$2\nu\beta\beta$ decay of deformed nuclei with realistic NN forces

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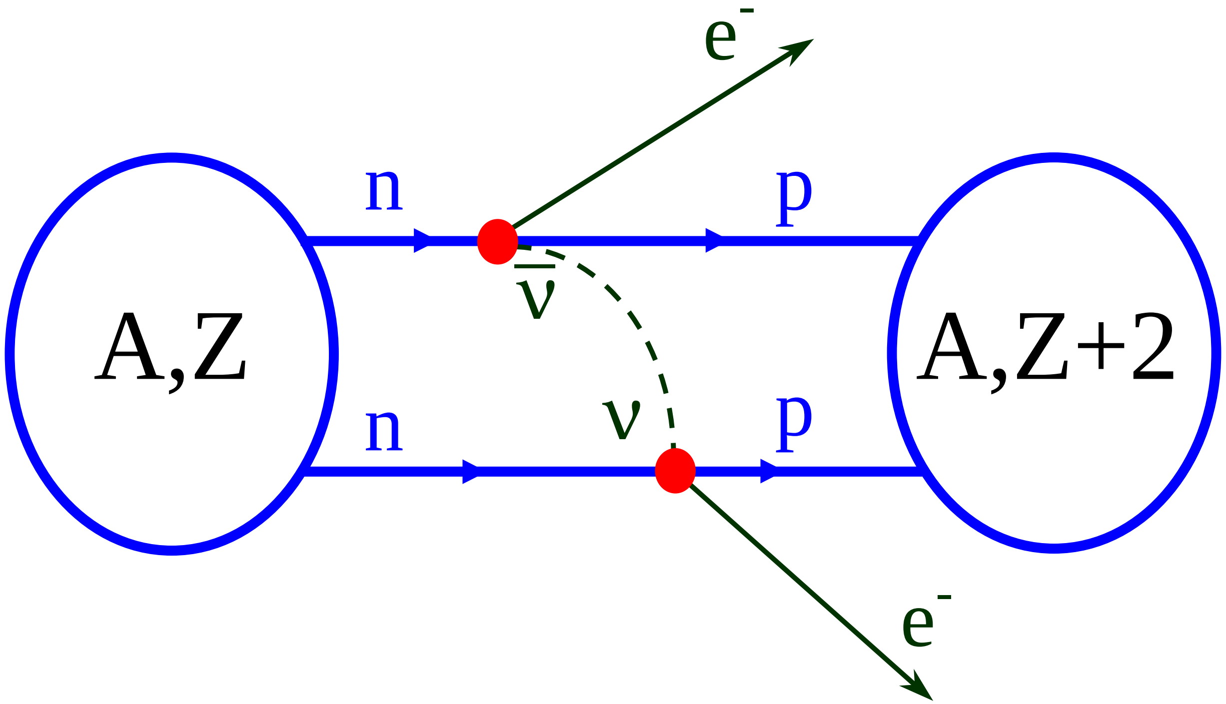
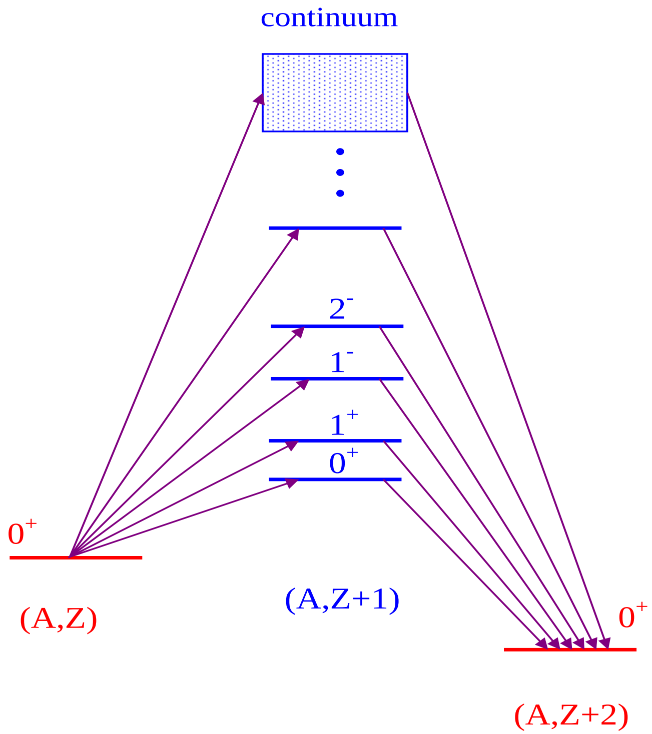
Introduction

