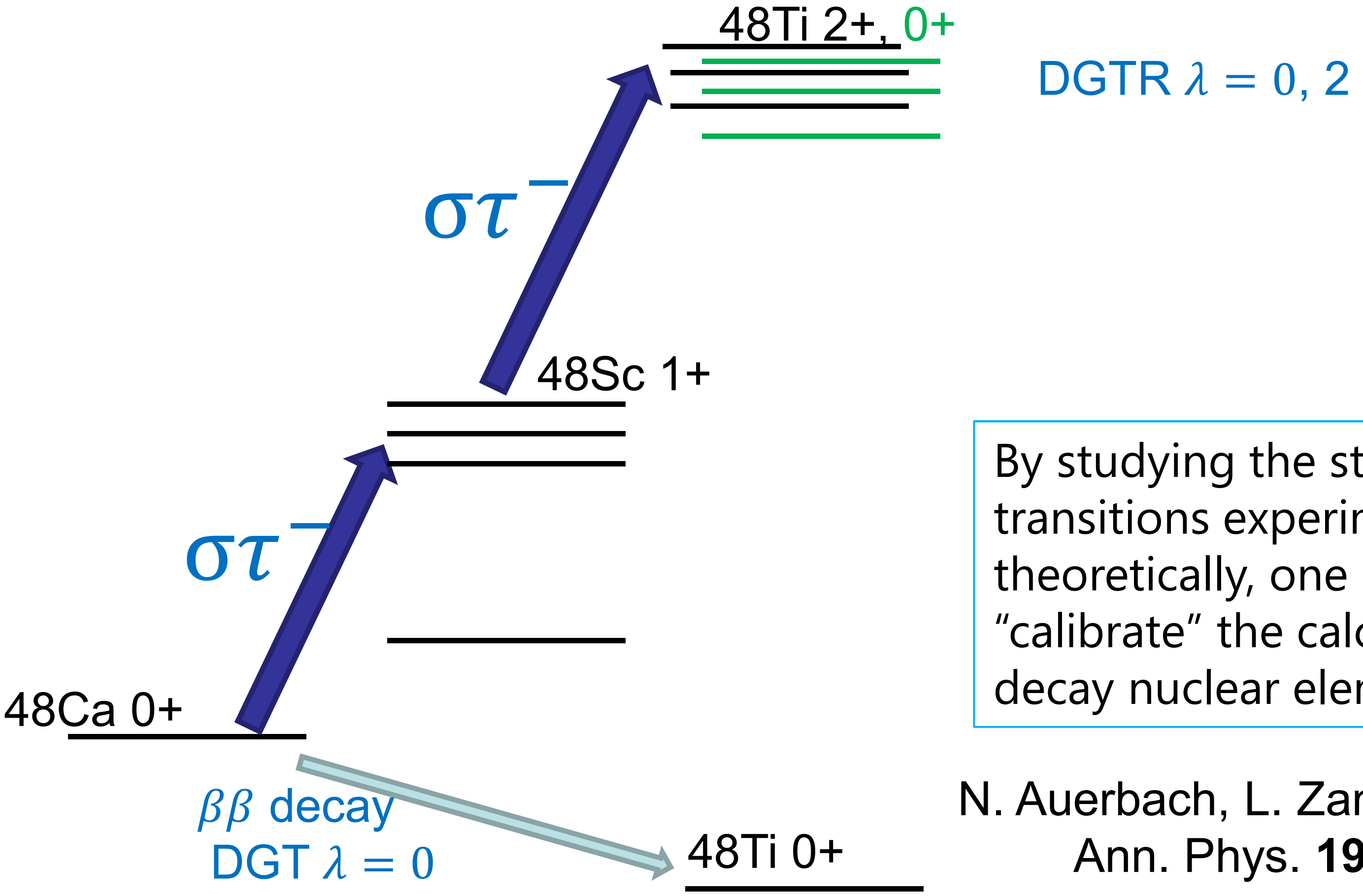
- DGT transition probability
  - $B(DGT;\lambda) = \frac{1}{2J_i+1}\left\langle J_f \middle|\middle| [\sigma t^- \otimes \sigma t^-]^{(\lambda)} \middle|\middle| J_i \right\rangle^2$

Theory: Auerbach 1989, Zheng 1989, Muto 1981, Sagawa 2016

- DGTR itself attracts attention as an exotic collective motion
- In the first half of this talk, focus on ^{48}Ca
  - one of $\beta\beta$ decay nuclei with large Q value
  - shell model calc. is a suitable theoretical method
  - DGT resonance (DGTR) was/will be measured experimentally

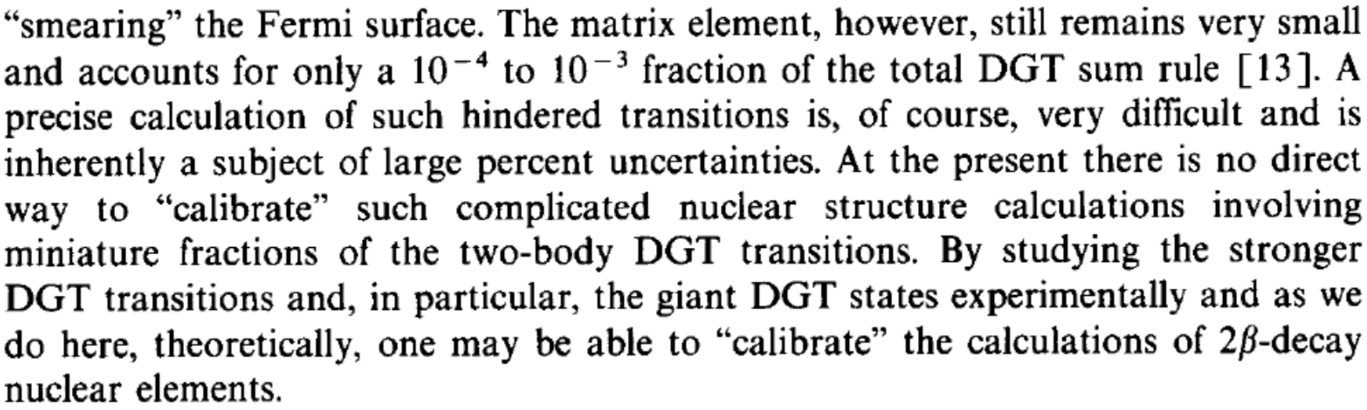
Takaki at RCNP/Osaka, plan: RIBF/RIKEN, INFN/Catania

c.f. Cappuzello et al., Euro Phys. J. A. 51 145 (2015)

