Can one measure $M^{0\nu}$?

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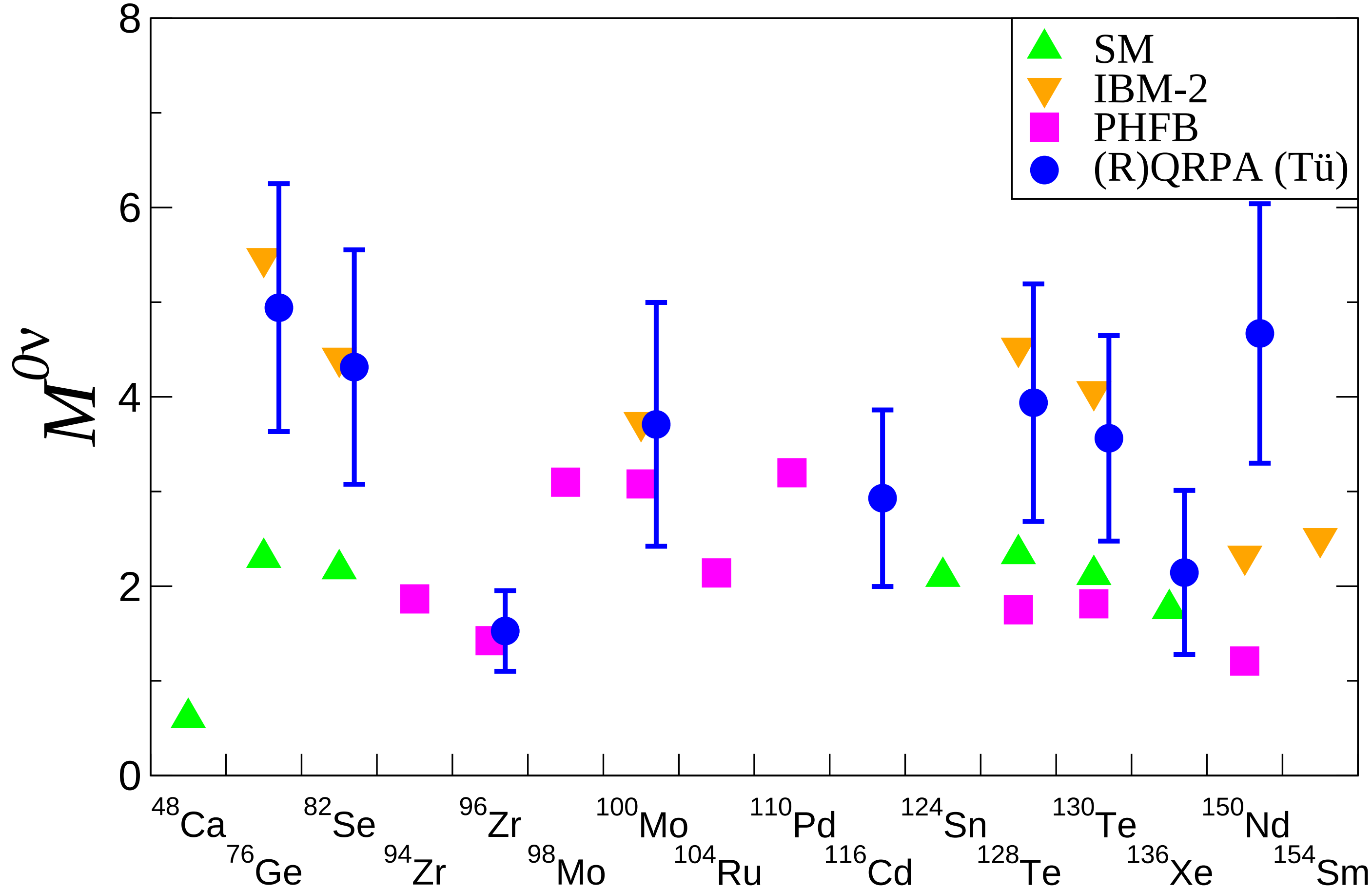
World status of $M^{0\nu}$, light neutrino mass mechanism

