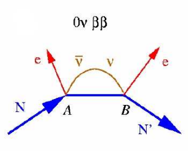
Towards reliable nuclear matrix elements for neutrinoless $\beta\beta$ decay

Frédéric Nowacki



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Université de Strasbourg

Nuclear physics and neutrinoless $\beta\beta$ decay

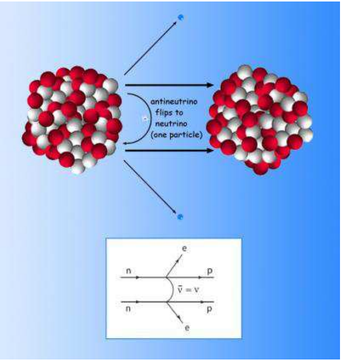
Neutrinos, dark matter studied in experiments using nuclei

Nuclear matrix elements depend on nuclear structure crucial to anticipate reach and fully exploit experiments

$0\nu\beta\beta$ decay: $[T^{0\nu}_{1/2}]^{-1} \propto |M^{0\nu}|^2 \langle m_\nu \rangle^2$

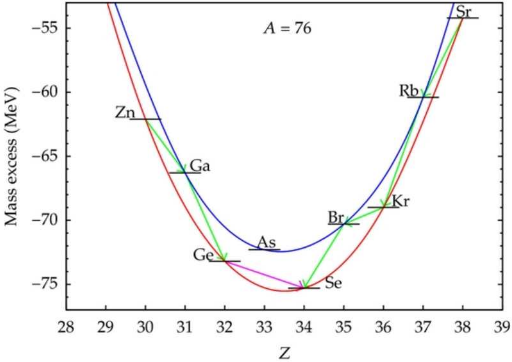
Dark matter: $\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} \propto |\sum_i c_i \zeta_i \mathcal{F}_i|^2$

$M^{0\nu}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor



Neutrinoless $\beta\beta$ decay

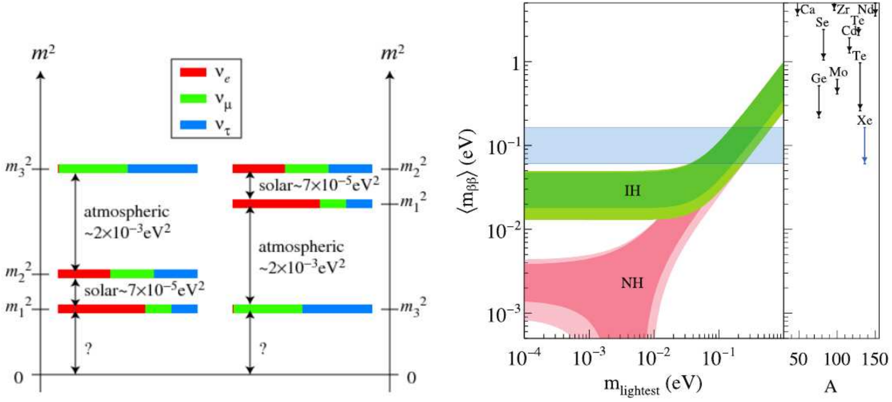
Lepton-number violation, Majorana nature of neutrinos
Second order process only observable in rare cases with β-decay energetically forbidden or hindered by ΔJ



Present best limits $T^{0\nu}_{1/2} \gtrsim 10^{25}$ y.:
^{76}Ge (GERDA, Majorana), ^{130}Te (CUORE), ^{136}Xe (EXO, KamLAND-Zen)

Next generation experiments: inverted hierarchy

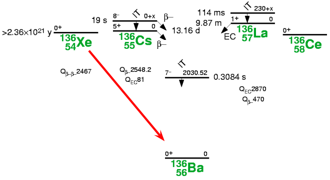
The decay lifetime is $[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} = G_{0\nu}|M^{0\nu}|^2\langle m_\nu^{\beta\beta}\rangle^2$
sensitive to absolute neutrino masses, $\langle m_\nu^{\beta\beta}\rangle = \sum_i U_{ei}^2 m_i$

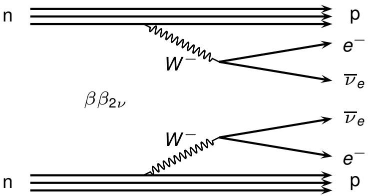


KamLAND-Zen, PRL117 082503 (2016)

Matrix elements needed to make sure next generation ton-scale experiments fully explore “inverted hierarchy”

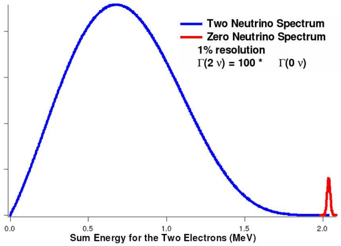
$\beta\beta$ decay



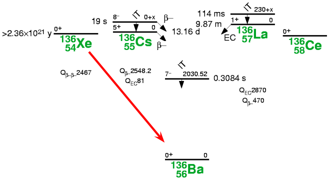


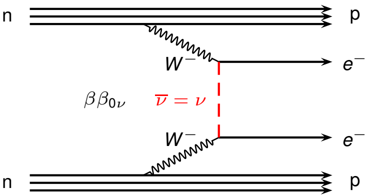
authorized by SM

Transition	$Q_{\beta\beta}$ (keV)	Abundance ($^{232}Th = 100$)
$^{110}Pd \rightarrow ^{110}Cd$	2013	12
$^{76}Ge \rightarrow ^{76}Se$	2040	8
$^{124}Sn \rightarrow ^{124}Te$	2288	6
$^{136}Xe \rightarrow ^{136}Ba$	2479	9
$^{130}Te \rightarrow ^{130}Xe$	2533	34
$^{116}Cd \rightarrow ^{116}Sn$	2802	7
$^{82}Se \rightarrow ^{82}Kr$	2995	9
$^{100}Mo \rightarrow ^{100}Ru$	3034	10
$^{96}Zr \rightarrow ^{96}Mo$	3350	3
$^{150}Nd \rightarrow ^{150}Sm$	3667	6
$^{48}Ca \rightarrow ^{48}Ti$	4271	0.2



