Reliability of nuclear matrix elements of neutrinoless double-β decay by QRPA

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1. Brief introduction
2. Check of application of QRPA to $^{136}Xe \rightarrow {}^{136}Ba$
3. Brief discussion on g_A
4. Prospect

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Abbreviations and notation

QRPA: quasiparticle random-phase approximation, an approximation for obtaining nuclear wave functions.

GT: Gamow-Teller, GT transition is a charge-change transition by the weak interaction involving spin operator

g_A: axial-vector current coupling, strength of the GT component of the weak interaction.

$0\nu\beta\beta$: neutrinoless double-β

$2\nu\beta\beta$: two-neutrino double-β

NME: nuclear matrix element

Introduction

My motivation: to obtain the neutrino mass

Background of my study

0νββ decay of nucleus gives one of the limited methods for this aim.

If the neutrino is a Majorana particle, and the half-life is measured, the effective neutrino mass can be obtained.

Theory needs to supply the NME and the phase-space factor.
The latter is OK.
The NME is distributed in the range of a factor of 2-3 depending on method.

Investigation of the reliability of NME calculation.

Examinations of NME calculation of ^{136}Xe $\rightarrow$ ^{136}Ba that I have done so far

Comparison with relevant exp. data

- Higher-order terms of 2νββ NME
- GT strength of ^{136}Xe $\rightarrow$ ^{136}Cs
- others

Self check of calculation

- GT sum rule
- Convergence of 0νββ NME with respect to intermediate states.
- others

Higher-order term of NME of 2νββ decay

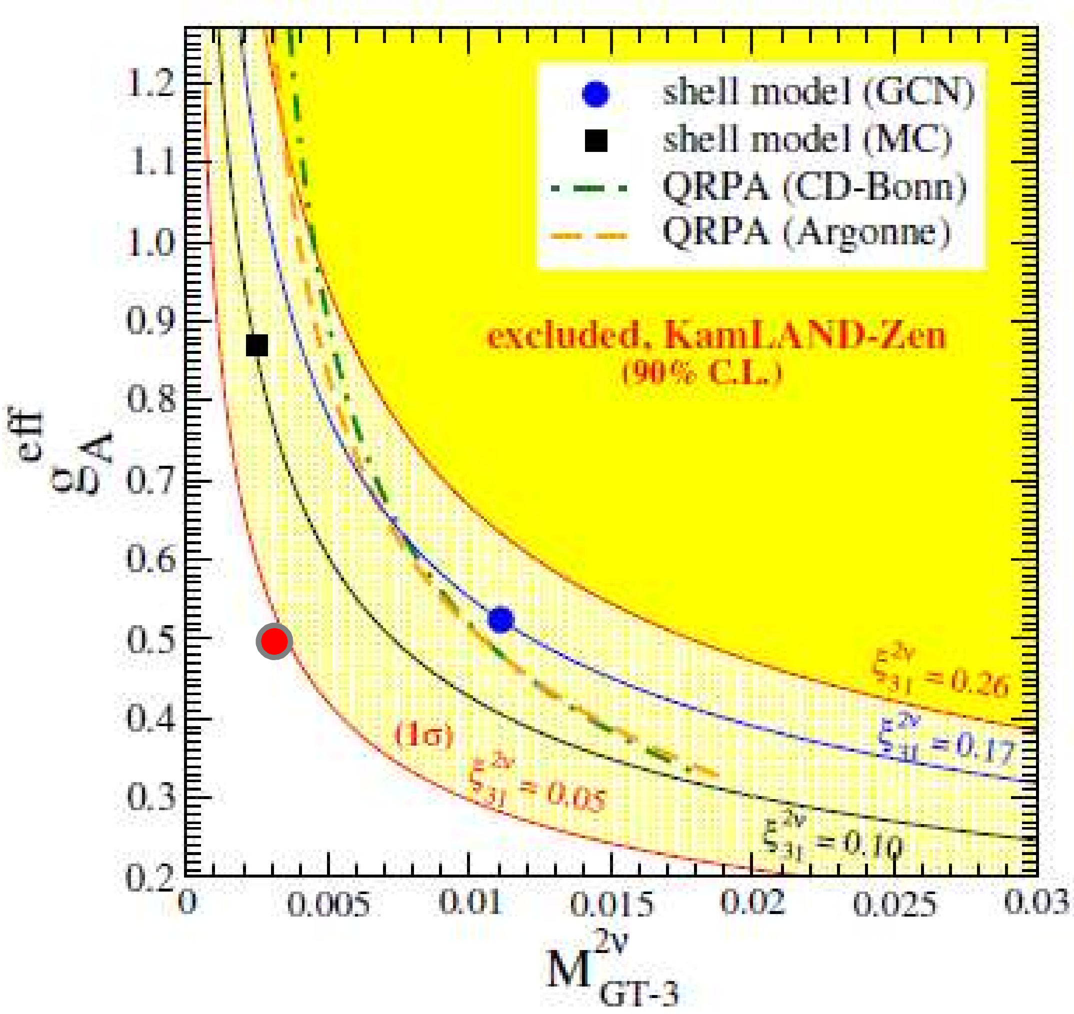
$$M^{2v}_{\text{GT-3}} = \sum_j \frac{4}{\{E_j - (E_i + E_f)/2\}^3} \langle 0_f^+ | \sum\nolimits_l (\boldsymbol{\sigma}\tau^-)_l | 1_j^+ \rangle \cdot \langle 1_j^+ | \sum\nolimits_l (\boldsymbol{\sigma}\tau^-)_l | 0_i^+ \rangle.$$