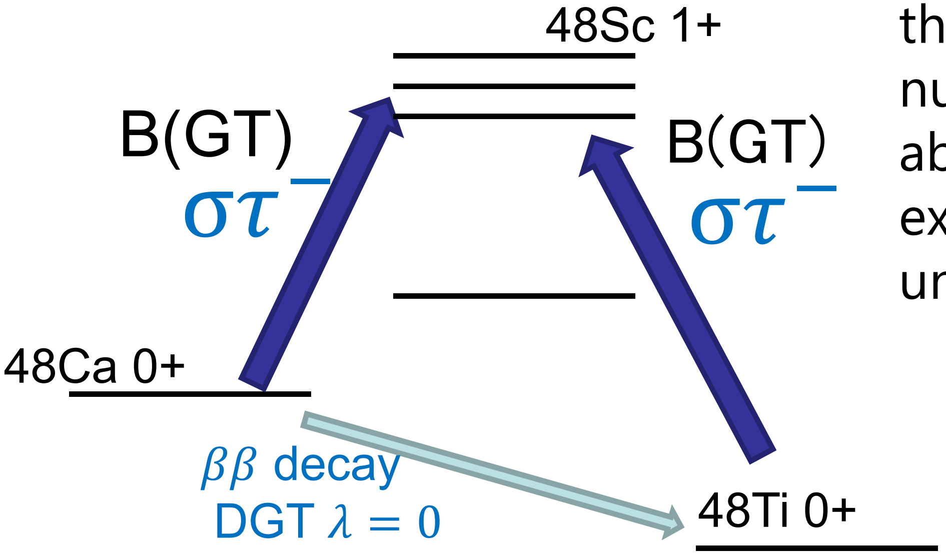


By studying the stronger DGT transitions experimentally (…), theoretically, one may be able to "calibrate" the calculations of 2β-decay nuclear elements.

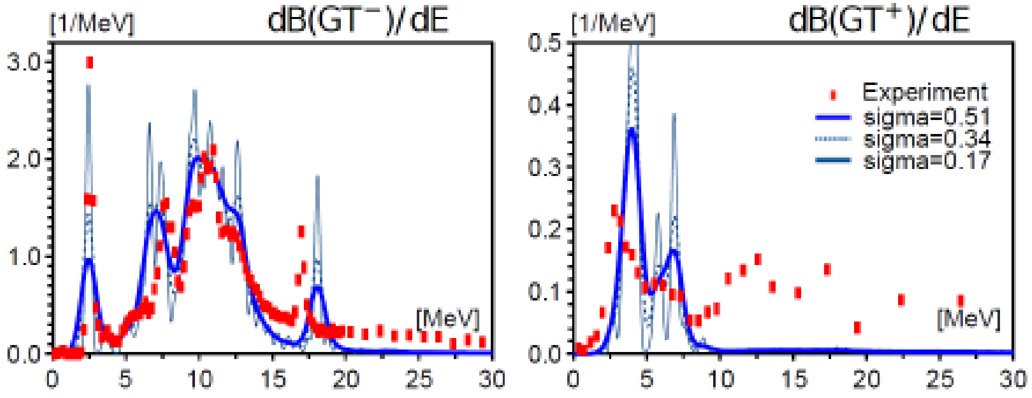
N. Auerbach, L. Zamick and D.C.Zheng
Ann. Phys. **192**, 197 (1989)



"smearing" the Fermi surface. The matrix element, however, still remains very small and accounts for only a 10^{-4} to 10^{-3} fraction of the total DGT sum rule [13]. A precise calculation of such hindered transitions is, of course, very difficult and is inherently a subject of large percent uncertainties. At the present there is no direct way to "calibrate" such complicated nuclear structure calculations involving miniature fractions of the two-body DGT transitions. By studying the stronger DGT transitions and, in particular, the giant DGT states experimentally and as we do here, theoretically, one may be able to "calibrate" the calculations of 2β-decay nuclear elements.



Both sides of the Gamow-Teller transitions are also useful for the “calibration” of the $\beta\beta$-decay nuclear elements. However only absolute values can be measured experimentally. (relative phase unknown)