A. Escuderos, A. Faessler, V. R., F. Šimkovic, arXiv:1001.3519 [nucl-th]



(R)QRPA (Tü) = F. Šimkovic, A. Faessler, V.R., P. Vogel and J. Engel, PRC **77** (2008)

SM = E. Caurier, J. Menendez, F. Nowacki, A. Poves, PRL **100** (2008)

IBM-2 = J. Barea and F. Iachello, PRC **79** (2009)

PHFB = K. Chaturvedi *et al.*, PRC **78** (2008)

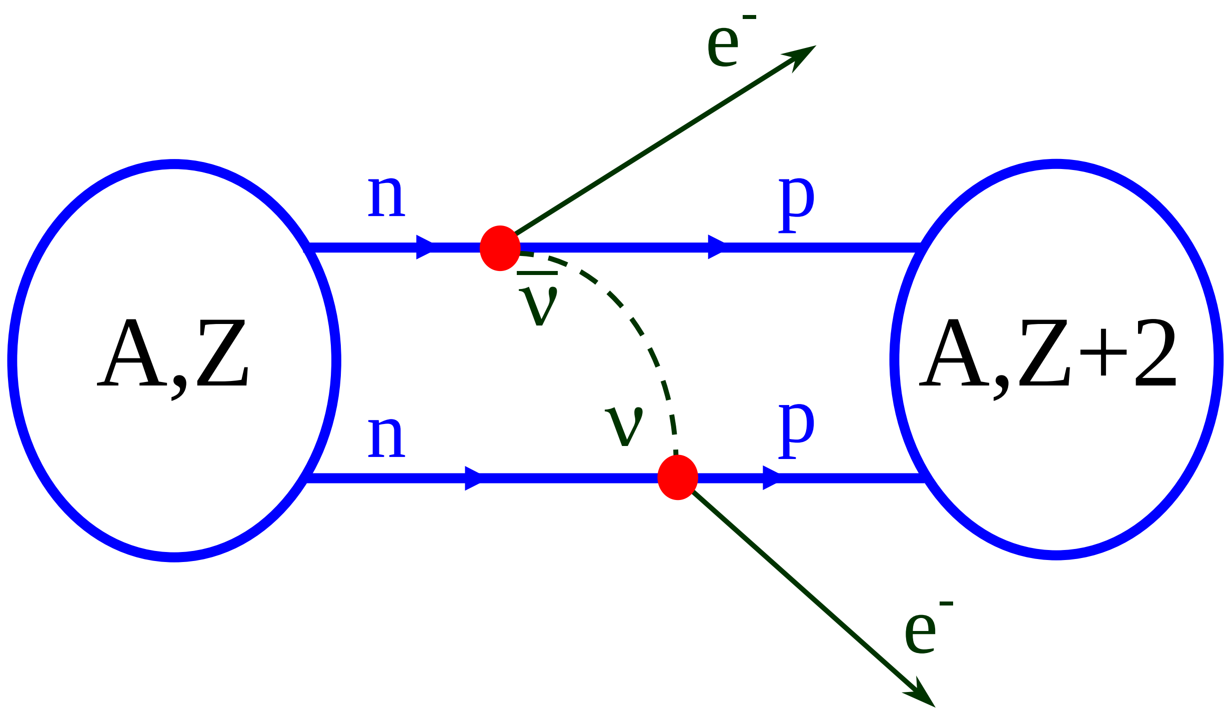
Can one measure nuclear matrix elements of neutrinoless double beta decay?

