Double beta decay in deformed nuclei
Why and how to describe ?

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Collaboration with

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- Matrix Elements
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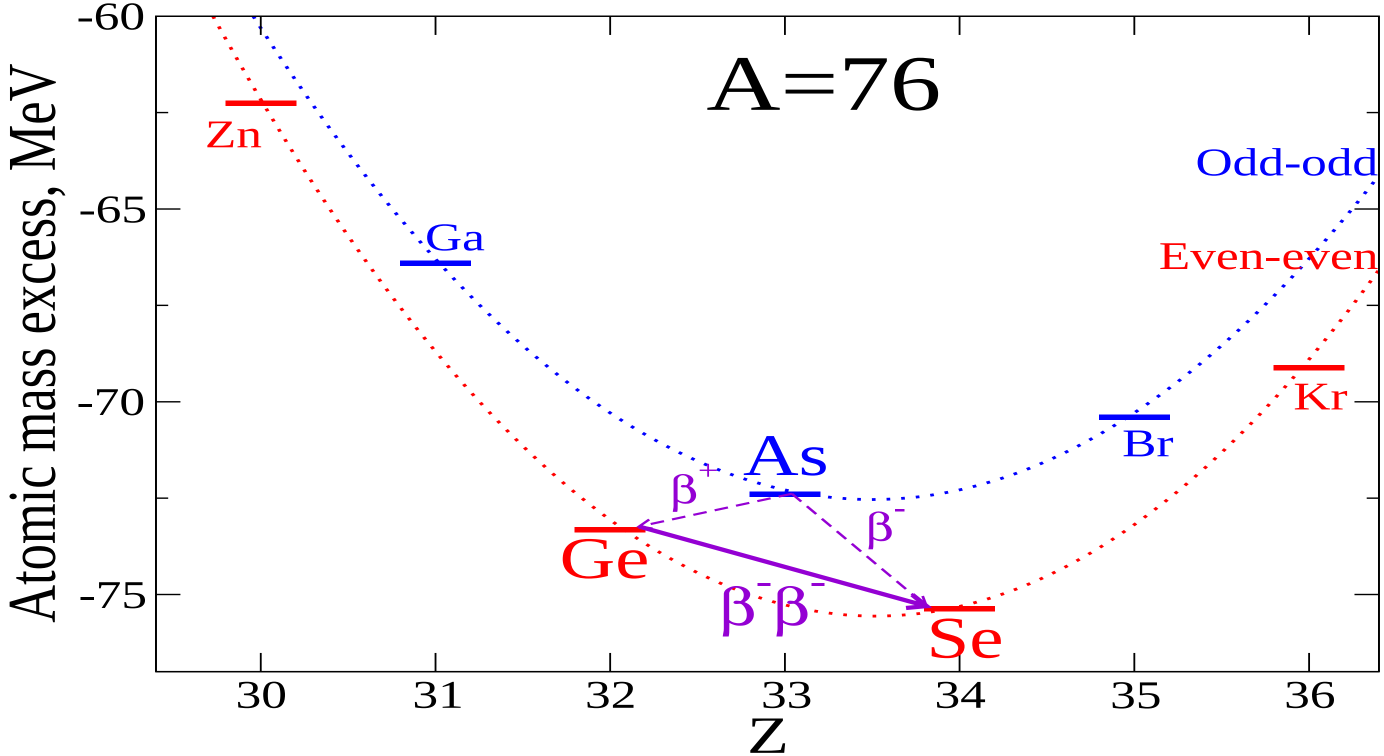
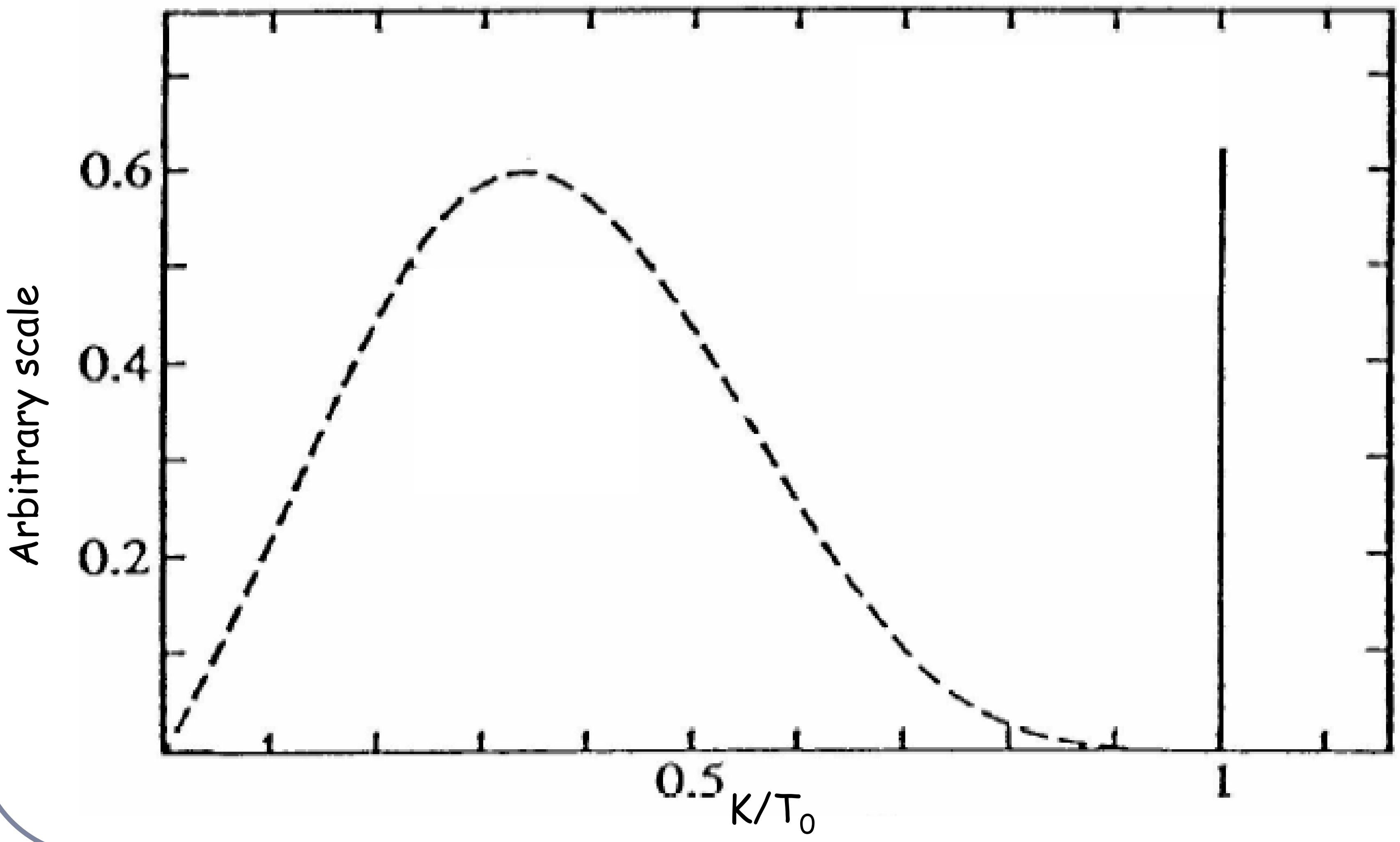
Introduction