F. Šimkovic *et al*., PRC **97**, 034315 (2018)

E_j: intermediate-state energy,
E_f: final-state energy,
E_i: initial-state energy

$$M^{2v}_{\text{GT}} = \sum_j \frac{1}{E_j - (E_i + E_f)/2} \langle 0_f^+ | \sum\nolimits_l (\boldsymbol{\sigma}\tau^-)_l | 1_j^+ \rangle \cdot \langle 1_j^+ | \sum\nolimits_l (\boldsymbol{\sigma}\tau^-)_l | 0_i^+ \rangle.$$

Higher-order term of NME of 2νββ decay



Statistical analysis with the exp. data of ββ spectrum of ^{136}Xe

A. Gando et al., PRL **122**, 192501 (2019)

My point (red circle), $g_A^{\mathrm{eff}} = 0.49$ is used

↑

Exp. 2νββ half-life

Running sum of 2νββ NME

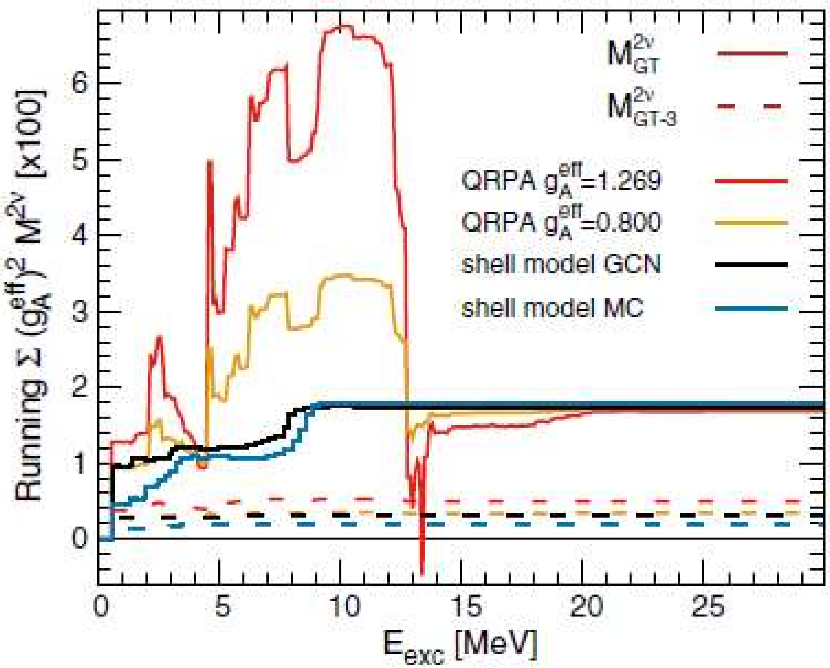
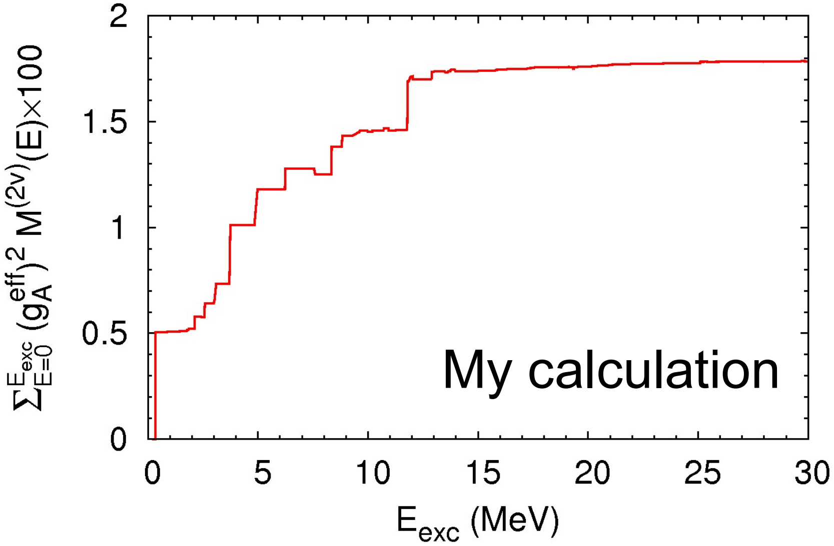