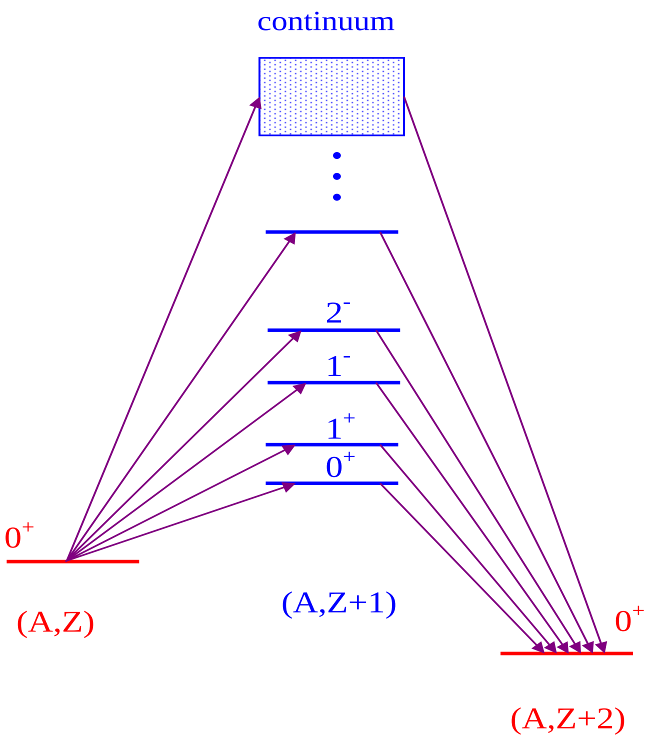
V.R., A. Faessler, PRC **80** , 041302(R) (2009) [arXiv:0906.1759 [nucl-th]]

Measuring $M_F^{0\nu}$

Nuclear $0\nu\beta\beta$-decay ($\overline{\nu} = \nu$)