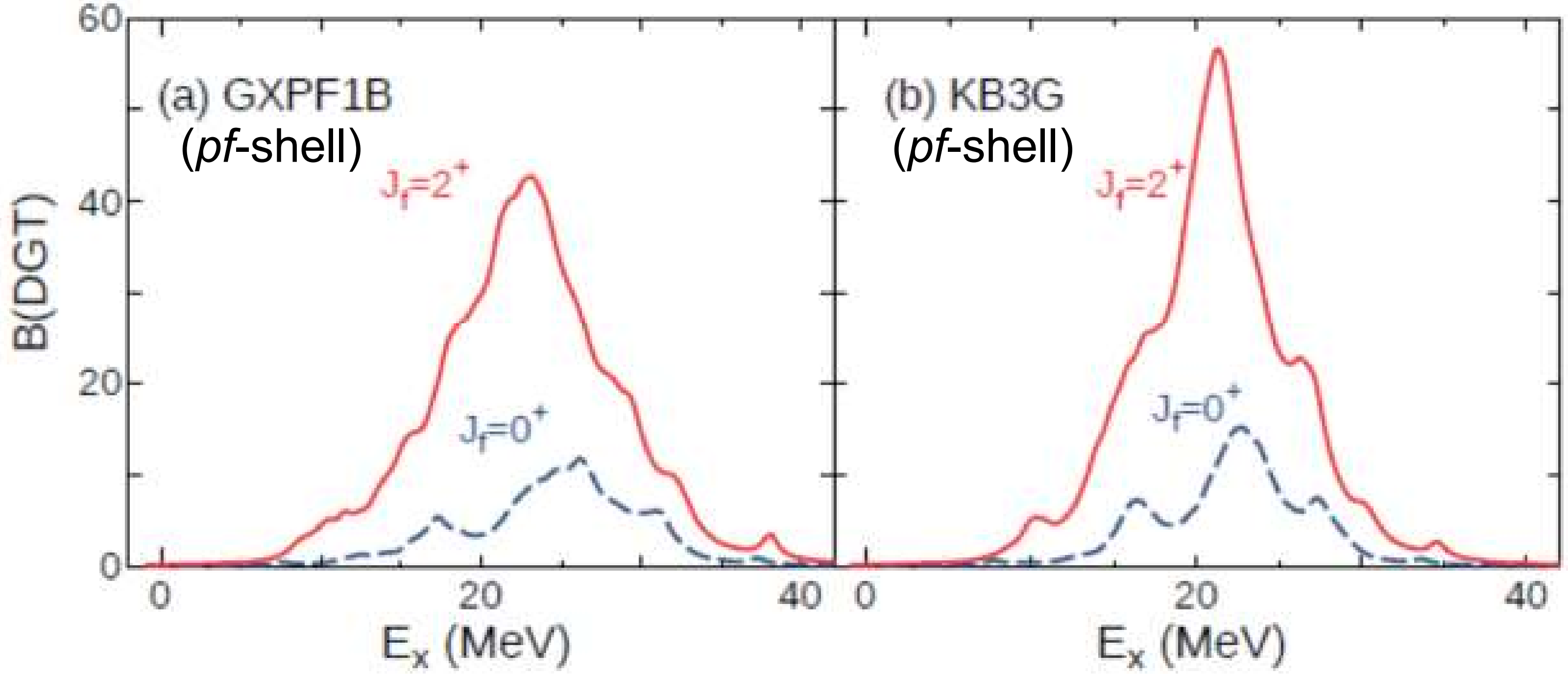


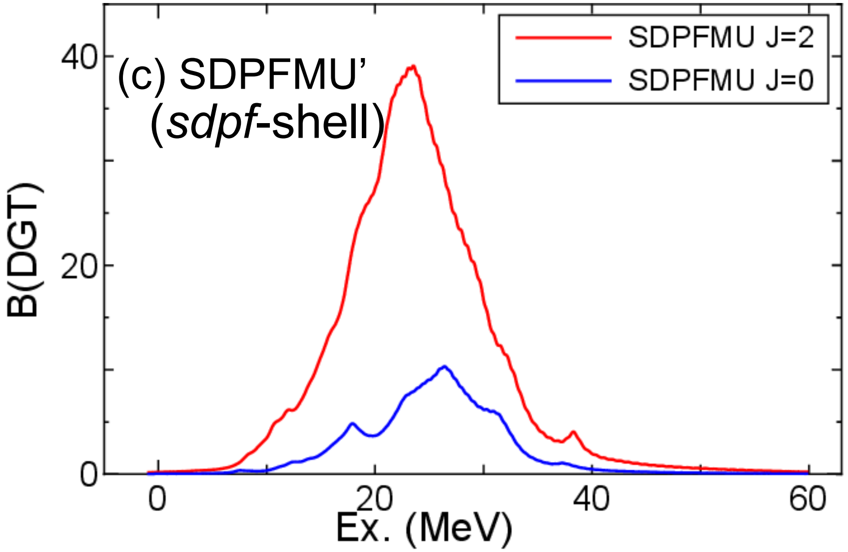
Red symbol : exp.
Blue line: shell-model calc.

Y. Iwata *et al.*, JPS Conf. Proc. **6**, 030057 (2015)
Exp. K. Yako *et al.*, Phys. Rev. Lett. **103**, 012503 (2009).

Double Gamow-Teller Resonance in ^{48}Ca by shell-model calculations

DGTR strength of ^{48}Ca by shell-model calc.





Lanczos strength function smeared out by Lorentzian $\Gamma = 1$ MeV

focus on GXPF1B and *pf* shell hereafter

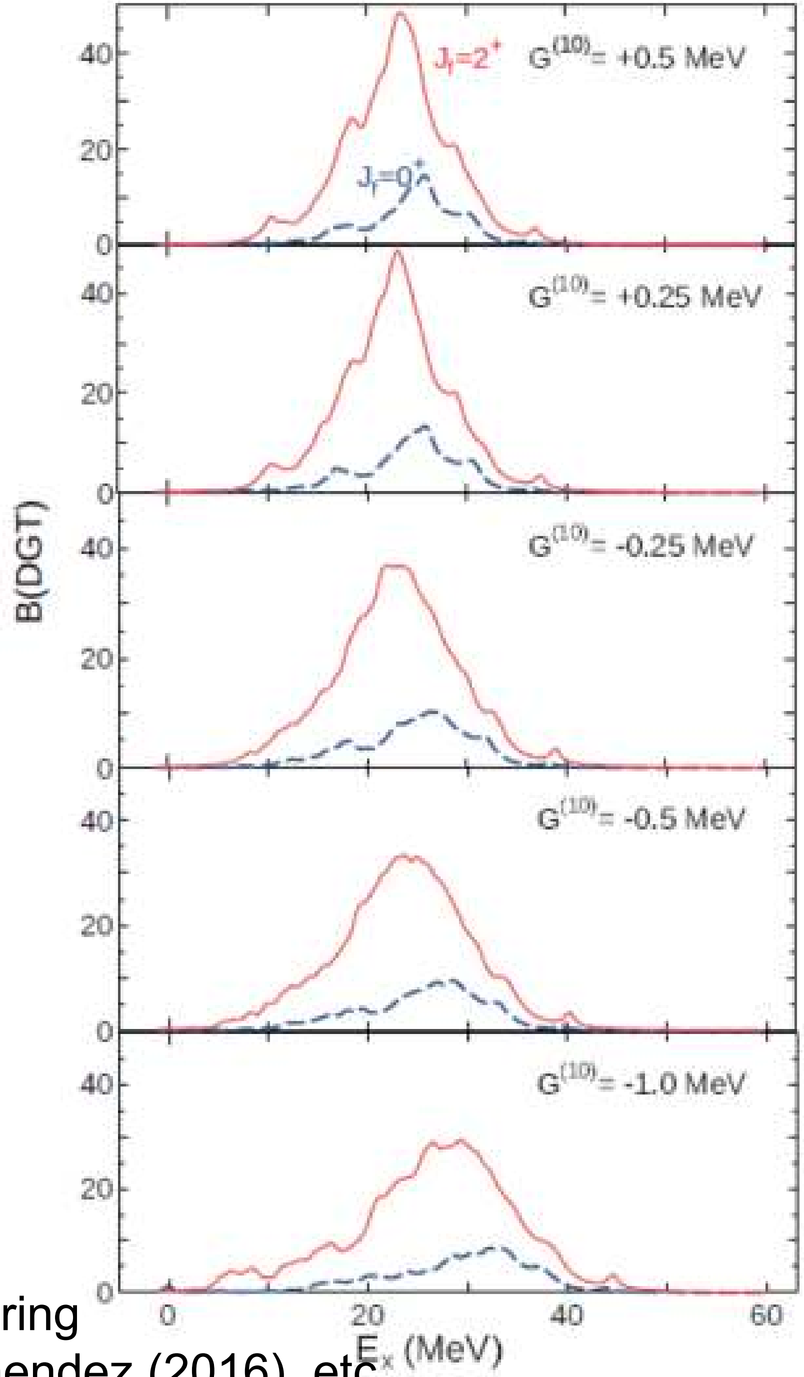
Dependence of isoscalar pairing

We artificially add
the isoscalar pairing interaction

$$H' = H + G^{10} P^{J=1,T=0}$$

GXPF1B

Isoscalar pairing int.



The NME is sensitive to the J=1
proton-neutron matrix element, or isoscalar pairing
Vogel (1986), Muto (1991), Rodin (2003) Menendez (2016), etc.