FIG. 4. Running sum of the ^{136}Xe $M_{GT}^{2\nu}$ (solid lines) and $M_{GT-3}^{2\nu}$ (dashed) $2\nu\beta\beta$ NMEs, as a function of the excitation energy of the 1^+ states in ^{136}Cs. Nuclear shell model results with the GCN (MC) interaction, indicated by black (blue) lines, are compared to the QRPA Argonne running sum with $g_A^{eff} = 1.269$ ($g_A^{eff} = 0.80$), shown by red (orange) lines.

A. Gando et al., PRL **122**, 192501 (2019)



$g_A^{\text{eff}} = 0.49$

No adjustment of interaction

GT$^-$ strength of ^{136}Xe $\rightarrow$ ^{136}Cs

D. Frekers et al., Nucl. Phys. A **916**, 219 (2013)

The authors obtained the GT strengths from the cross section of ^{136}Xe(^{3}He,t)^{136}Cs reaction and calibrated them using the *logft* values of electron capture.

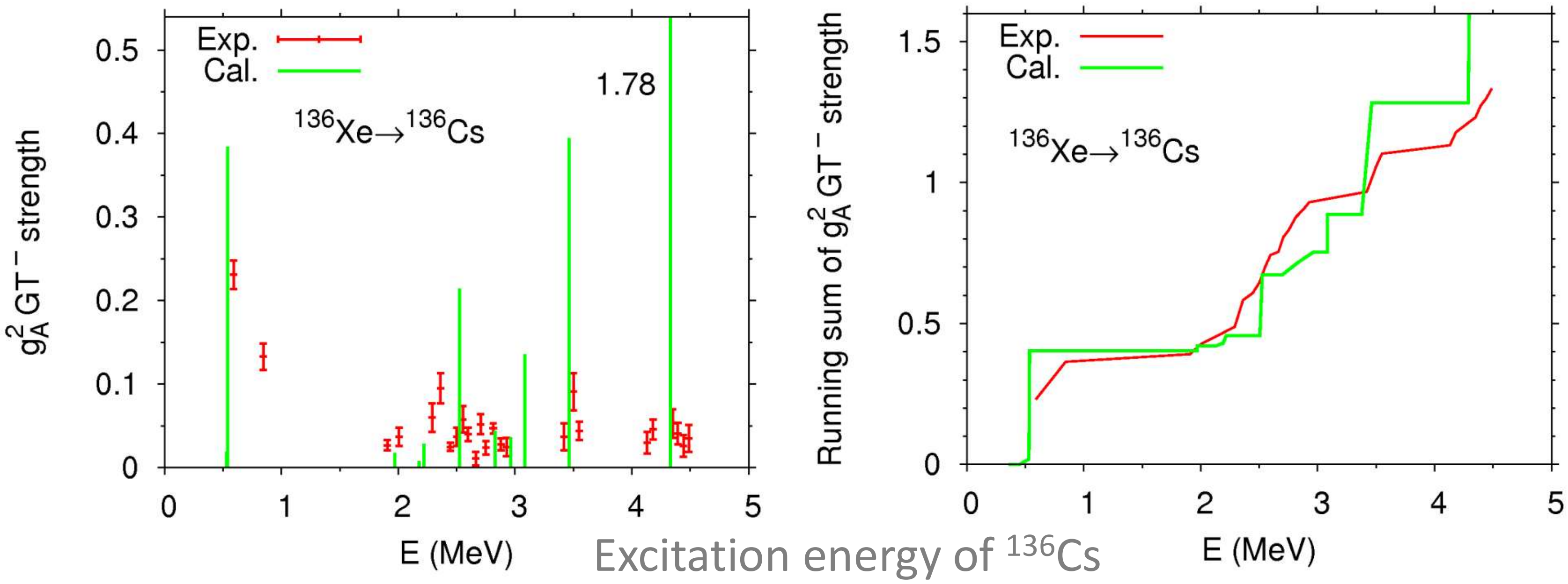
Textbook of J. Suhonen, (Springer, Berlin, 2007)