Light neutrino
exchange mechanism



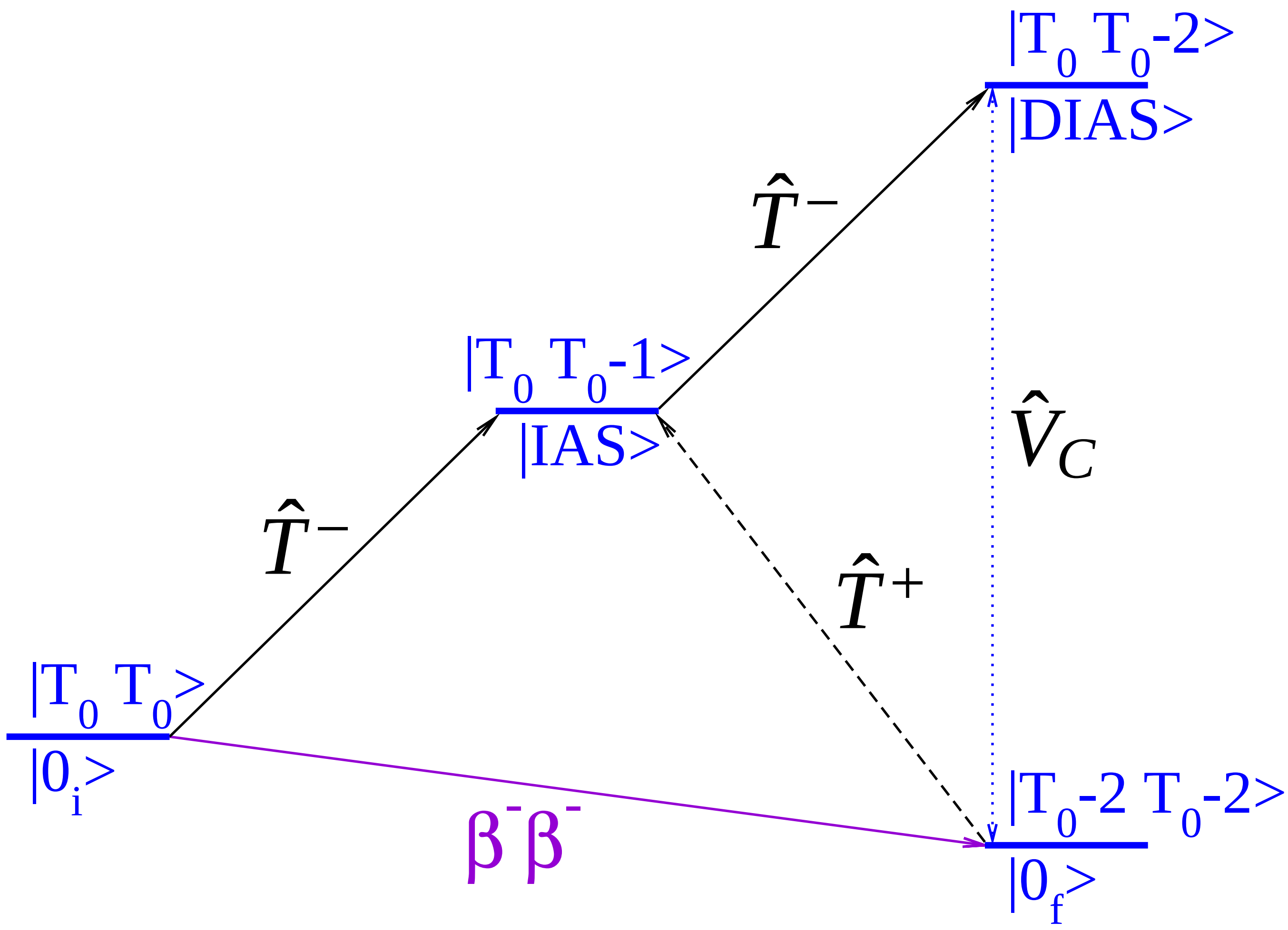


virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

Gamow-Teller amplitudes to 1^+ — from charge-exchange reactions (D. Frekers)

Measuring $M_F^{0\nu}$

Double Fermi transition ($J_s^\pi = 0^+$)



$M_F^{2\nu} = 0$ if isospin SU(2) symmetry is exact — Violated by Coulomb

Measuring $M_F^{0\nu}$

$$\hat{W}_F^{0\nu} = \sum_{ab} P_\nu(r_{ab})\tau_a^- \tau_b^- = \frac{1}{e^2}\left[\hat{T}^-, [\hat{T}^-, \hat{V}_C]\right]$$

Isospin lowering operator $\hat{T}^- = \sum_a \tau_a^-$; Coulomb interaction $\hat{V}_C = \frac{e^2}{8}\sum_{a \neq b} \frac{(1-\tau_a^{(3)})(1-\tau_b^{(3)})}{r_{ab}}$

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$$\hat{V}_C = \hat{V}_C^{(0)} + \hat{V}_C^{(1)} + \hat{V}_C^{(2)}$$