$\beta\beta$ decay





violation of leptonic number conservation

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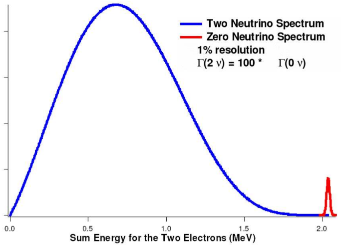

$(\beta\beta)_{0\nu}$ decay

Specificity of $(\beta\beta)_{0\nu}$:

NO EXPERIMENTAL DATA !!!

prediction for m_ν very difficult
easier for m_ν(A)/m_ν(A')

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What is the best isotope to observe $(\beta\beta)_{0\nu}$ decay ?

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What is the best isotope to observe $(\beta\beta)_{0\nu}$ decay ?

What is the influence of the structure of the nucleus on $(\beta\beta)_{0\nu}$ matrix elements ?

Calculating nulear matrix elements

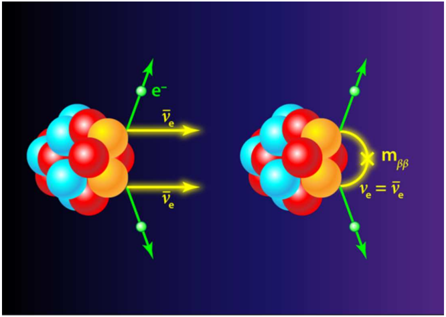
Nuclear matrix elements needed to study fundamental symmetries

$$\langle \text{ Final } |\mathcal{L}_{leptons-nucleus}| \text{ Initial } \rangle = \langle \text{ Final } |dx\, j^{\mu}(x)J_{\mu}(x)| \text{ Initial } \rangle$$

- Nuclear structure calculation of the initial and final states:

Shell model Retamosa, Caurier, FN...
Energy-density functional Rodriguez, Yao...
QRPA Vogel, Faesller, Simkovic, Suhonen...
Interacting boson model Iachello, Barea...
Ab Initio many-body methods

Green's Function MC, Coupled-Cluster, IM-SRG



- Lepton-nucleus interaction:

Study hadronic current in nucleus: phenomenological approaches, effective theory of QCD

Two neutrinos mode

The theoretical expression of the half-life of the 2ν mode can be written as:

$$[T_{1/2}^{2\nu}]^{-1} = G_{2\nu}|M_{GT}^{2\nu}|^2,$$

with

$$M_{GT}^{2\nu} = \sum_m \frac{\langle 0_f^+||\vec{\sigma}t_-||1_m^+\rangle\langle 1_m^+||\vec{\sigma}t_-||0_i^+\rangle}{E_m + E_0}$$

- $G_{2\nu}$ contains the phase space factors and the axial coupling constant g_A

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- to quench or not to quench ? $(\sigma\tau_{eff.})$

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- $G_{2\nu}$ contains the phase space factors and the axial coupling constant g_A
- summation over intermediate states
- to quench or not to quench ? $(\sigma\tau_{eff.})$
- does a good 2ν ME guarantee a good 0ν ME ?

$(\beta\beta)_{2\nu}$ structure function

$$M_{GT}^{2\nu} = \sum_m \frac{\langle \ 0_f^+ \ ||\vec{\sigma} t_-||1_m^+\rangle\langle 1_m^+||\vec{\sigma} t_-|| \ 0_i^+ \ \rangle}{E_m + E_0}$$

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- calculate the final and initial states

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- at iteration N, N 1^+ states in the intermediate nucleus, with excitation energies E_m

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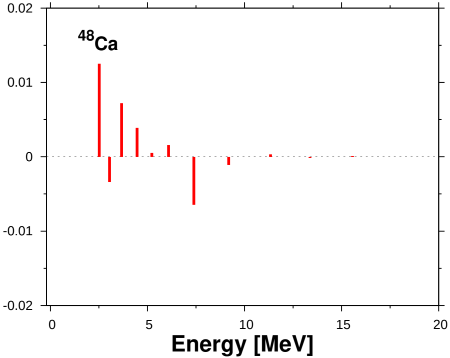
$$M^{2\nu}_{GT} = \sum_m \frac{\langle\ 0^+_f\ ||\vec{\sigma}t_-||1^+_m\rangle\langle 1^+_m||\vec{\sigma}t_-||\ 0^+_i\ \rangle}{E_m + E_0}$$

Calculation in three steps:

- calculate the final and initial states
- generate the doorway states $\vec{\sigma}t_-|0^+_i\rangle$ and $\vec{\sigma}t_+|0^+_f\rangle$
- take a doorway and use of Lanczos Strength Function method:

• at iteration N, N 1^+ states in the intermediate nucleus, with excitation energies E_m
• overlap with the other doorway, enter energy denominators and add up the N contributions