$$\tilde{B}_{GT} + \tilde{B}_F = 6147 \times 10^{-\log ft},$$

$$\tilde{B}_{GT} = \frac{g_A^2}{2J_I + 1} \left| \langle F | \boldsymbol{\sigma} \tau_\pm | I \rangle \right|^2 = g_A^2 B_{GT}, (J_I = 0)$$

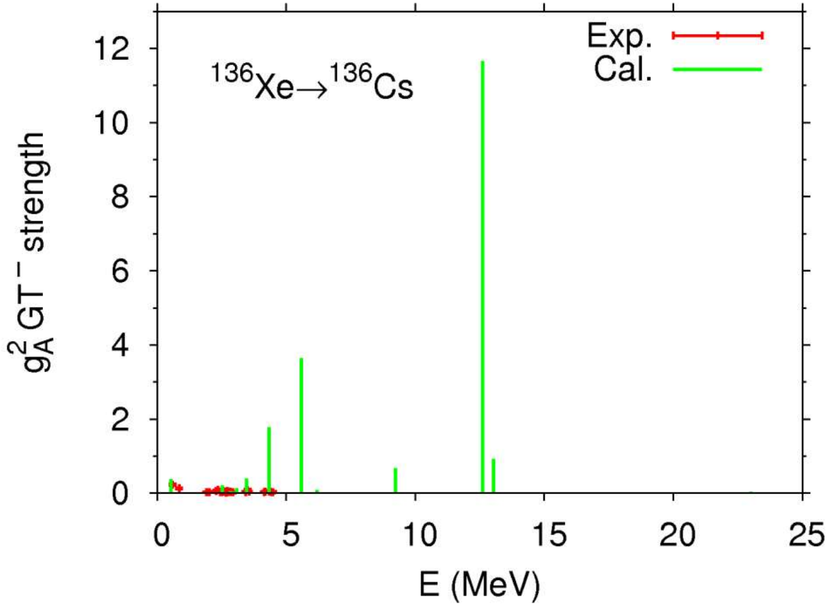
I calculated $g_A^2 B_{GT}$ using g_A 0.49 reproducing the exp. 2νββ-decay half-life.

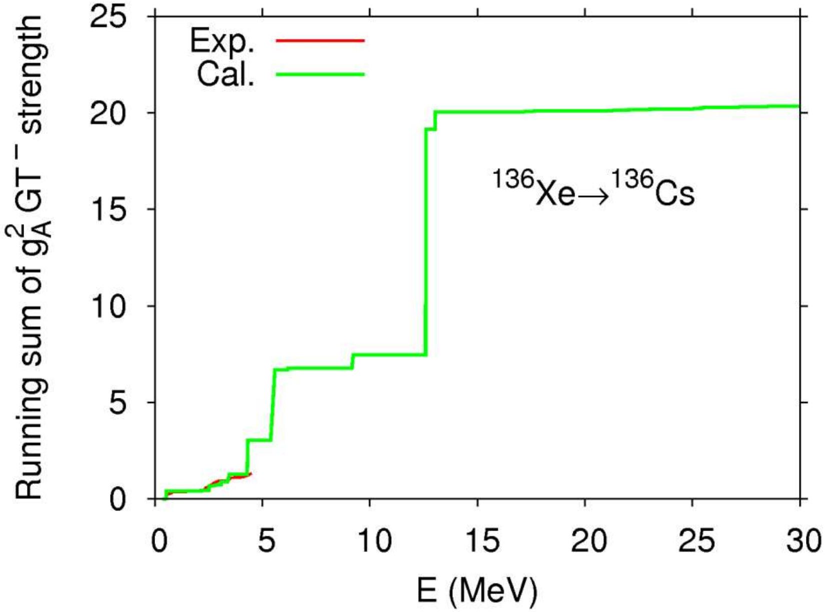
Exp. data and calculation of g_A^2 x GT⁻ strength



- The tendency of the exp. level distribution is well reproduced.
- The calculation with g_A from the exp. data of 2νββ decay is consistent with the electron capture in terms of the GT strength.