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

Light neutrino
exchange mechanism

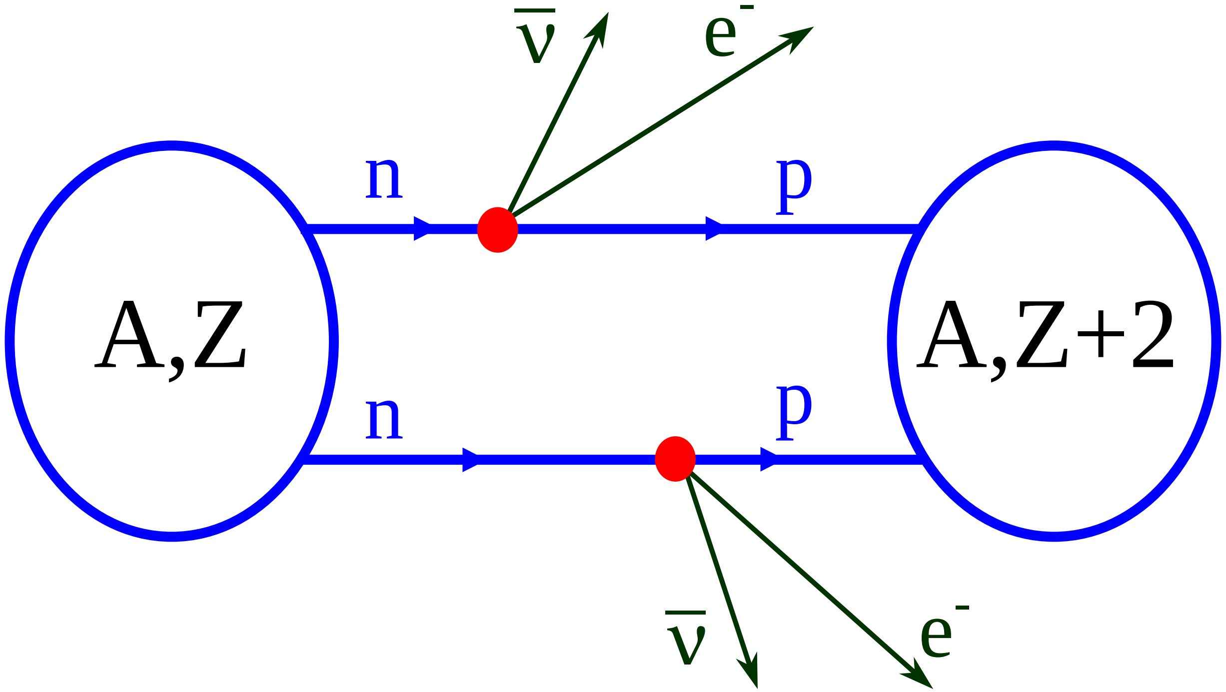




virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

Nuclear $2\nu\beta\beta$-decay

second order weak process
within SM



measured $T_{1/2}^{2\nu}$ (compilation of A. Barabash, 2005)

Isotope	$T_{1/2}^{2\nu}$, in 10^{19} y
^{48}Ca	$4.2^{+2.1}_{-1.0}$
^{76}Ge	150 ± 10
^{82}Se	9.2 ± 0.7
^{96}Zr	2.0 ± 0.3
^{100}Mo	0.71 ± 0.04
^{116}Cd	3.0 ± 0.2
^{128}Te	$(2.5 \pm 0.3) \times 10^5$
^{130}Te	90 ± 10
^{136}Xe	> 81 (90% CL)
^{150}Nd	0.78 ± 0.07
^{238}U	200 ± 60