Mass parabola

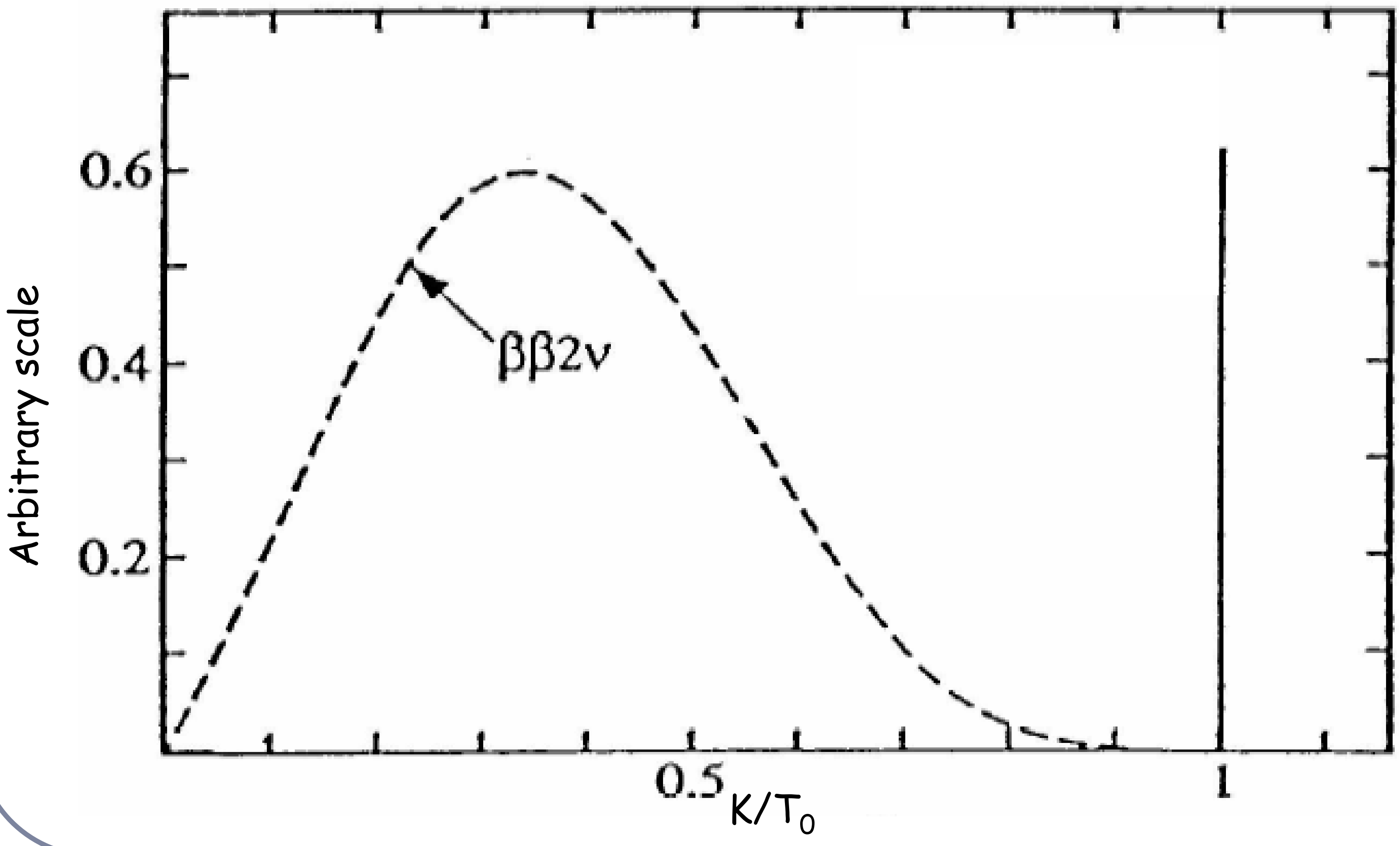


Mass parabolas: Coulomb interation + Nucleon pairing

Two electron energy spectrum



Two electron energy spectrum