Exp. data and calculation of $g_A{}^2$ x GT^- strength





GT sum rule is satisfied.

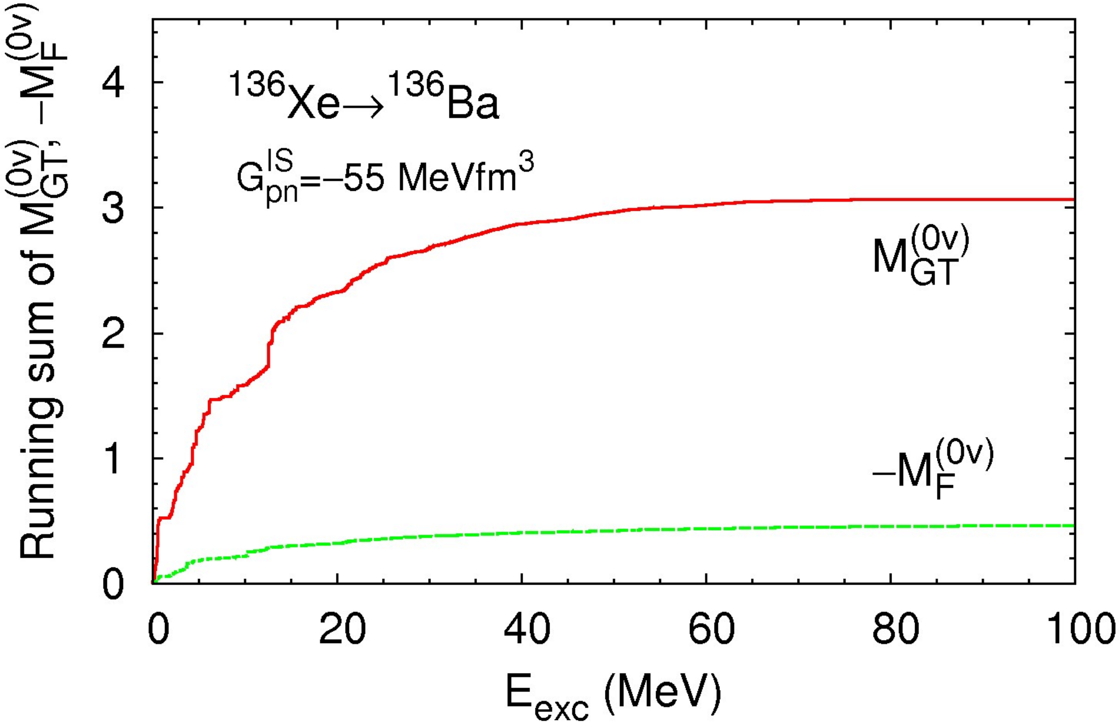
$\Sigma GT^-({}^{136}Xe \rightarrow {}^{136}Cs) - \Sigma GT^+({}^{136}Xe \rightarrow {}^{136}I)$

$= 85.145 - 1.138 = 84.007.$

Analytical value is $3(N-Z) = 84$.

→The single-particle space is large enough for the sum rule.

Running sum of 0νββ NME



Convergence around E_{exc} = 60 MeV.

A much larger energy region is necessary than for GT sum rule and 2νββ NME.