$2\nu\beta\beta$ $0\nu\beta\beta$

Inverse Half-Lives $[T_{1/2}(0^+ \to 0^+)]^{-1}$

$$G^{2\nu}(Q,Z)\,|M_{GT}^{2\nu}|^2$$

$$m_{\beta\beta}^2\, G^{0\nu}(Q,Z)\,\left|M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}\right|^2$$

Eff. neutrino mass $m_{\beta\beta} = \sum_j m_j U_{ej}^2$

U_{ej} — first raw of the neutrino mixing matrix

$2\nu\beta\beta$ $0\nu\beta\beta$

Nuclear Matrix Elements

$$M_{GT}^{2\nu} = \sum_s \frac{\langle 0_f || \hat{\beta}^- || s \rangle \langle s || \hat{\beta}^- || 0_i \rangle}{E_s - (M_i + M_f)/2}$$

$$\hat{\beta}^- = \sum_k \boldsymbol{\sigma}_k \tau_k^-$$

$$M_{GT}^{0\nu} = \langle 0_f | \sum_{ik} P_\nu(r_{ik}, \overline{\omega}) \tau_i^- \tau_k^- \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_k | 0_i \rangle$$

Neutrino potential : $P_\nu(r, \overline{\omega}) =$

$$\frac{2R}{\pi r} \int_0^\infty dq \frac{q \sin(qr)}{\omega(\omega + \overline{\omega})}$$

$$\approx \frac{R}{r} \ \phi(\overline{\omega} r)$$

Introduction

V.R., A. Faessler, F. Simkovic, P. Vogel, PRC 68 (2003); NPA 766 (2006); NPA 793 (2007)

g_{pp} fitted to $2\nu\beta\beta$-decay half-life $\Rightarrow$ stable $M^{0\nu}$

$0\nu\beta\beta$ half-lives $T^{0\nu}_{1/2}$ (in years) assuming $\langle m_{\beta\beta}\rangle = 50$ meV.

Transition	$M^{0\nu}$	$T^{0\nu}_{1/2}$
$^{76}Ge \rightarrow {}^{76}Se$	3.92	$8.6\ 10^{26}$
$^{82}Se \rightarrow {}^{82}Kr$	3.49	$2.4\ 10^{26}$
$^{130}Te \rightarrow {}^{130}Xe$	2.95	$2.2\ 10^{26}$
$^{150}Nd \rightarrow {}^{150}Sm$	4.16	$2.2\ 10^{25}$

↑

strongly deformed $\Leftarrow$ SM (Nowacki'04): "you can forget about it!"

SNO+ (& SuperNEMO): 0.1% of ^{nat}Nd $\Rightarrow$ 56 kg of ^{150}Nd $\Rightarrow$ $m_{\beta\beta} \simeq 0.1$ eV

But: $M^{0\nu} = 1.57$ pseudo-SU(3) model of Hirsch *et al.* NPA**582** (1995)

$M^{0\nu} = 1.61$ projected HFB appr. of K. Chaturvedi *et al.* arXiv:0805.4073 [nucl-th]

QRPA in deformed nuclei

- $2\nu\beta\beta$ in deformed nuclei; QRPA with schematic separable forces

  F. Šimkovic, L. Pacearescu, A. Faessler, NPA **733** (2004)

  R. Alvarez-Rodriguez *et al.*, PRC **70** (2004)

- QRPA with realistic forces in deformed nuclei ($0\nu\beta\beta$ of ^{150}Nd) applied first to $2\nu\beta\beta$ (PhD thesis of M. Saleh Yousef)

  M. Saleh Yousef, V.R., A. Faessler, F. Šimkovic – arXiv:0806.0964 [nucl-th]

  $0\nu\beta\beta$ (PhD thesis of D. Fang, work in progress)