$$\hat{V}_C^{(0)} = \frac{e^2}{8}\sum_{a\neq b}\frac{1+\frac{\boldsymbol{\tau}_a\boldsymbol{\tau}_b}{3}}{r_{ab}} \qquad \hat{V}_C^{(1)} = -\frac{e^2}{8}\sum_{a\neq b}\frac{\tau_a^{(3)}+\tau_b^{(3)}}{r_{ab}} \qquad \hat{V}_C^{(2)} = \frac{e^2}{8}\sum_{ab}\frac{T_{ab}^{(2)}}{r_{ab}} \quad \left(T_{ab}^{(2)} \equiv \tau_a^{(3)}\tau_b^{(3)} - \frac{\boldsymbol{\tau}_a\boldsymbol{\tau}_b}{3}\right)$$

Only isotensor $\hat{V}_C^{(2)}$ contributes to $\left[\hat{T}^-, [\hat{T}^-, \hat{V}_C]\right]$

Measuring $M_F^{0\nu}$

$$\hat{W}_F^{0\nu} = \sum_{ab} P_\nu(r_{ab})\tau_a^- \tau_b^- = \frac{1}{e^2}\left[\hat{T}^-,[\hat{T}^-,\hat{V}_C]\right]$$

$$\left[\hat{T}^-,[\hat{T}^-,\hat{V}_C^{(2)}]\right] = \hat{V}_C^{(2)}\left(\hat{T}^-\right)^2 + \left(\hat{T}^-\right)^2\hat{V}_C^{(2)} - 2\hat{T}^-\hat{V}_C^{(2)}\hat{T}^-$$

$$e^2 M_F^{0\nu} \approx \langle 0_f^+|V_C^{(2)}\left(\hat{T}^-\right)^2|0_i^+\rangle =$$
$$\langle 0_f^+|\hat{V}_C^{(2)}|DIAS\rangle\langle DIAS|\left(\hat{T}^-\right)^2|0_i^+\rangle$$