2ν half-lifes



2ν strength function in ^{48}Ca, ^{130}Te and ^{136}Xe

Parent nuclei	^{48}Ca	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
$T^{2\nu}_{1/2}(g.s.)$ th.	$3.7E19$	$1.15E21$	$3.4E19$	$4E20$	$6E20$
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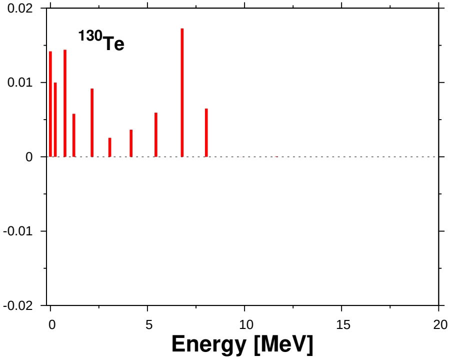

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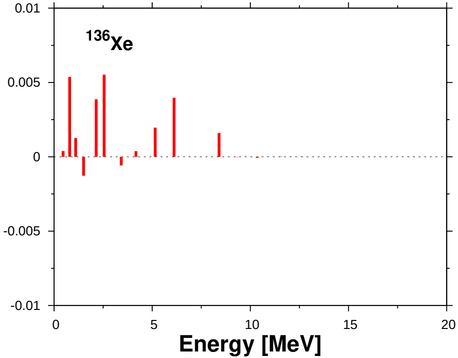

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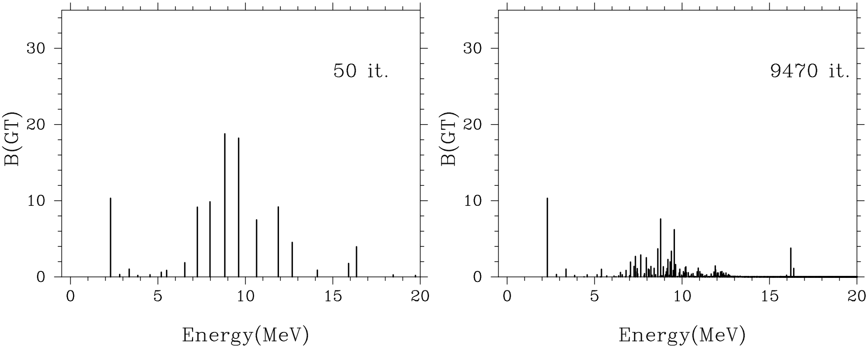
Evolution of Strength Distribution

GT Strength in ^{48}Sc



Evolution of Strength Distribution

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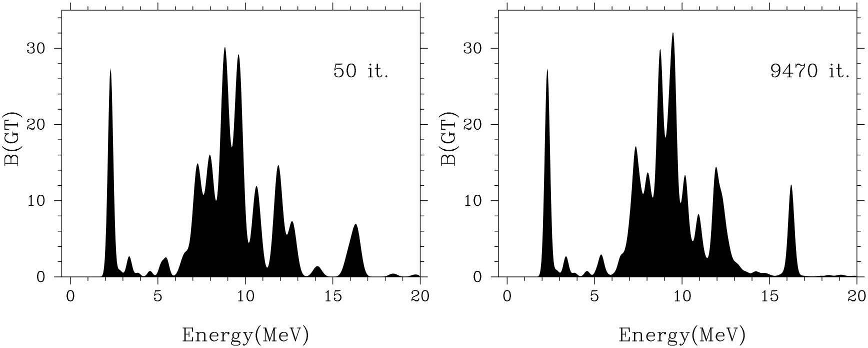
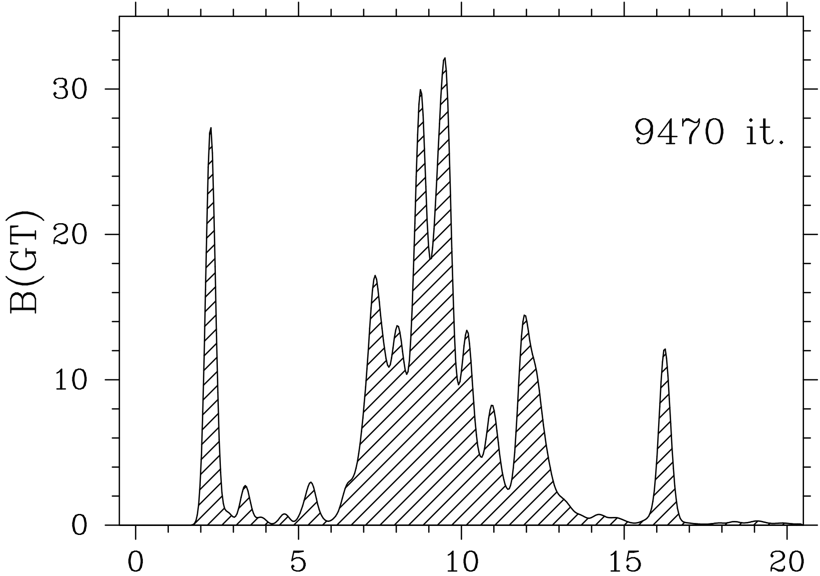