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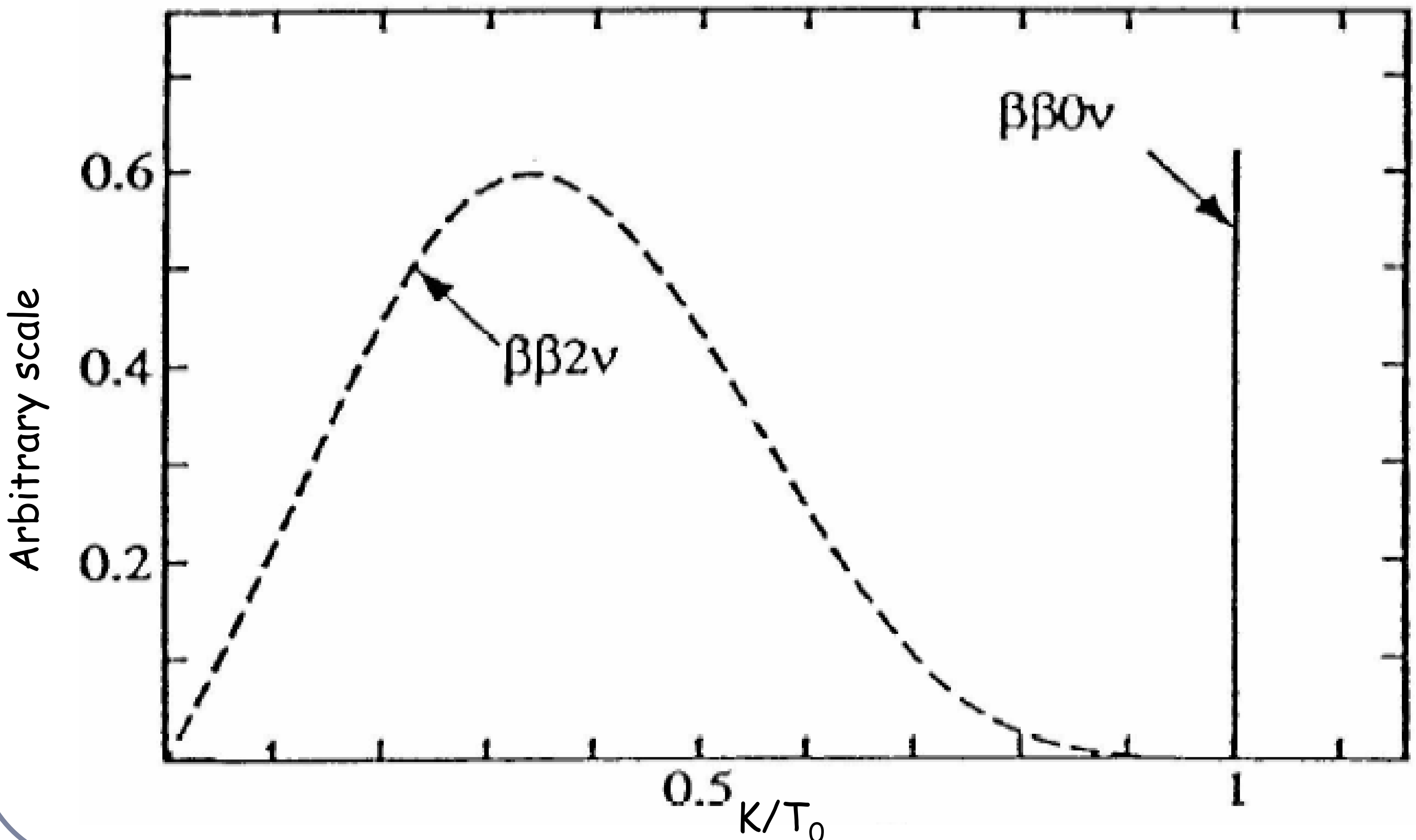
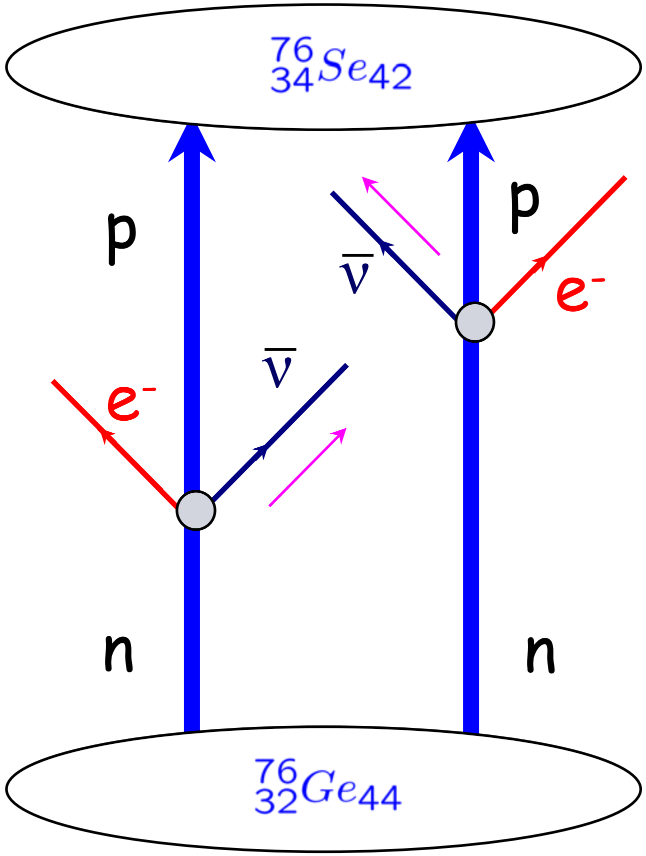


Two neutrino double beta decay ($2\nu\beta\beta$)