QRPA in deformed nuclei

Basic relationships

$$|1M(K),m\rangle = \sqrt{\frac{3}{16\pi^2}}[\mathcal{D}^1_{MK}(\phi,\theta,\psi)Q^\dagger_{m,K} + (-1)^{1+K}\mathcal{D}^1_{M-K}(\phi,\theta,\psi)Q^\dagger_{m,-K}]|0^+_{g.s.}\rangle \quad (K=\pm 1),$$

$$|1M(K),m\rangle = \sqrt{\frac{3}{8\pi^2}}\mathcal{D}^1_{MK}(\phi,\theta,\psi)Q^\dagger_{m,K}|0^+_{g.s.}\rangle \quad (K=0)$$

$$M^{2\nu}_{GT} = \sum_{K=0,\pm 1}\sum_{m_i m_f} \frac{\langle 0^+_f|\bar{\beta}^-_K|K^+,m_f\rangle\langle K^+,m_f|K^+,m_i\rangle\langle K^+,m_i|\beta^-_K|0^+_i\rangle}{\bar{\omega}_{K,m_i m_f}}$$

case I (shifted QRPA spectrum)

$$\bar{\omega}_{K,m_i m_f} = (\omega_{K,m_f} - \omega_{K,1_f} + \omega_{K,m_i} - \omega_{K,1_i})/2 + \bar{\omega}_{1^+_{1,exp}}$$

case II (unshifted QRPA spectrum)

$$\bar{\omega}_{K,m_i m_f} = (\omega^{m_f}_K + \omega^{m_i}_K)/2$$

QRPA in deformed nuclei

Deformed Woods-Saxon s.p. wave functions $|\tau\Omega_\tau\rangle$
decomposed over the spherical harmonic oscillator ones $|\eta\Omega\rangle$

$$|\tau\Omega_\tau\rangle = \sum_\eta B_\eta^\tau |\eta\Omega_\tau\rangle$$

$|\eta\Omega\rangle = \sum_\Sigma C^{j\Omega}_{l\ \Omega-\Sigma\ 1/2\ \Sigma} |Nl\Lambda = \Omega_\tau - \Sigma\rangle|\Sigma\rangle$ is the spherical harmonic oscillator wave function
in the j-coupled scheme

QRPA in deformed nuclei

Two-body deformed wave function

$$|p\overline{n}\rangle = \sum_{\eta_p\eta_n,J} F^{JK}_{p\eta_p n\eta_n} |\eta_p\eta_n, JK\rangle$$

$|\eta_p\eta_n, JK\rangle = C^{JK}_{j_p\Omega_p j_n\Omega_n} |\eta_p\Omega_p\rangle|\eta_n\Omega_n\rangle$ and $F^{JK}_{p\eta_p n\eta_n} = B^p_{\eta_p} B^n_{\eta_n} (-1)^{j_n-\Omega_n} C^{JK}_{j_p\Omega_p j_n-\Omega_n}$

Two-body residual interaction m.e.