$^{48}Ca(p,n)^{48}Sc$ Strength Function



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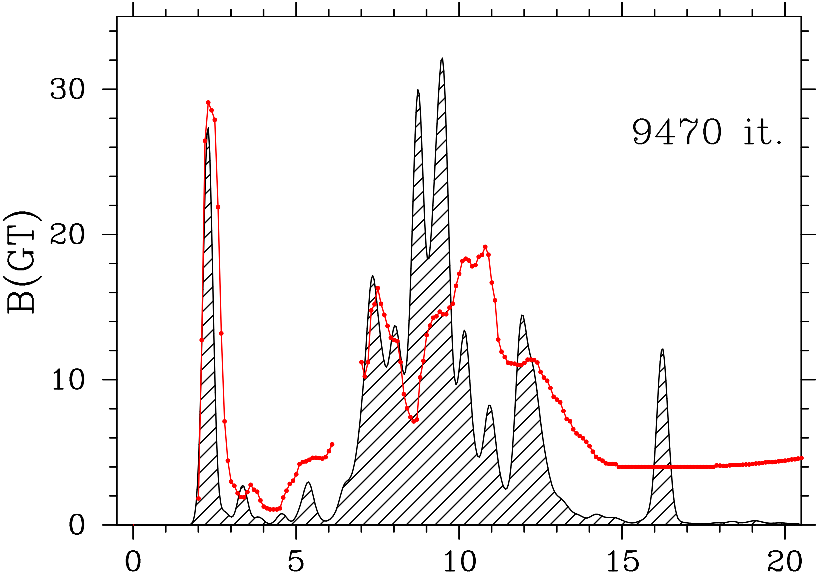
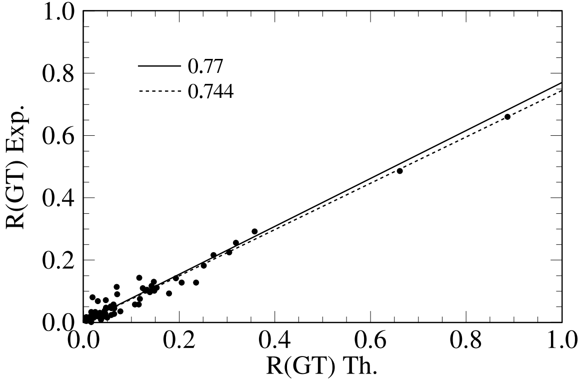


Quenching of GT operator in the *pf*-shell

Nucleus	Uncorrelated	Correlated		Expt.
		Unquenched	$Q = 0.74$	
^{51}V	5.15	2.42	1.33	1.2 ± 0.1
^{54}Fe	10.19	5.98	3.27	3.3 ± 0.5
^{55}Mn	7.96	3.64	1.99	1.7 ± 0.2
^{56}Fe	9.44	4.38	2.40	2.8 ± 0.3
^{58}Ni	11.9	7.24	3.97	3.8 ± 0.4
^{59}Co	8.52	3.98	2.18	1.9 ± 0.1
^{62}Ni	7.83	3.65	2.00	2.5 ± 0.1

Quenching of GT strength in the *pf*-shell



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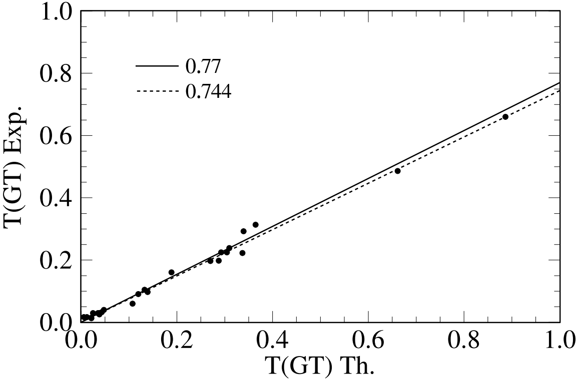
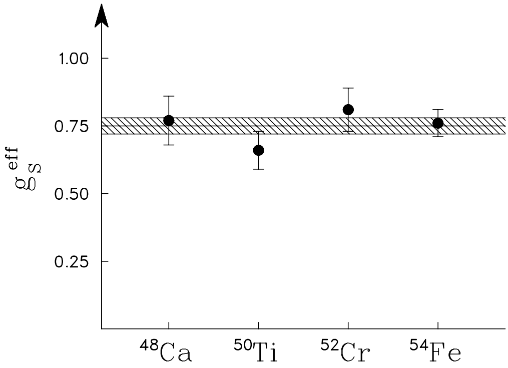


Quenching of M1 operator in the *pf*-shell

KB3 interaction



Neumann-Cosel et al.

Phys. Lett. **B433** 1 (1998)

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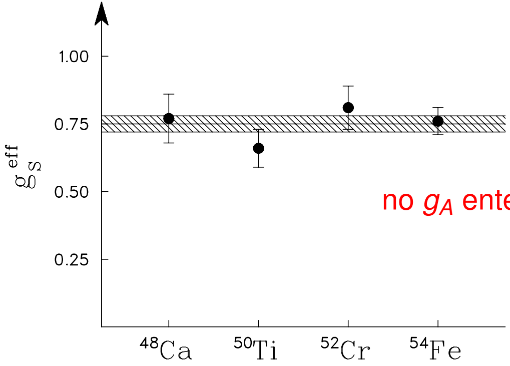

no g_A entering in the operator !

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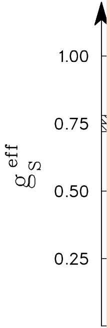
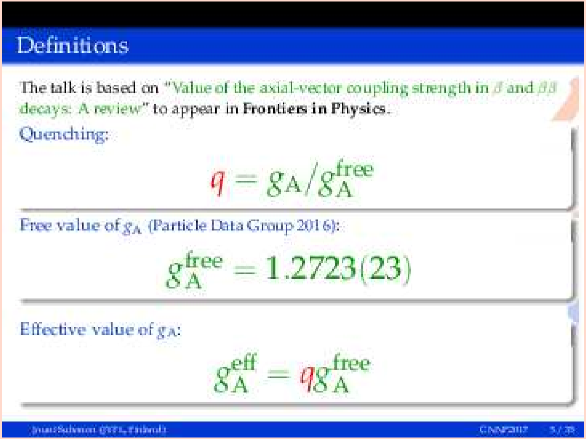



Definitions

The talk is based on "Value of the axial-vector coupling strength in β and $\beta\beta$ decays: A review" to appear in **Frontiers in Physics**.