Isoscalar pairing dependence: $0\nu\beta\beta$ decay NME and DGT

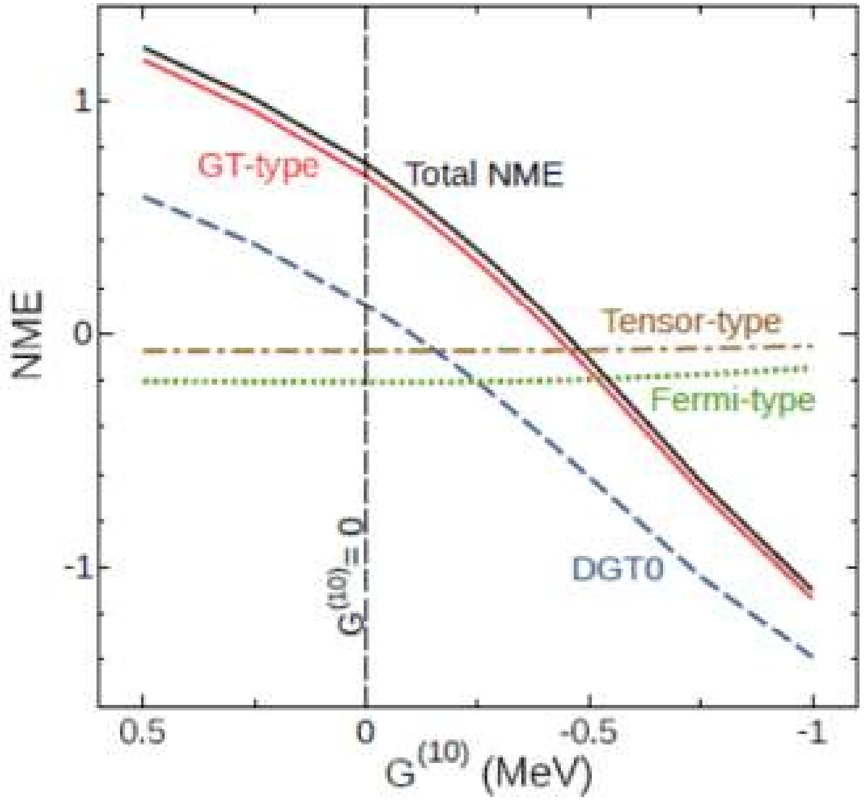
$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{F} + M^{0\nu}_{T}$$

$$M^{0\nu}_{GT} = \langle f|\sum_{jk} \tau_j\sigma_j\tau_k\sigma_k V_{GT}(r_{jk})|i\rangle$$

$$M^{0\nu}_{F} = \langle f|\sum_{jk} \tau_j\tau_k V_{F}(r_{jk})|i\rangle$$

$$M^{0\nu}_{T} = \langle f|\sum_{ik} \tau_j\tau_k S_{jk} V_{T}(r_{jk})|i\rangle,$$

$$M^{\mathrm{DGT}} = -\langle {}^{48}\mathrm{Ti}, 0_1^+||\mathcal{O}_{-}^{(\lambda=0)}||{}^{48}\mathrm{Ca}, 0_1^+\rangle$$



isoscalar pairing strength

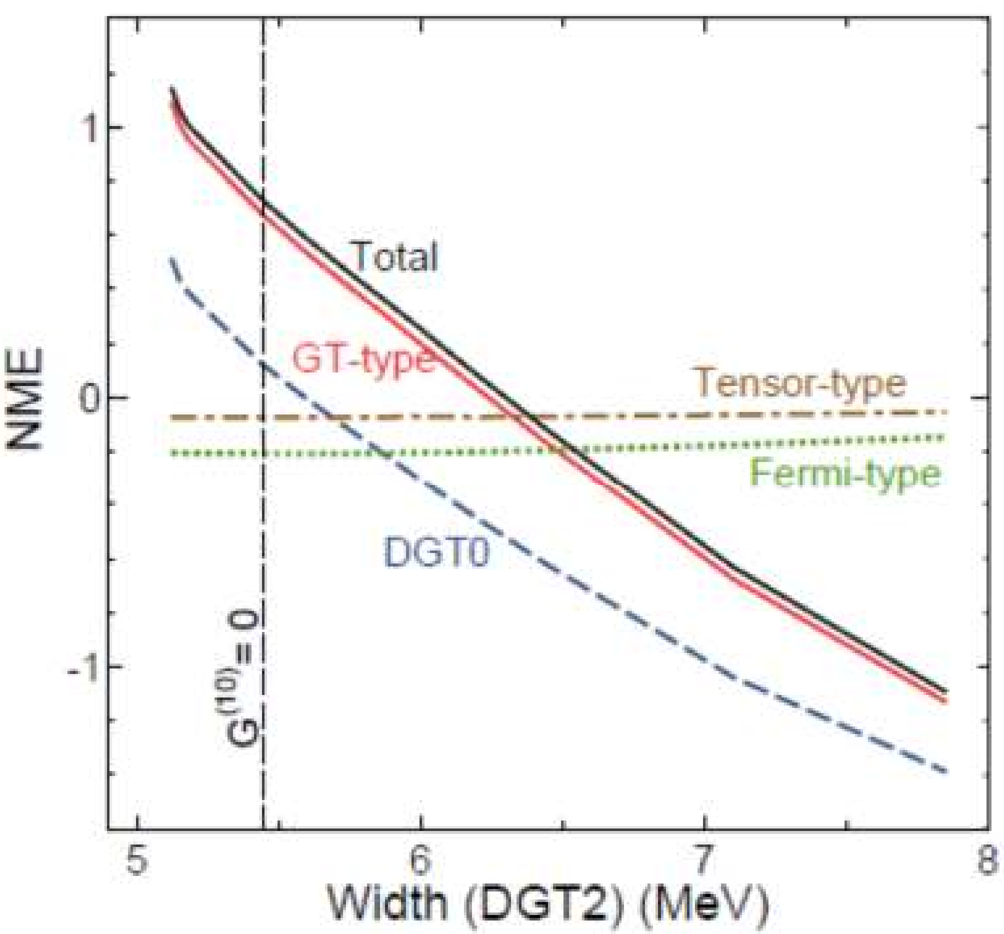
The NME is sensitive to the J=1 proton-neutron matrix element, or isoscalar pairing

Vogel (1986), Muto (1991), Rodin (2003) Menendez (2016), etc.