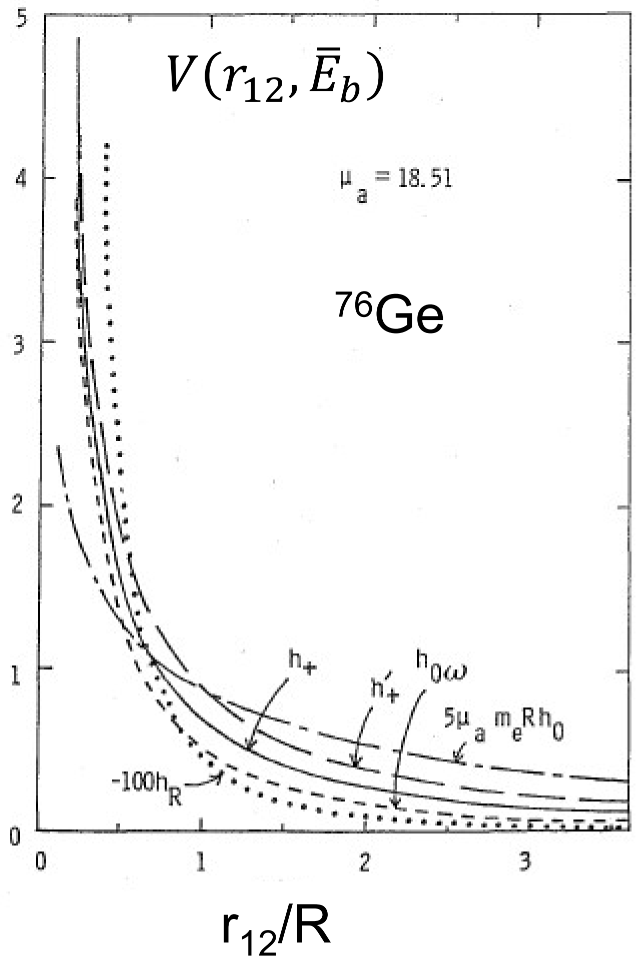
0vββ NME

$$M^{(0\nu)} \cong \sum_{b} \sum_{pp'} \sum_{nn'} \langle pp' | V(r_{12}, \bar{E}_b) | nn' \rangle \langle 0_f^+ | c_{p'}^\dagger c_{n'} | b \rangle \langle b | c_p^\dagger c_n | 0_i^+ \rangle$$

Final state

Intermediate state

Initial state



M. Doi et al., Prog. Theor. Phys. **83**, 1 (1985).

Effective g_A

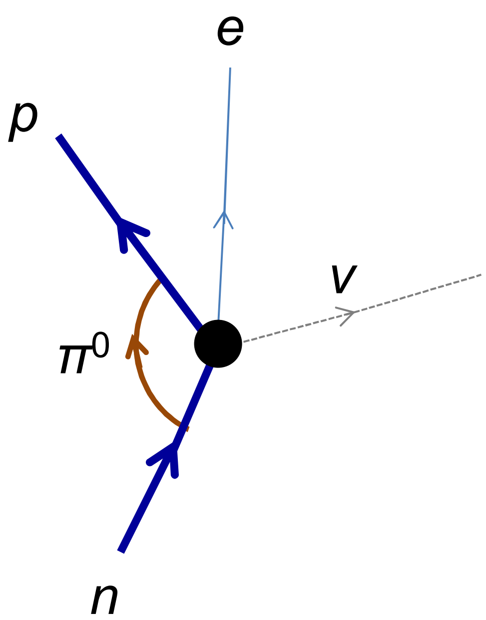
Looking around data and calculations of nuclear physics, the following tendency is seen:

The appreciable quenching is necessary for the GT transition.

This is confirmed in E < 10-15 MeV roughly. Enhancement may be necessary in the higher-energy region at least for the result of QRPA.

The isobaric-analog transition does not need a quenching factor; vector current coupling $g_V = 1$.

Electric transition can be reproduced approximately well by using the ***bare charge*** in QRPA for magic, near-magic and well-deformed nuclei.



Is the vertex correction more important, if the transition operator ● includes the spin operator? If so, why?

Comments are welcome.

Is effective g_A for 0νββ equal to that for other weak phenomena?