Quenching:

$$q = g_{\rm A}/g_{\rm A}^{\rm free}$$

Free value of $g_{\rm A}$ (Particle Data Group 2016):

$$g_{\rm A}^{\rm free} = 1.2723(23)$$

Effective value of $g_{\rm A}$:

$$g_{\rm A}^{\rm eff} = q g_{\rm A}^{\rm free}$$

From J. Suhonen, CNNP 2017, Catania

Ne

Phys. Lett. **B433** 1 (1998)

Quenching of GT operator in the *pf*-shell

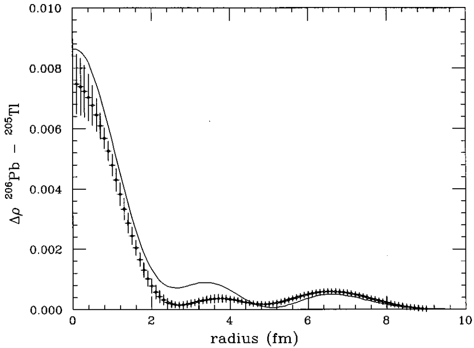
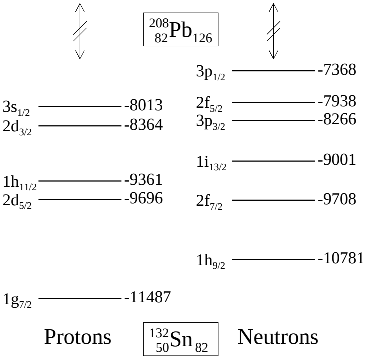


FIG. 3. Density difference between ^{206}Pb and ^{205}Tl. The experimental result of Cavendon *et al.* (1982) is given by the error bars; the prediction obtained using Hartree-Fock orbitals with adjusted occupation numbers is given by the curve. The systematic shift of 0.0008 fm^{-3} at $r \lesssim 4$ fm is due to deficiencies of the calculation in predicting the core polarization effect.

V. R. Pandharipande, I. Sick and P. K. A. deWitt Huberts, Rev. mod. Phys. **69** (1997) 981



Quenching of GT operator in the *pf*-shell

If we write

$$|\hat{i}\rangle = \alpha|0\hbar\omega\rangle + \sum_{n\neq 0} \beta_n |n\hbar\omega\rangle,$$

$$|\hat{f}\rangle = \alpha'|0\hbar\omega\rangle + \sum_{n\neq 0} \beta'_n |n\hbar\omega\rangle$$

then

$$\langle \hat{f} \parallel \mathcal{T} \parallel \hat{i}\rangle^2 = \left(\alpha\alpha' T_0 + \sum_{n\neq 0} \beta_n \beta'_n T_n\right)^2,$$

- $n \neq 0$ contributions negligible
- $\alpha \approx \alpha'$

→ projection of the physical wavefunction in the $0\hbar\omega$ space is $Q \approx \alpha^2$

→ transition quenched by Q^2

Renormalisation of the GT operator by MBPT

PHYSICAL REVIEW C **95**, 064324 (2017)

Calculation of Gamow-Teller and two-neutrino double-β decay properties for ^{130}Te and ^{136}Xe with a realistic nucleon-nucleon potential

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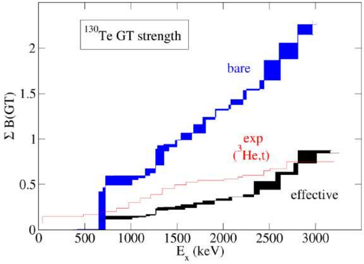

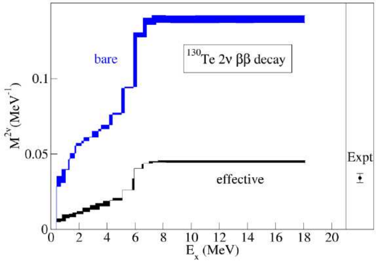

Renormalisation of the GT by Many-Body Perturbation Theory

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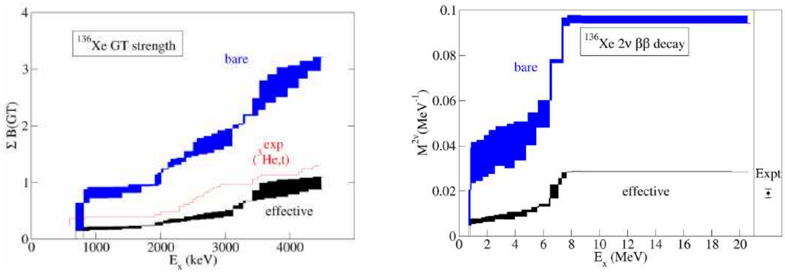

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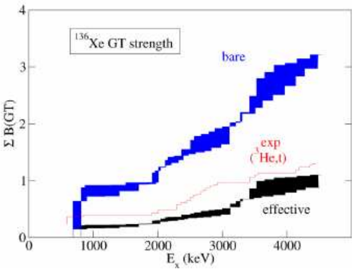
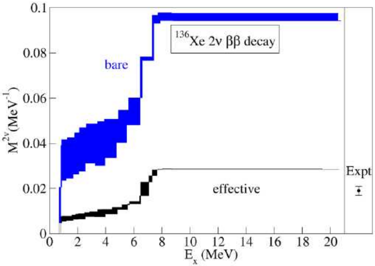
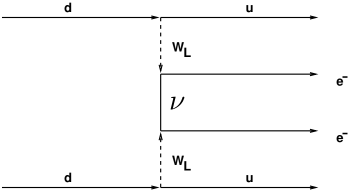