Measuring $M_F^{0\nu}$

$$\hat{H}_{tot} = \hat{T} + \hat{H}_{str} + \hat{V}_C$$

If $\hat{H}_{str}$ exactly isospin-symmetric: $\left[\hat{T}^-, \hat{H}_{str}\right] = 0$

$$\Downarrow$$

$$\hat{W}_F^{0\nu} = \frac{1}{e^2}\left[\hat{T}^-, [\hat{T}^-, \hat{H}_{tot}]\right]$$

Measuring $M_F^{0\nu}$

$$M_F^{0\nu} =$$

$$-\frac{2}{e^2}\sum_s \bar{\omega}_s \langle 0_f^+|\hat{T}^-|0_s^+\rangle\langle 0_s^+|\hat{T}^-|0_i^+\rangle$$

$$\bar{\omega}_s = E_s - (E_{0_i^+} + E_{0_f^+})/2$$

Just equivalent representation of

$$M_F^{0\nu} = \frac{1}{e^2}\langle 0_f^+|\left[\hat{T}^-,[\hat{T}^-,\hat{V}_C^{(2)}]\right]|0_i^+\rangle$$

Measuring $M_F^{0\nu}$

$$M_F^{0\nu} \approx -\frac{2}{e^2}\,\bar{\omega}_{IAS}\langle 0_f^+|\hat{T}^-|IAS\rangle\langle IAS|\hat{T}^-|0_i^+\rangle$$

$$\approx \frac{1}{e^2}\langle 0_f^+|\hat{V}_C^{(2)}|DIAS\rangle\langle DIAS|\left(\hat{T}^-\right)^2|0_i^+\rangle$$

Measuring $M_F^{0\nu}$

Measure the $\Delta T = 2$ isospin-forbidden matrix element $\langle 0_f^+ | \hat{T}^- | IAS \rangle$

charge-exchange (n, p)-type reaction

Challenge: $\langle 0_f^+ | \hat{T}^- | IAS \rangle \sim 0.005$

$\langle IAS | \hat{T}^- | 0_i^+ \rangle \approx \sqrt{N - Z} \sim 5$

$$M_F^{0\nu}(QRPA)/M_F^{0\nu}(SM) \approx 3 \div 5$$

Measuring $M_F^{0\nu}$

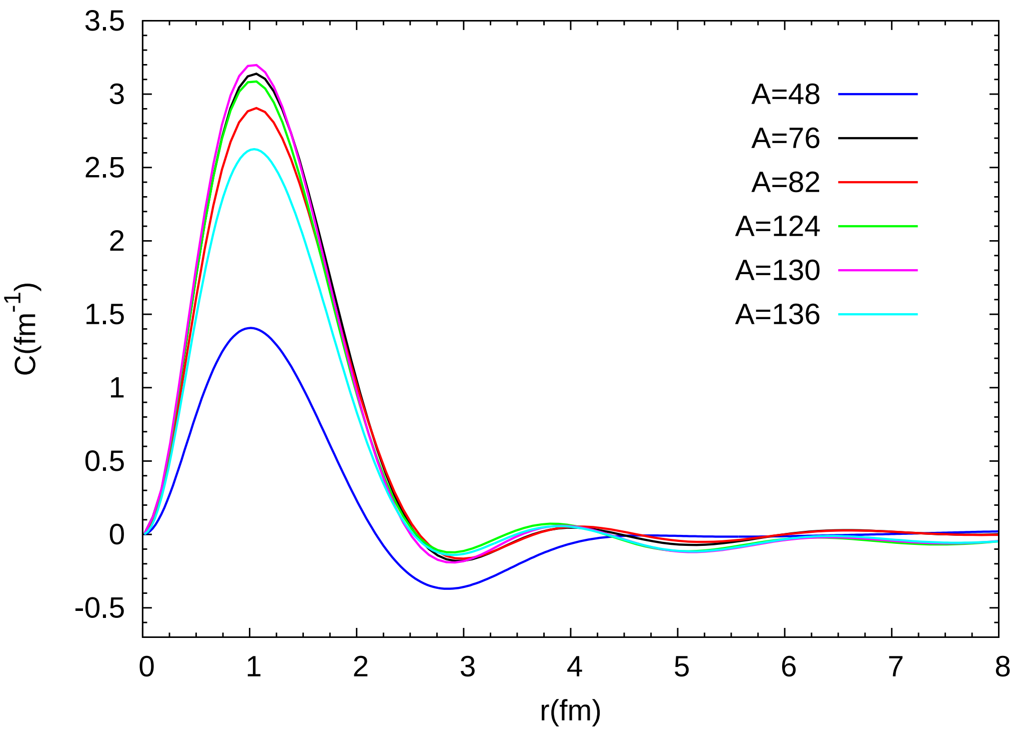
But $M_F^{0\nu}/M_{GT}^{0\nu} \approx 0.3$