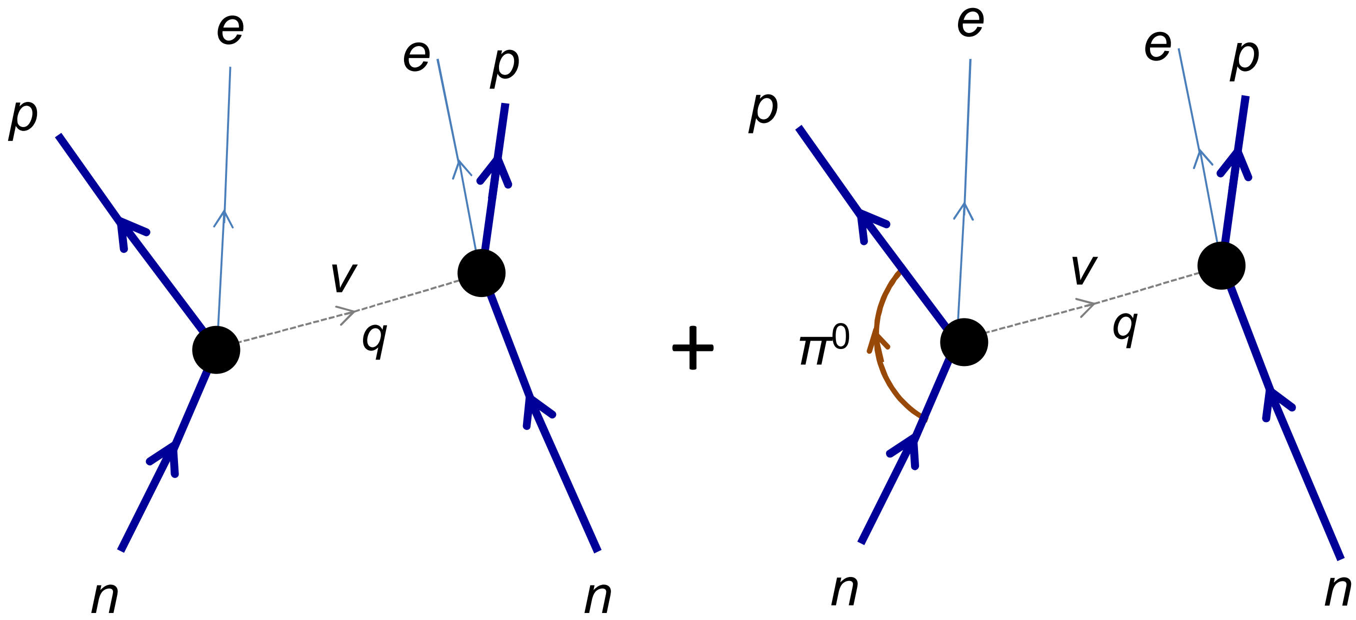
The difference between the 0νββ and other weak phenomena is the neutrino potential, which is obtained by the Fourier transformation of the neutrino propagator + correction terms. The integrand has a peak around 200 MeV/c.

If different, there are possible two reasons.

1. If the single-particle space is not sufficiently large, obviously g_A for 0νββ ≠ g_A for others.

   This is not the case for my calculation.

2. If the vertex correction depends on the major value of q, g_A for 0νββ might be different from g_A for others.



These diagrams are embedded in a nucleus.

Prospect

Advantage of QRPA

Very large single-particle space can be used, so that the convergence of the 0νββ NME is possible to obtain for all candidate nuclei up to ^{150}Nd of the 0νββ decay.

Disadvantage

Effect of the many-particle many-hole correlations is included only perturbatively. The importance of this effect depend on nucleus.

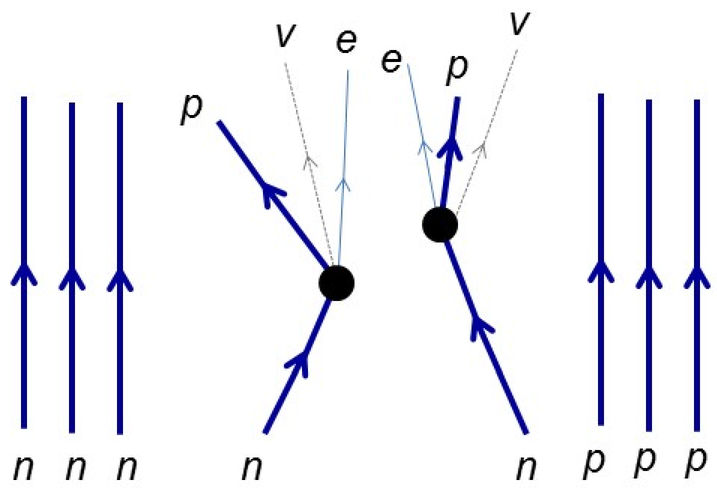
My short-term goal

To find the candidate nuclei with the minimum disadvantage of QRPA.

Currently ^{136}Xe is one of the best candidates.

Reserved

Nuclear matrix element of 2vββ decay



This matrix element includes

$$\frac{1}{E_j - (E_i + E_f)/2}$$

E_j: energy of intermediate states, which are virtual state
E_f: final-state energy,
E_i: initial-state energy

QRPA has two sets of intermediate-state energies. One is obtained from the initial state. Another is obtained from the final state.

If the two energy sets give close NMEs, the approximation is good. J.T. PRC **100**, 034325 (2019)