Renormalisation of the GT by Many-Body Perturbation Theory
Further step, apply MBPT to Neutrinoless operator

Neutrinoless mode:

Exchange of a light neutrino, only left-handed currents



The theoretical expression of the half-life of the 0ν mode can be written as:

$$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} = G_{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$

Neutrinoless mode:

CLOSURE APPROXIMATION then

$$\langle \Psi_f || \mathcal{O}^{(K)} || \Psi_i \rangle \quad \text{with} \quad \mathcal{O}^{(K)} = \sum_{ijkl} W_{ijkl}^{\lambda,K} \left[(a_i^\dagger a_j^\dagger)^\lambda (\tilde{a}_k \tilde{a}_l)^\lambda \right]^K$$

Neutrinoless mode:

CLOSURE APPROXIMATION then

$$\langle \Psi_f || \mathcal{O}^{(K)} || \Psi_i \rangle \quad \text{with} \quad \mathcal{O}^{(K)} = \sum_{ijkl} W^{\lambda,K}_{ijkl} \left[(a^\dagger_i a^\dagger_j)^\lambda (\tilde{a}_k \tilde{a}_l)^\lambda \right]^K$$

two-body operator

Neutrinoless mode:

CLOSURE APPROXIMATION then

$$\langle \Psi_f || \mathcal{O}^{(K)} || \Psi_i \rangle \quad \text{with} \quad \mathcal{O}^{(K)} = \sum_{ijkl} W_{ijkl}^{\lambda,K} \left[(a_i^\dagger a_j^\dagger)^\lambda (\tilde{a}_k \tilde{a}_l)^\lambda \right]^K$$

two-body operator

We are left with a "standard" nuclear structure problem

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - (\frac{g_V}{g_A})^2 M_F^{(0\nu)} - M_T^{(0\nu)}$$

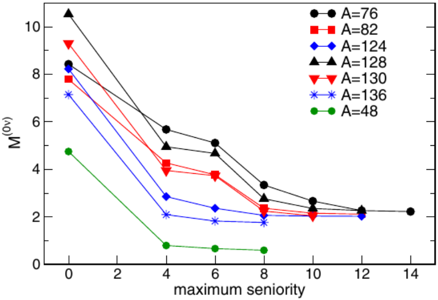
SM results for $(\beta\beta)_{0\nu}$

emitter	$\langle m_\nu \rangle$ ($T_{\frac{1}{2}} = 10^{25}$ y.)	$M_{0\nu}^{tot}$(UCOM)
^{48}Ca	0.63	0.85
^{76}Ge	0.72	2.81
^{82}Se	0.37	2.64
^{96}Zr		
^{100}Mo		
^{110}Pd		
^{116}Cd	0.46	1.60
^{124}Sn	0.37	2.62
^{128}Te	1.32	2.88
^{130}Te	0.28	2.65
^{136}Xe	0.38	2.19
^{150}Nd	**heavy and deformed !**	

Pairing correlations and $0\nu\beta\beta$ decay

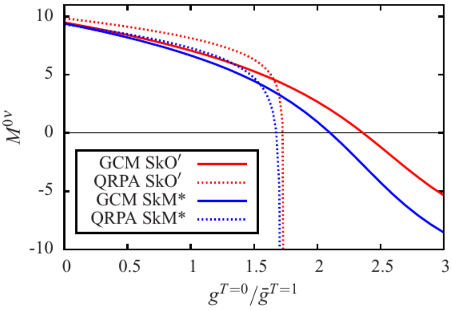
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



E. Caurier et al., PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value



Hinohara, Engel, PRC 90 031301 (2014)

Related to approximate SU(4) symmetry of the $\sum H(r)\sigma_i\sigma_j\tau_i\tau_j$ operator

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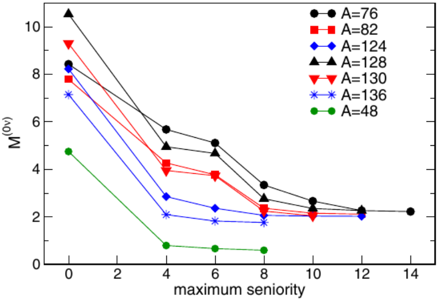

E. Caurier et al., PRL100 052503 (2008)

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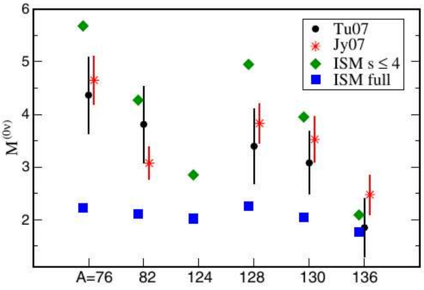
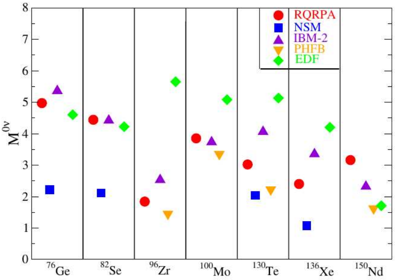