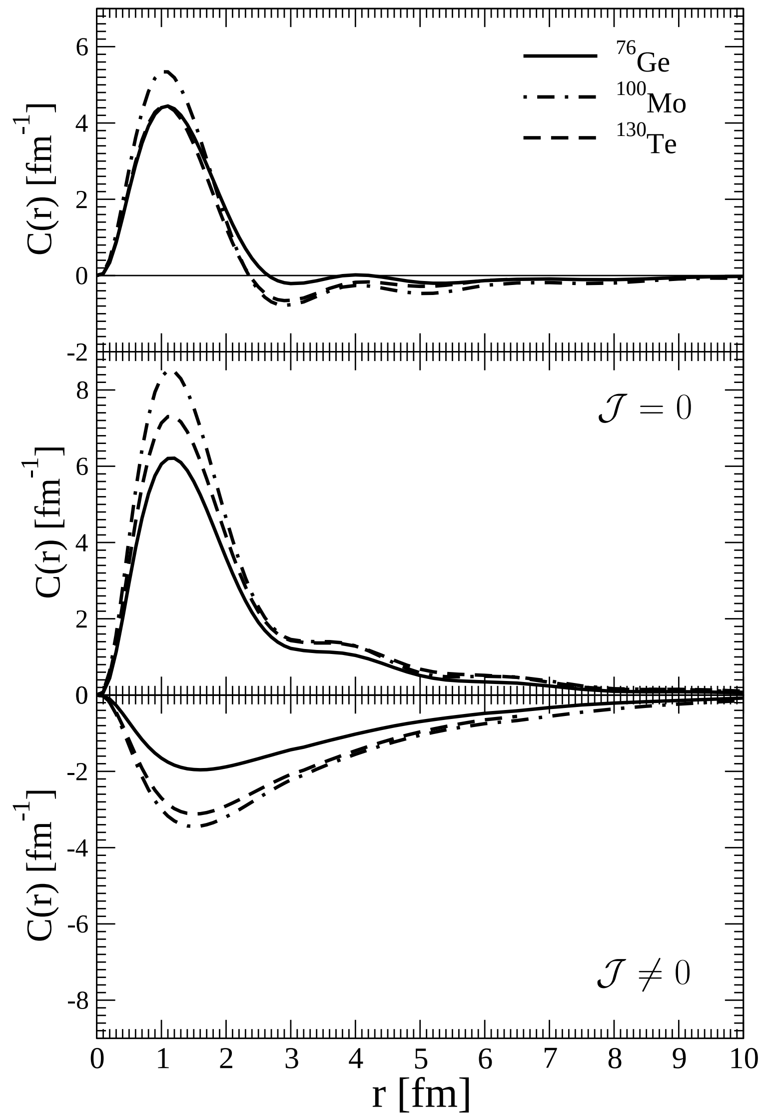
Ratio $M_F^{0\nu}/M_{GT}^{0\nu}$

may be more reliably calculable than $M_F^{0\nu}$ and $M_{GT}^{0\nu}$ separately

Measuring $M_F^{0\nu}$

$$\int_0^\infty C(r)dr = M^{0\nu}$$





Measuring $M_F^{0\nu}$

Only small r_{ab} ~1–2 fm determine $M^{0\nu}$

$\Rightarrow$ nucleon pairs in the relative s-wave contribute $\Rightarrow$ $T = 1, S = 0$ pairs

$$\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 |S = 0, T = 1\rangle = -3|S = 0, T = 1\rangle$$

$$\Downarrow$$

$$M_{GT}^{0\nu} = -3 M_F^{0\nu}$$

provided the neutrino potential is the same in both F and GT cases

High-order terms of nucleon weak current $\Rightarrow$ $M_{GT}^{0\nu}/M_F^{0\nu} \approx -2.5$

Basic requirements for a charge-exchange probe

Measure cross section ≡ Know $\langle IAS|\hat{T}^{+}|0^{+}_{f}\rangle$???

Reaction analysis

Any hadronic probe adds isospin to nuclear system
(weak interaction probe would be ideal)

to probe small admixture of $|DIAS\rangle$ to $|0^+_f\rangle$
$\Rightarrow$ must be forbidden to connect in reaction
main components of $|IAS\rangle$ and $|0^+_f\rangle$ ($\Delta T = 2$)

Only $T = \frac{1}{2}$ probes ((n, p), (t,^{3}He),...)

Reaction analysis

$$\sigma_{np}(0^+_f \to IAS) \propto \langle IAS|\hat{T}^+|0^+_f\rangle$$

???

$$|0^+_i\rangle = |T_0\,T_0\rangle; \qquad |IAS\rangle = \frac{\hat{T}^-}{\sqrt{2T_0}}|0^+_i\rangle + \alpha\,|T_0-1\;T_0-1\rangle$$

$$|0^+_f\rangle = |T_0-2\;T_0-2\rangle + \beta\,|T_0-1\;T_0-2\rangle + \gamma\,\frac{(\hat{T}^-)^2}{\sqrt{4T_0(2T_0-1)}}|0^+_i\rangle$$

$$= |DIAS\rangle$$

Reaction analysis

^{82}Se

$\sigma_{np}(\gamma DIAS \rightarrow IAS)$ is 10 times large than other mechanisms

Reaction analysis

IAS of ^{48}Ca ($T = 4, T_z = 3$) in ^{48}Sc

1. locates at E_x =6.678 MeV
2. 100% γ-decay to 1^+ state at E_x =2.517 MeV (E_γ=4.160 MeV)

Conclusions

- $M_F^{0\nu}$ can be related to Coulomb m.e. determining $\Delta T = 2$ isospin admixture of the DIAS in the final g.s.

- $M_F^{0\nu}$ can be reconstructed if one is able to measure Fermi m.e.
  $\langle IAS|\hat{T}^{+}|0_f\rangle$
  (e.g. charge-exchange (n, p)-type reactions)

- can help to discriminate between nuclear structure models (difference in $M_F^{0\nu}$ as much as the factor of 5)

- Estimate $M_{GT}^{0\nu}/M_F^{0\nu} \approx -2.5$ must hold

Conclusions

- Estimates show that $\sigma_{np}(0_f \rightarrow IAS) \propto \langle IAS|\hat{T}^{+}|0_f\rangle$ (weak mixing regime)

- Choice of a target: better well-isolated IAS. ^{48}Ca ?