DGTR width vs NME

$$\sigma = \sqrt{\sum_f (E_f - E_c)^2 B(DGT2, f) / \sum_f B(DGT2, f)}$$

$$E_c = \sum_f E_f B(DGT2, f) / \sum_f B(DGT2, f).$$

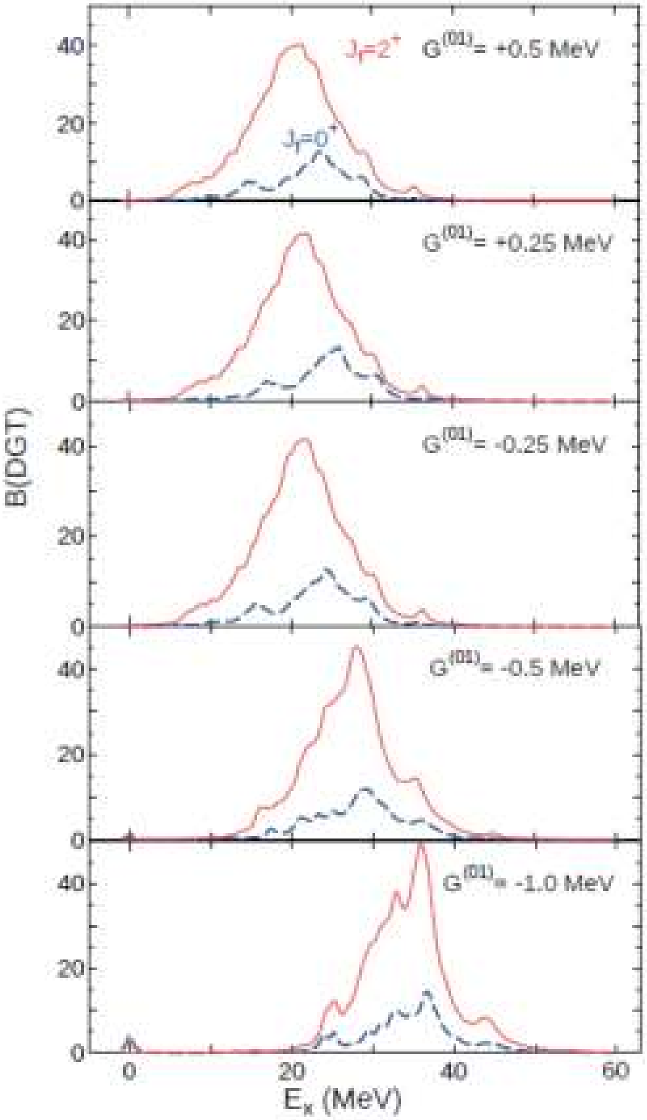


N. B. width is independent of quenching factor.

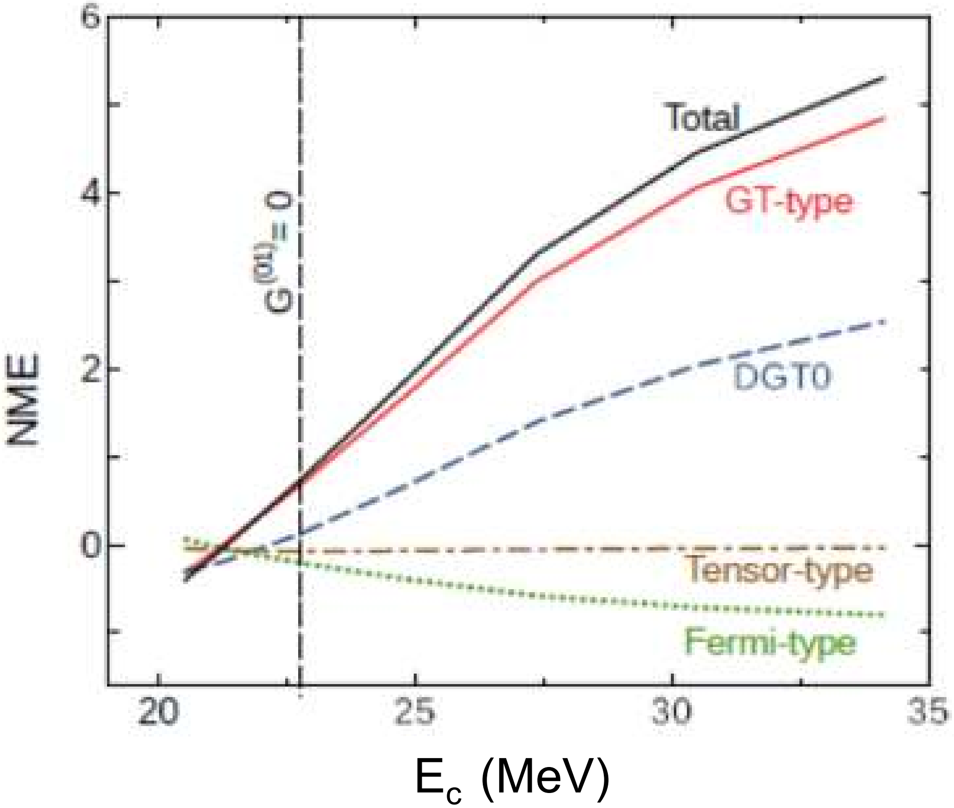
DGTR and Isovector pairing

$$H' = H + G^{01} P^{J=0,T=1}$$

$$E_c = \sum_f E_f B(DGT2,f) / \sum_f B(DGT2,f).$$



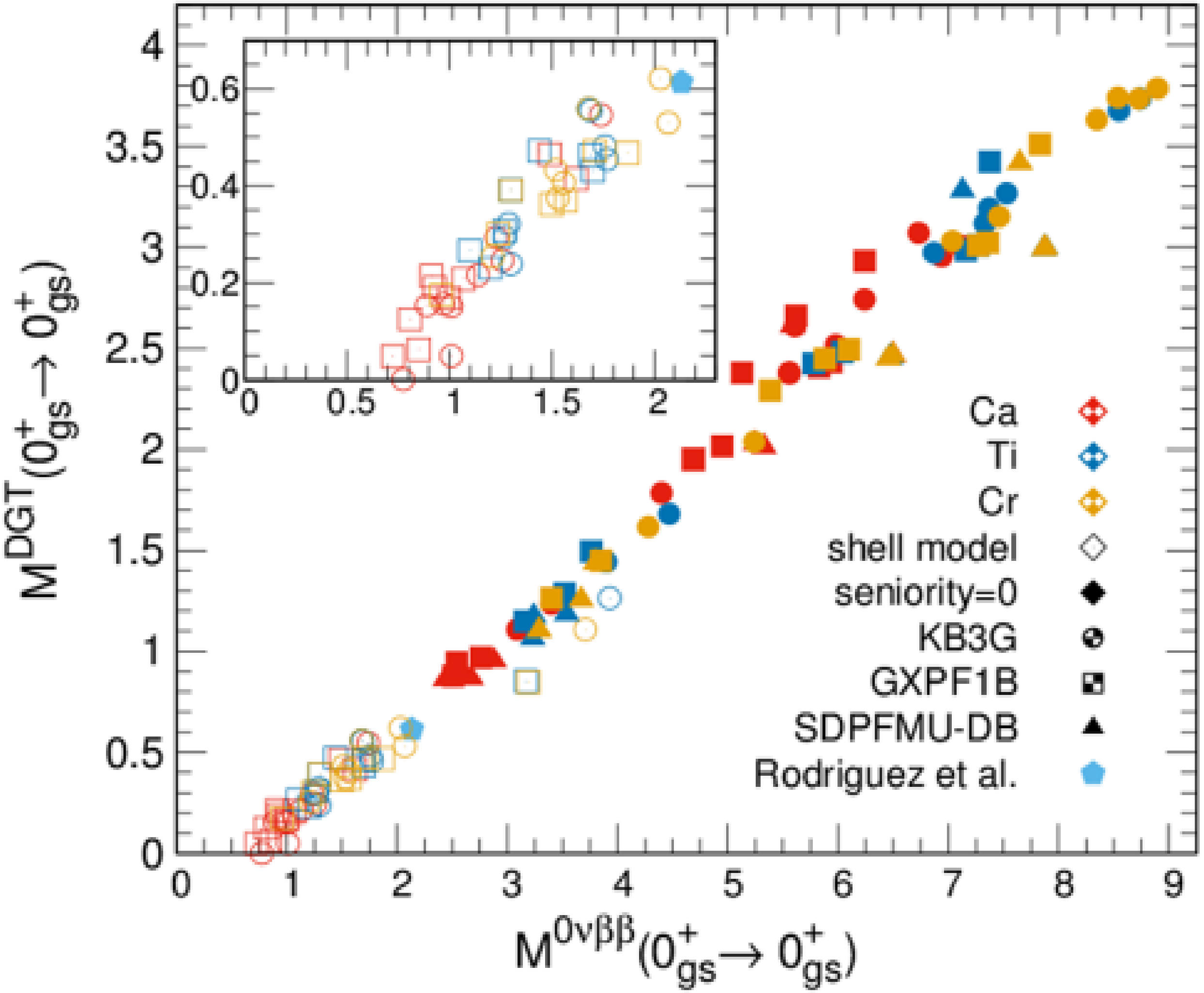
DGTR centroid energy vs. NME