E. Caurier et al., PRL100 052503 (2008)

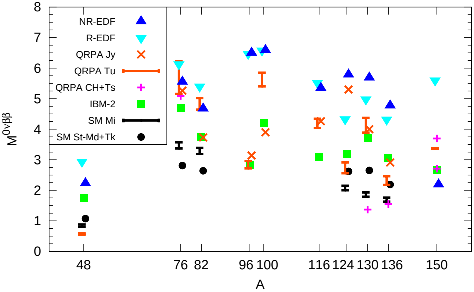
Related to approximate SU(4) symmetry of the $\sum H(r)\sigma_i\sigma_j\tau_i\tau_j$ operator

$0\nu\beta\beta$ matrix elements: last 5 years

Comparison of nuclear matrix elements calculations: 2012 vs 2017



P. Vogel, J. Phys. G39 124002 (2012)

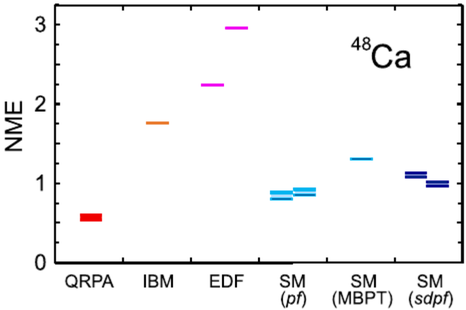


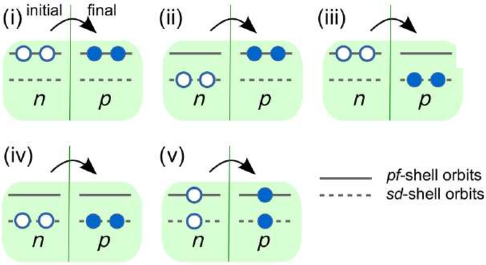
J. Engel, Rep. Prog. Phys.80 046301 (2017)

What have we learned in the last 5 years ?

Shell model configuration space: two shells

For ^{48}Ca enlarge configuration space
from *pf* to *sdpf*
4 to 7 orbitals, dimension 10^5 to 10^9
increases matrix elements
but only moderatly 30%
Iwata et al. PRL116 112502 (2016)

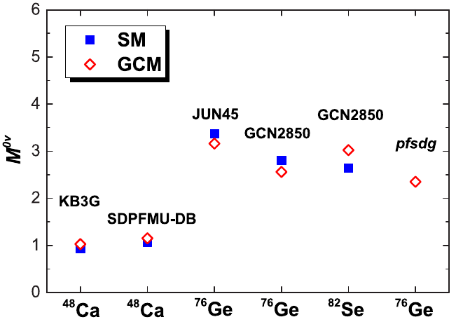




Contributions dominated by pairing
2 particle - 2 hole excitations
enhance the $\beta\beta$ matrix element,
Contributions dominated by
1 particle - 1 hole excitations
suppress the $\beta\beta$ matrix element

^{76}Ge matrix element in two shells: approximate

Large configuration space calculations in 2 major oscillator shells include all relevant correlations: isovector/isoscalar pairing, deformation
Many-body approach: Generating Coordinate Method (GCM)



GCM approximates shell model calculation

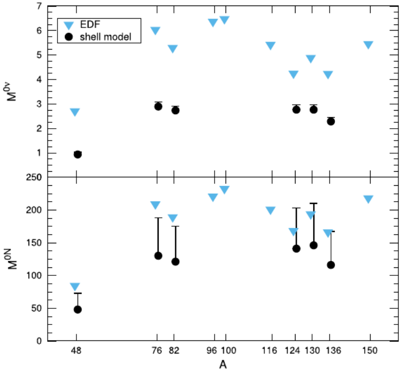
Degrees of freedom,
or generating coordinates
validated against
exact shell model
in restricted configuration space

Jiao et al., PRC96 054310 (2017)

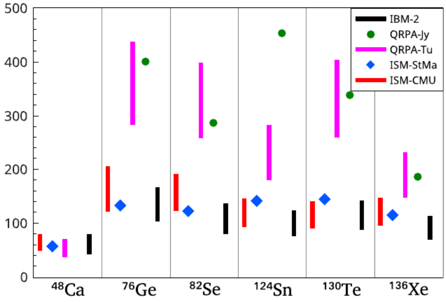
^{76}Ge nuclear matrix elements in 2 major shells
very similar to shell model nuclear matrix element in 1 major shell

Heavy-neutrino exchange nuclear matrix elements

Contrary to light-neutrino exchange, for heavy-neutrino exchange decay shell model, IBM and EDF matrix elements agree reasonably!



J. Menendez, JPG 45 014003 (2018)



A. Neacsu et al., PRC 93 024308 (2016)

Suggests differences in treating longer-range nuclear correlations dominant in light-neutrino echange

Heavy-neutrino matrix element

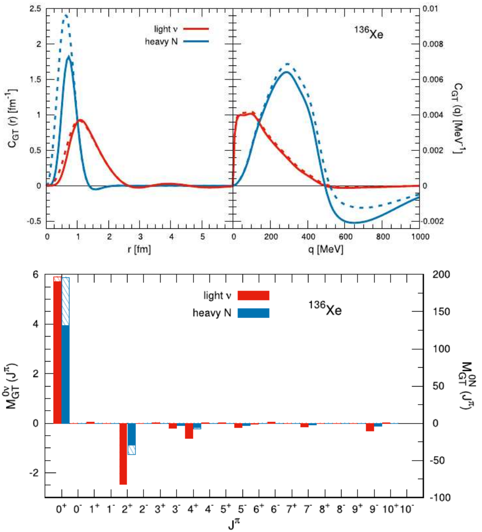
Compared to
light-neutrino exchange

heavy neutrino exchange dominated by shorter inter-nucleon range,
larger momentum transfers

heavy neutrino exchange contribution
from $J > 0$ pairs smaller:
pairing most relevant