- Role of spread of IAS in heavy nuclei to be investigated

Supported by: DFG SFB TR27 “Neutrinos and beyond”

Backup

$$M_F^{0\nu} \approx -\frac{2}{e^2}\,\bar{\omega}_{IAS}\langle 0_f|\hat{T}^-|IAS\rangle\langle IAS|\hat{T}^-|0_i\rangle$$

$$\langle 0_f|\hat{T}^-|IAS\rangle\langle IAS|\hat{T}^-|0_i\rangle = \langle 0_f|DIAS\rangle\langle DIAS|\hat{T}^-|IAS\rangle\langle IAS|\hat{T}^-|0_i\rangle$$

$$\langle 0_f|DIAS\rangle = -\frac{\langle 0_f|\hat{V}_C^{(2)}|DIAS\rangle}{E_{DIAS}-E_{0_f}}, \quad \text{with } E_{DIAS}-E_{0_f} \approx 2\bar{\omega}_{IAS}.$$

$$M_F^{0\nu} \approx \frac{1}{e^2}\langle 0_f|\hat{V}_C^{(2)}|DIAS\rangle\langle DIAS|\left(\hat{T}^-\right)^2|0_i\rangle$$

Backup

Switching off Coulomb

$$\hat{H}_{tot}(\lambda) = \hat{T} + \hat{H}_{str} + \lambda \hat{V}_C$$

$$\hat{W}_F^{0\nu} = \frac{1}{e^2\lambda}\left[\hat{T}^-, [\hat{T}^-, \hat{H}_{tot}]\right]$$

$$M_F^{0\nu} = -\frac{2}{e^2\lambda}\sum_s \bar{\omega}_s \langle 0_f|\hat{T}^-|0_s^+\rangle\langle 0_s^+|\hat{T}^-|0_i\rangle$$

Backup

$$\lambda \to 0$$

$$e^2 M_F^{0\nu} = \langle 0_f | \left[\hat{T}^-, [\hat{T}^-, \hat{V}_C] \right] | 0_i \rangle$$

$$= \langle 0_f | \hat{V}_C \hat{T}^- \hat{T}^- | 0_i \rangle$$

$$= \langle 0_f | \hat{V}_C | DIAS \rangle \langle DIAS | \hat{T}^- \hat{T}^- | 0_i \rangle$$

Backup

$$\hat{V}_C = \bar{V}_C + \Delta\hat{V}_C$$

$$\bar{V}_C = \hat{V}_C^{(0)} + \bar{V}_C^{(1)} + \bar{V}_C^{(2)}$$

$$\bar{V}_C^{(1)} = -\frac{e^2}{8}\sum_{a\neq b}\frac{\tau_a^{(3)}+\tau_b^{(3)}}{R_1} = -\frac{e^2 A}{2R_1}\hat{T}^{(3)}$$

$$\Delta\hat{V}_C^{(1)} = -\frac{e^2}{8}\sum_{a\neq b}(\tau_a^{(3)}+\tau_b^{(3)})(\frac{1}{r_{ab}}-\frac{1}{R_1})$$

$$\bar{V}_C^{(2)} = \frac{e^2}{8}\sum_{ab}\frac{T_{ab}^{(2)}}{R_2} = \frac{e^2}{2R_2}(\hat{T}^{(3)}\hat{T}^{(3)} - \frac{\mathbf{T}^2}{3})$$

$$\Delta\hat{V}_C^{(2)} = \frac{e^2}{8}\sum_{ab}T_{ab}^{(2)}(\frac{1}{r_{ab}}-\frac{1}{R_2})$$

$\bar{V}_C$ does not mix $|T\ T_z\rangle$

Backup

$$\langle 0_f | \overline{V}_C^{(2)} \left(\hat{T}^-\right)^2 |0_i\rangle =$$

$$\frac{e^2}{2R_2}\langle 0_f | \left(\hat{T}^-\right)^2 |0_i\rangle = \frac{e^2}{2R_2}\sum_s \langle 0_f|\hat{T}^-|0_s^+\rangle\langle 0_s^+|\hat{T}^-|0_i\rangle$$

Suppression by $\frac{e^2}{4R_2\overline{\omega}_{IAS}} \ll 1$

$$\langle DIAS|\hat{V}_C^{(2)}|0_f^+\rangle = \langle DIAS|\Delta\hat{V}_C^{(2)}|0_f^+\rangle.$$