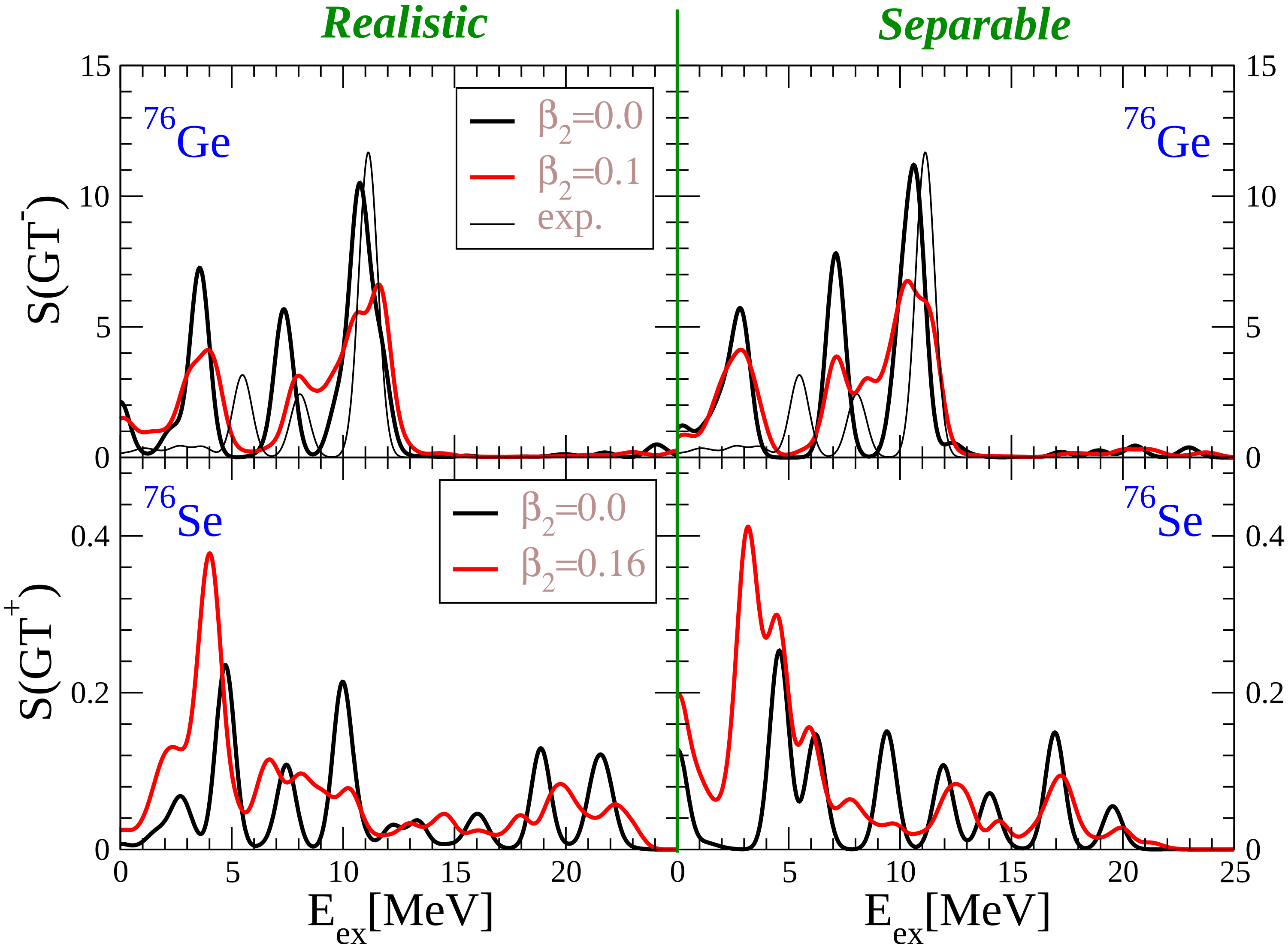
$$V_{p\overline{n},\, p'\overline{n'}} = -\,2 \sum_J \sum_{\eta_p\eta_n} \sum_{\eta_{p'}\eta_{n'}} F^{JK}_{p\eta_p n\eta_n} F^{JK}_{p'\eta_{p'} n'\eta_{n'}} G(\eta_p\eta_n\eta_{p'}\eta_{n'}, J)$$

$$V_{pn',\, p'n} = 2 \sum_J \sum_{\eta_p\eta_n} \sum_{\eta_{p'}\eta_{n'}} F^{JK'_{pn'}}_{p\eta_p \overline{n'}\eta_{n'}} F^{JK'_{pn'}}_{p'\eta_{p'} \overline{n}\eta_n} G(\eta_p\eta_{n'}\eta_{p'}\eta_n, J)$$