DGT transition between the ground states

See the relation between DGT($\lambda = 0$) and $0\nu\beta\beta$ NME (initial and final states are common)

DGT($\lambda = 0$) transition vs. $0\nu\beta\beta$ decay NME



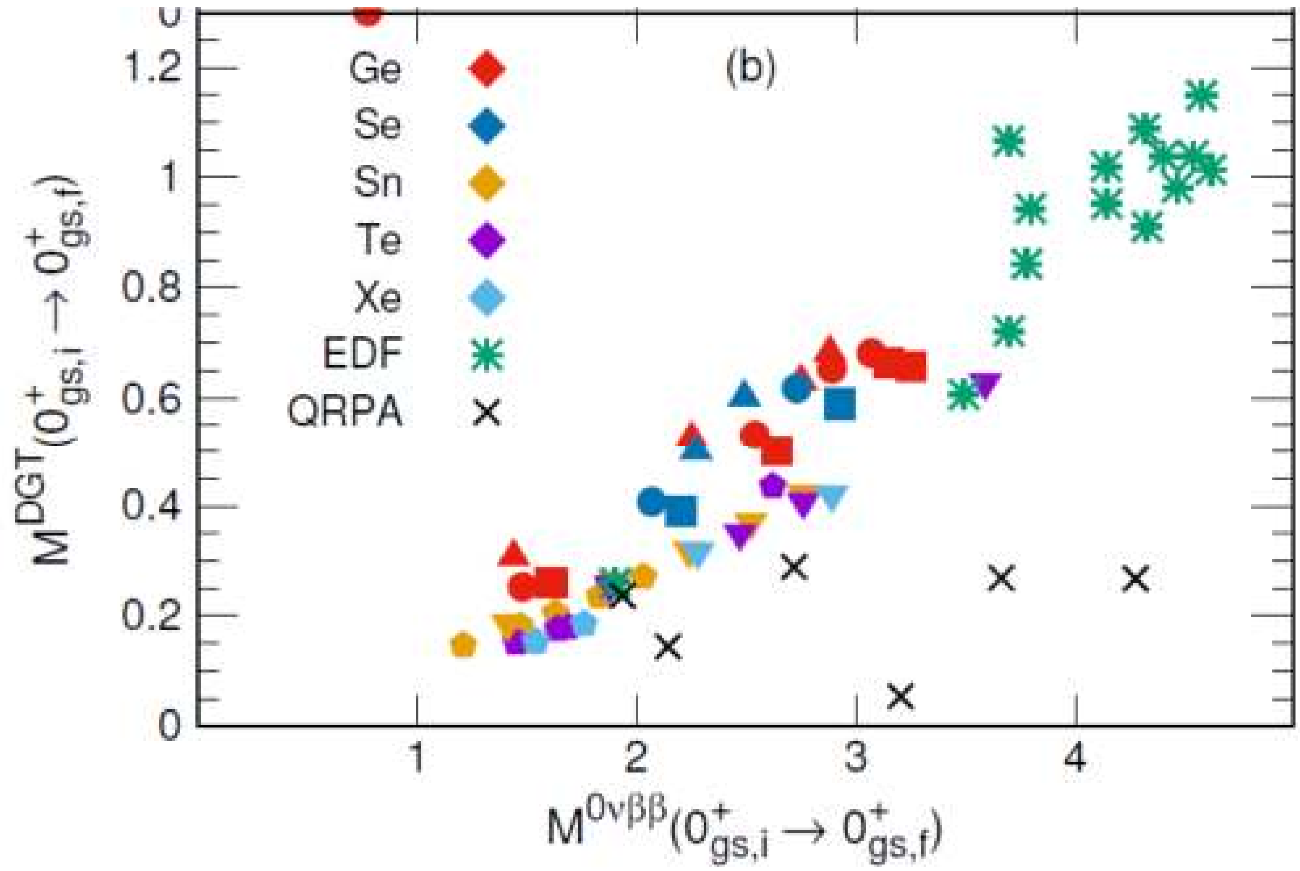
Ca, Ti, Cr isotopes
(N=22, 24, ..., 36)

SM: KB3G, GXPF1B,
SDPFMU-DB
interactions

filled symbol: SM w/
seniority-zero
approximation

EDF: ^{48}Ca Gogny+GCM
Rodriguez *et al.*,
PLB719 174 (2013)