Long-range correlations
(except pairing)
not under control

J. Menendez, JPG 45 014003 (2018)



Summary

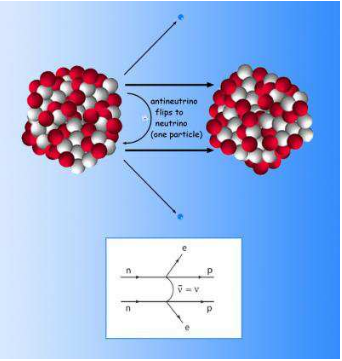
Reliable nuclear matrix elements needed to plan and fully exploIt impressive experiments looking for neutrinoless double-beta decay

- Matrix elements differences between present calculations, factor 2-3 besides additionnal “quenching” ?

- ^{48}Ca and ^{76}Ge matrix elements in larger configuration space increase $\lesssim$ 30% , missing correlations introduced in IBM, EDF

- First Ab-initio calculations of β decays do not need additionnal “quenching”, Ab-initio ^{48}Ca matrix elements in progress

- $2\nu\beta\beta$ decay, μ-capture/ν-nucleus scattering and double Gamow-Teller transitions can give insight on $0\nu\beta\beta$ matrix elements



$(\beta\beta)_{0\nu}$ matrix elements

$$M_{GT}^{(0\nu)} = \langle 0_f^+ \| \sum_{n,m} h(\sigma_n.\sigma_m) t_{n-} t_{m-} \| 0_i^+ \rangle, \qquad \chi_F = \langle 0_f^+ \| \sum_{n,m} h t_{n-} t_{m-} \| 0_i^+ \rangle \left(\frac{g_V}{g_A}\right)^2 / M_{GT}^{(0\nu)},$$

$$\chi'_{GT} = \langle 0_f^+ \| \sum_{n,m} h'(\sigma_n.\sigma_m) t_{n-} t_{m-} \| 0_i^+ \rangle / M_{GT}^{(0\nu)}, \qquad \chi'_F = \langle 0_f^+ \| \sum_{n,m} h' t_{n-} t_{m-} \| 0_i^+ \rangle \left(\frac{g_V}{g_A}\right)^2 / M_{GT}^{(0\nu)},$$

$$\chi^\omega_{GT} = \langle 0_f^+ \| \sum_{n,m} h_\omega(\sigma_n.\sigma_m) t_{n-} t_{m-} \| 0_i^+ \rangle / M_{GT}^{(0\nu)}, \qquad \chi^\omega_F = \langle 0_f^+ \| \sum_{n,m} h_\omega t_{n-} t_{m-} \| 0_i^+ \rangle \left(\frac{g_V}{g_A}\right)^2 / M_{GT}^{(0\nu)},$$

$$\chi_T = \langle 0_f^+ \| \sum_{n,m} h'[(\sigma_n.\hat{r}_{n,m})(\sigma_m.\hat{r}_{n,m}) - \frac{1}{3}\sigma_n.\sigma_m] t_{n-} t_{m-} \| 0_i^+ \rangle / M_{GT}^{(0\nu)},$$

$$\chi_P = \langle 0_f^+ \| i \sum_{n,m} h' \left(\frac{r_{+n,m}}{2r_{n,m}}\right) [(\sigma_n - \sigma_m).(\hat{r}_{n,m} \times \hat{r}_{+n,m})] t_{n-} t_{m-} \| 0_i^+ \rangle \frac{g_V}{g_A} / M_{GT}^{(0\nu)},$$

$$\chi_R = \frac{1}{6}(g^s_{-\frac{1}{2}} - g^s_{\frac{1}{2}}) \langle 0_f^+ \| \sum_{n,m} h_R(\sigma_n.\sigma_m) t_{n-} t_{m-} \| 0_i^+ \rangle \frac{g_V}{g_A} / M_{GT}^{(0\nu)}.$$

back

$(\beta\beta)_{0\nu}$ matrix elements

$$
\begin{aligned}
h(r,\langle\mu\rangle) &= \frac{R_0}{r}\phi(\langle\mu\rangle m_e r),\\
h'(r,\langle\mu\rangle) &= h + \langle\mu\rangle m_e R_0 h_0(\langle\mu\rangle r),\\
h_\omega(r,\langle\mu\rangle) &= h - \langle\mu\rangle m_e R_0 h_0(\langle\mu\rangle r),\\
h_R(r,\langle\mu\rangle) &= -\frac{\langle\mu\rangle m_e}{M_i}(\frac{2}{\pi}\left(\frac{R_0}{r}\right)^2 - \langle\mu\rangle m_e R_0 h) + \frac{4\pi R_0^2}{M_p}\delta(r),\\
h_0(x) &= -\frac{d\phi}{dx}(x),\\
\phi(x) &= \frac{2}{\pi}[\sin(x)C_{int}(x) - \cos(x)S_{int}(x)],\\
\frac{d\phi}{dx} &= \frac{2}{\pi}[\sin(x)C_{int}(x) + \cos(x)S_{int}(x)].
\end{aligned}
$$

$S_{int}(x)$ and $C_{int}(x)$ being the integral sinus and cosinus functions,

$$
S_{int}(x) = -\int_x^\infty \frac{\sin(\zeta)}{\zeta}d\zeta, \quad C_{int}(x) = -\int_x^\infty \frac{\cos(\zeta)}{\zeta}d\zeta
$$

back