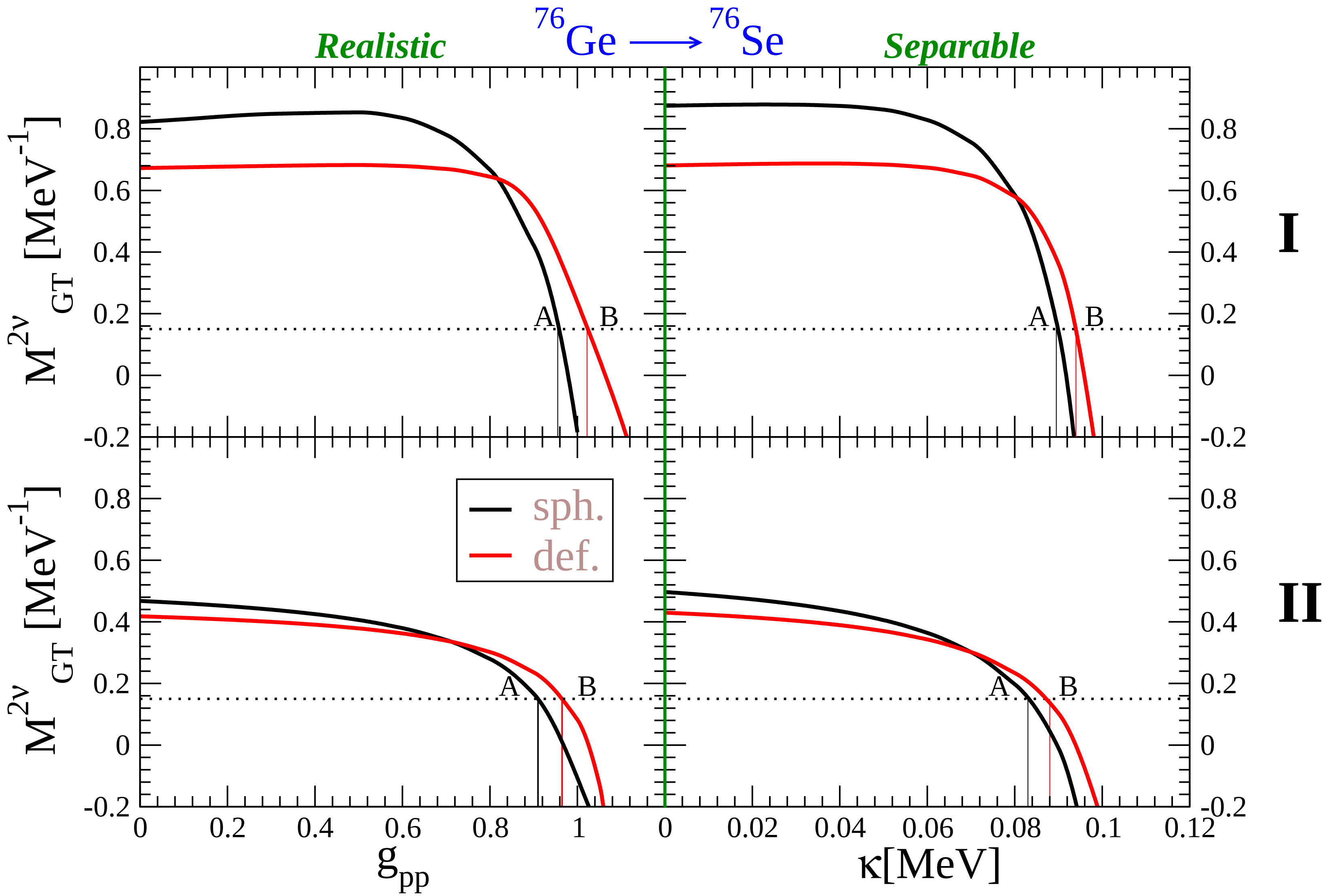
$K'_{pn'} = \Omega_p + \Omega_{n'} = \Omega_{p'} + \Omega_n$

Results

GT strength functions ($g_{ph} = 1.15;\ \chi = 3.73/A^{0.7}$ MeV)