DGT transition vs 0vbb decay NME



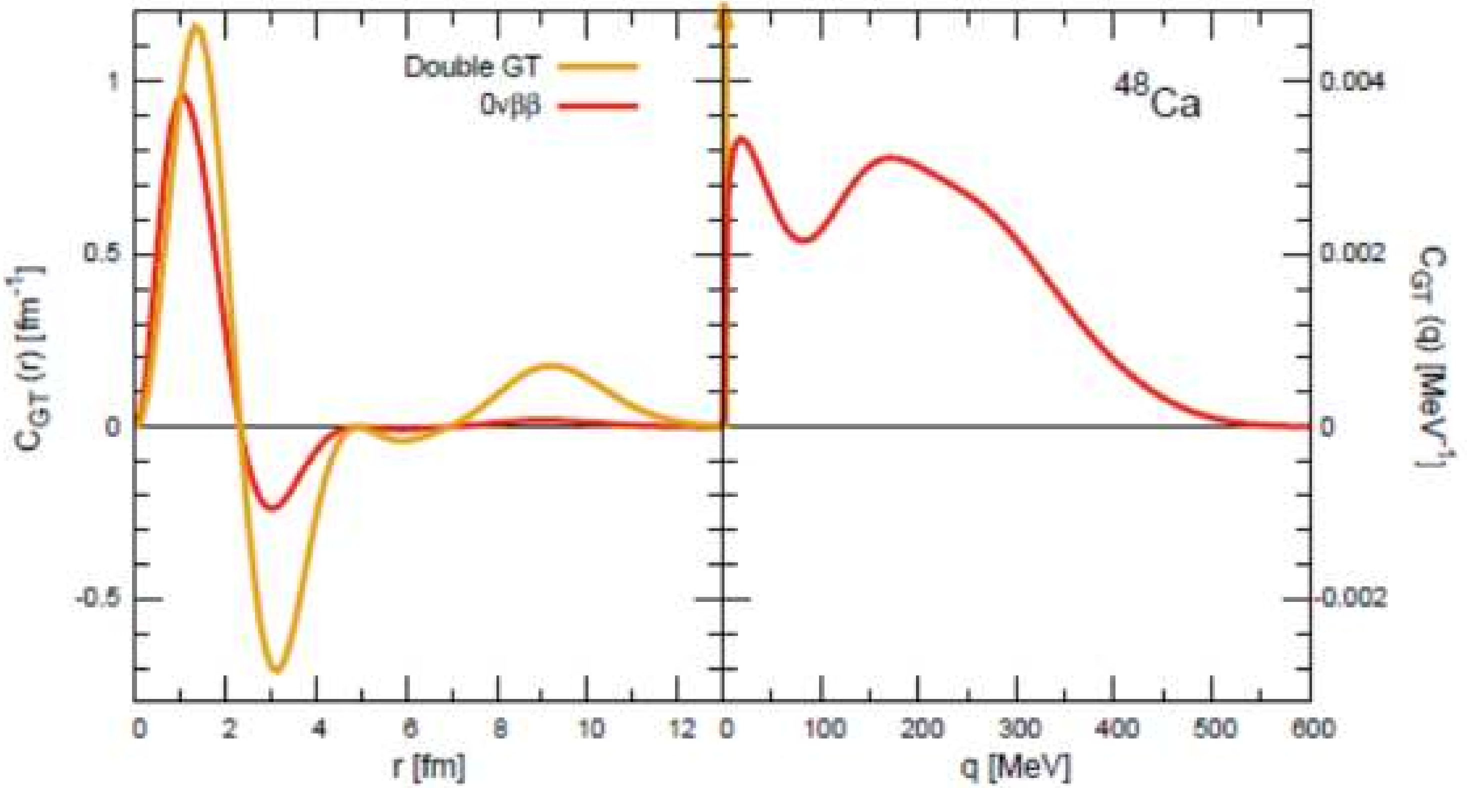
$^{74-82}$Ge, ^{74,76}Se, $^{124-132}$Sn, $^{128-130}$Te, ^{134,136}Xe

SM: shell model
GCN2850, jj44b,
JUN45,
GCN5082,QX

EDF: Gogny+GCM
Rodriguez *et al.*,
PLB719 174 (2013)

QRPA: AV18+G-matrix
F. Simkovic *et al.*,
PRC83, 015502 (2011).

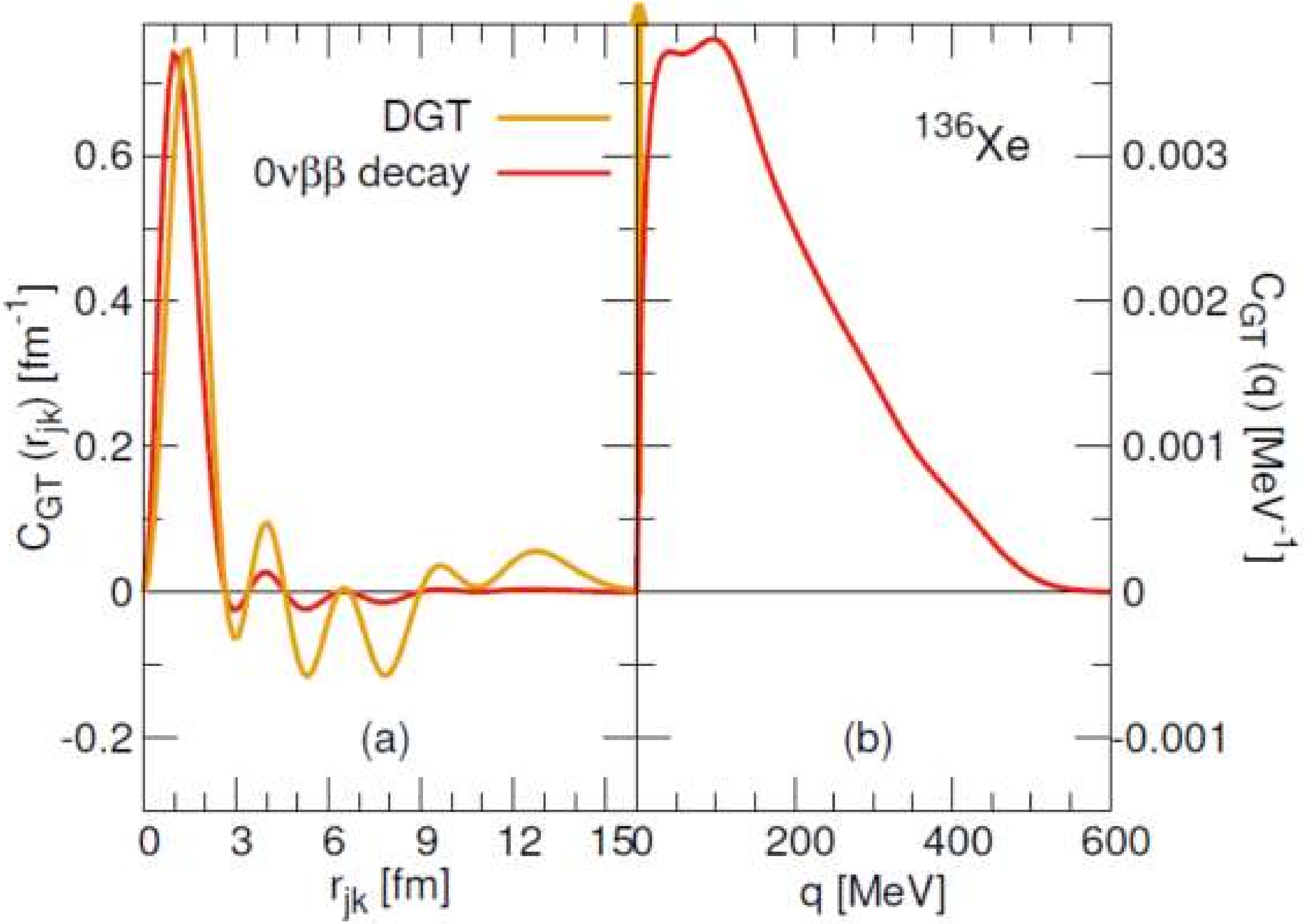
DGT and $0\nu\beta\beta$ NMEs: distance and momentum dependences : ^{48}Ca



$M = \int C(r_{ab}) dr_{ab}$ internucleon distance

$M = \int C(|\boldsymbol{q}|) d|\boldsymbol{q}|$ momentum transfer

DGT and $0\nu\beta\beta$ NMEs: distance and momentum dependences : ^{136}Xe

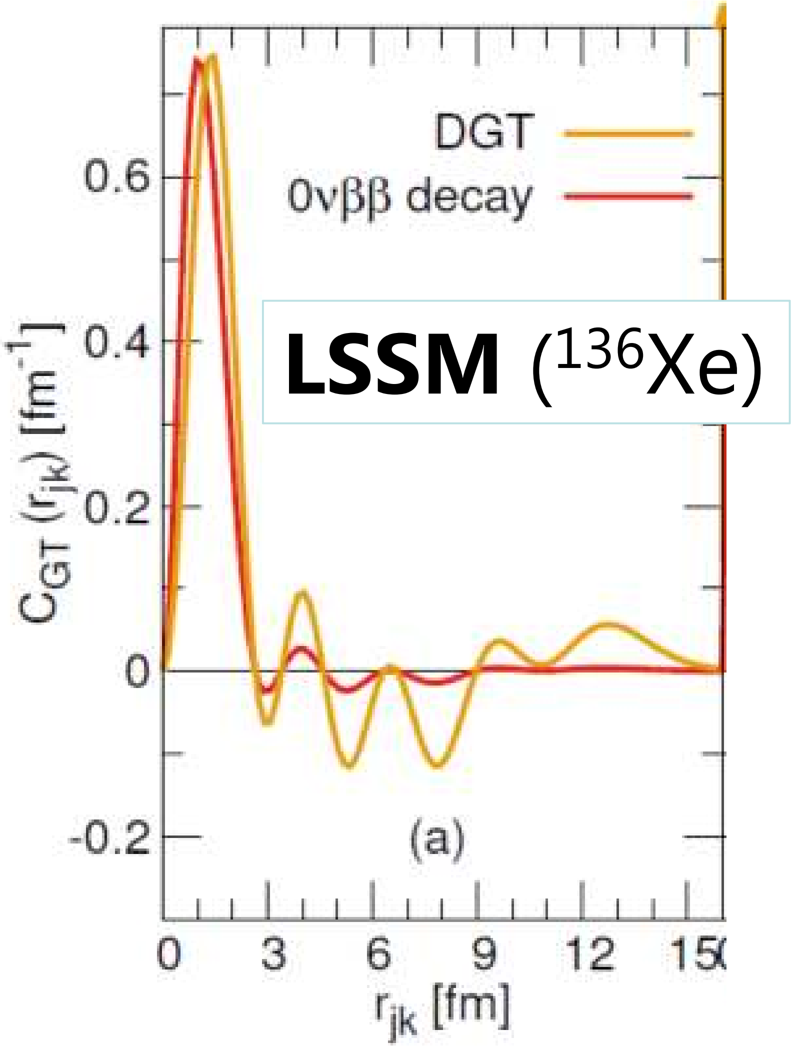


$M = \int C(r_{ab}) dr_{ab}$ $\quad$ $M = \int C(|\boldsymbol{q}|) d|\boldsymbol{q}|$

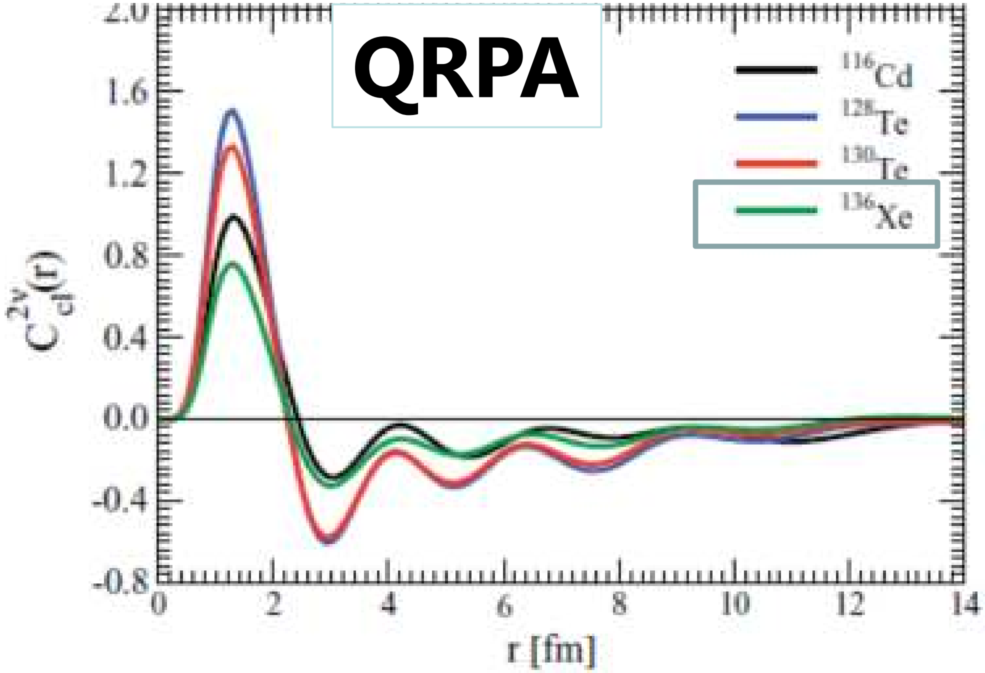
Why linear correlation between DGT and $0\nu\beta\beta$ NMEs?

- Similar dependence in distance dependence, contrary to momentum dependence
- Intermediate and long-range parts show cancellation, resulting small contribution to the NME. The short-range character dominates

- factorization: short-distance details decouple from long-distance dynamics
  - E. R. Anderson, S. K. Bogner, R. J. Furnstahl, and R. J. Perry, Phys. Rev. C **82**, 054001 (2010)
  - S. K. Bogner and D. Roscher, Phys. Rev. C **86**, 064304 (2012).



LSSM (^{136}Xe)



QRPA

NO cancellation
⇒ small M(DGT)

F. Simkovic *et al.*, PRC 83 015502 (2012)

Summary

- Using the shell-model calculations, double Gamow-Teller Resonance of ^{48}Ca and its relation to $0\nu\beta\beta$ NME is studied.
  - DGTR is correlated to the $0\nu\beta\beta$ NME via isovector and isoscalar pairing correlations.
- DGT and $0\nu\beta\beta$ NMEs show clear linear correlation. They are dominated by the short-range character.
- The HIDCX reaction may be useful to “calibrate” theoretical studies of $0\nu\beta\beta$ NME. Challenges remain: reaction theory of HIDCX, …