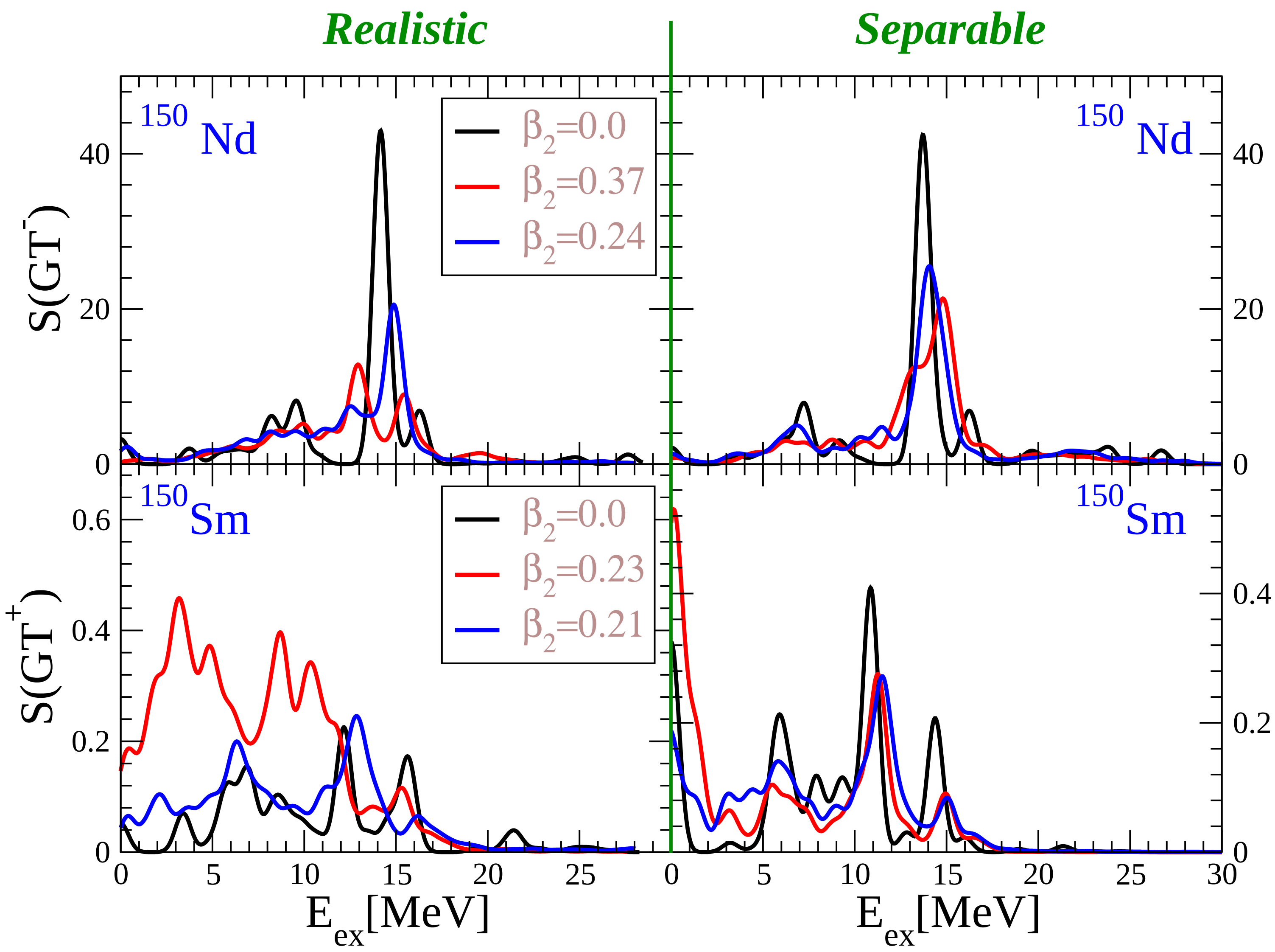
Results

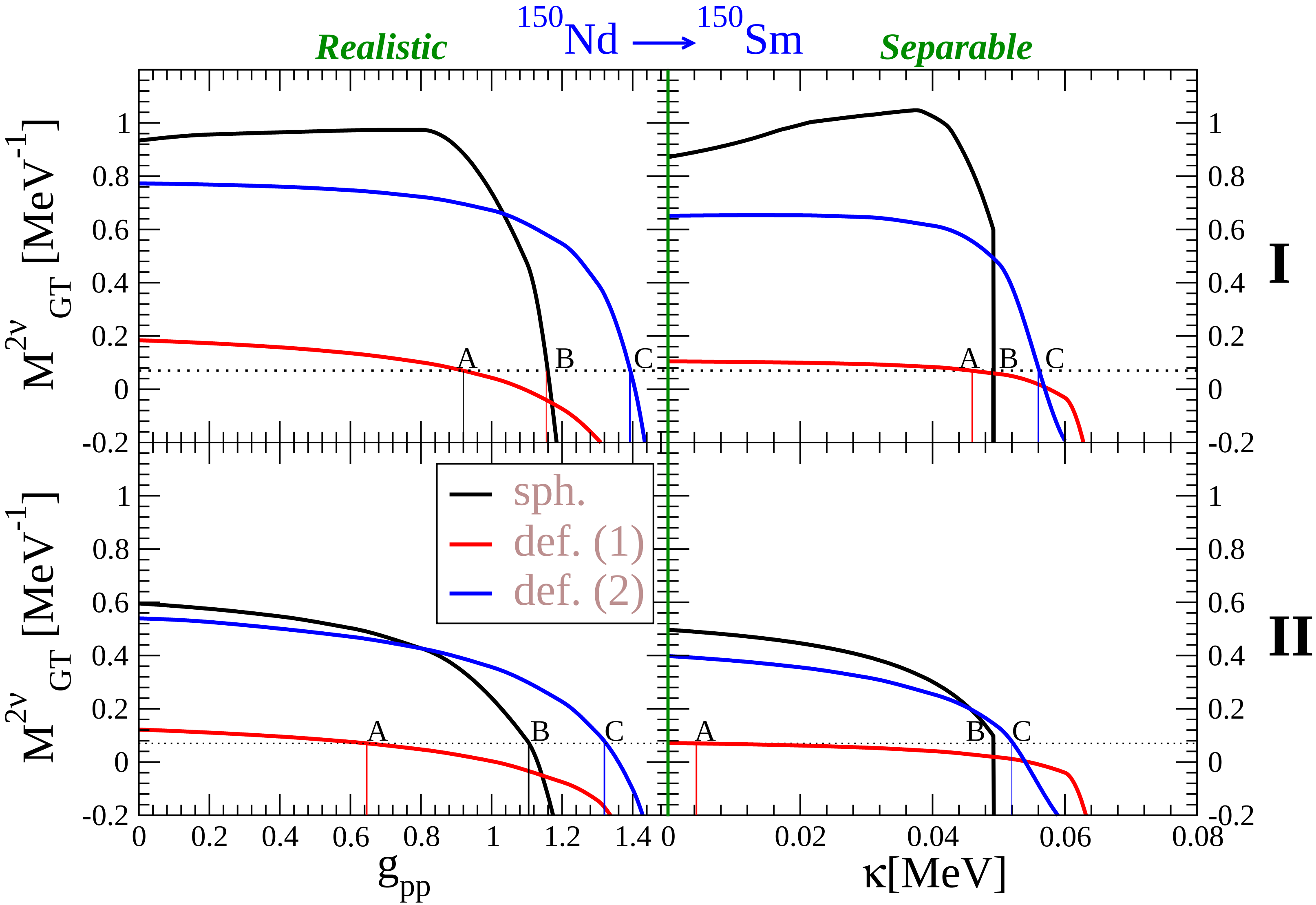


def.= exp. defor.: $\beta_2(^{76}Ge)= 0.1$, $\beta_2(^{76}Se)= 0.16$ (P. Raghavan, At. Data Nucl. Data Tabl. **42** (1989))

Results

GT strength functions





def. (1) — exp. defor.: $\beta_2(^{150}\mathrm{Nd}) = 0.37 \pm 0.09$, $\beta_2(^{150}\mathrm{Sm}) = 0.23 \pm 0.03$
(P. Raghavan, At. Data Nucl. Data Tabl. **42** (1989))

def. (2) — calc. defor.: $\beta_2(^{150}\mathrm{Nd}) = 0.24$, $\beta_2(^{150}\mathrm{Sm}) = 0.21$
(P. Moeller et al., At. Data Nucl. Data Tabl. **59** (1995))

Conclusions

- Realistic (G-matrix based) NN interaction is implemented in the QRPA equations for deformed nuclei

- GT strength functions and $2\nu\beta\beta$ decay matrix element are calculated for ^{76}Ge and ^{150}Nd.

- Prospect for QRPA calculation of $M^{0\nu}$ for ^{150}Nd is opened

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