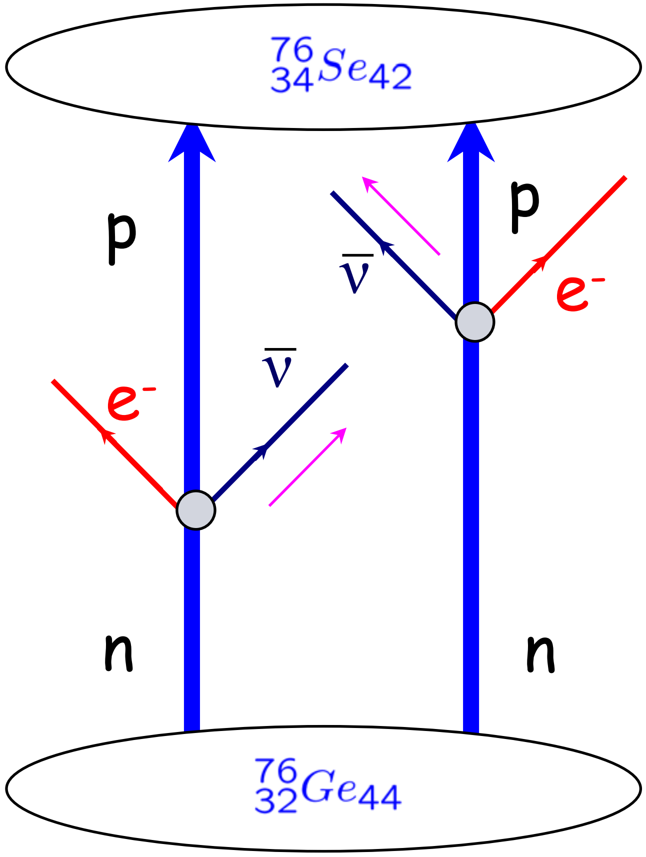
$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\overline{\nu}_e$$



Two neutrino double beta decay (2νββ)

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\overline{\nu}_{e}$$

This process fully consistent with SM of electroweak interaction.



measured $T^{2\nu}_{1/2}$ (A. Barabash, 2005)

Isotope	$T^{2\nu}_{1/2}$, in 10^{19} y
^{48}Ca	$4.2^{+2.1}_{-1.0}$
^{76}Ge	150 ± 10
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^{130}Te	90 ± 10
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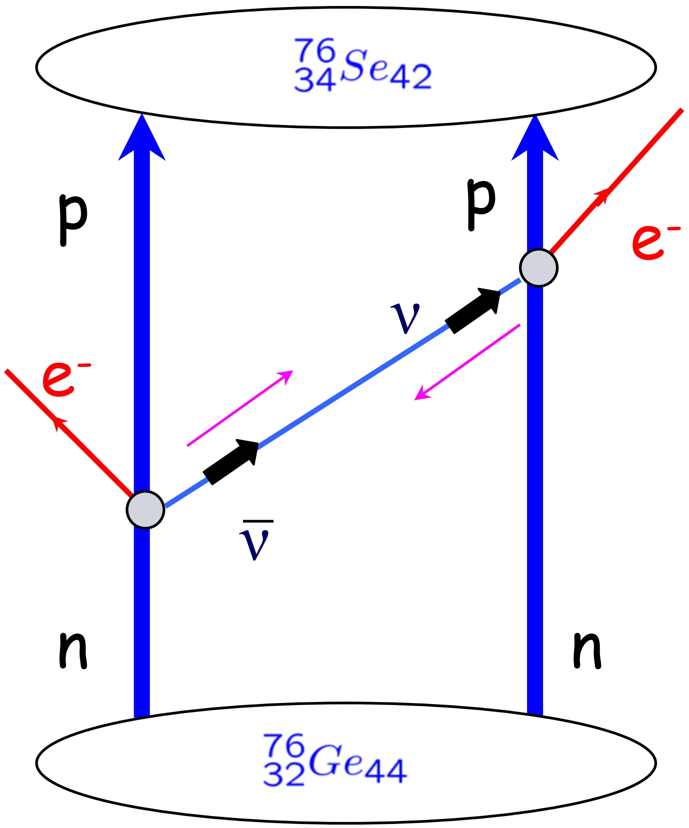
^{150}Nd	0.78 ± 0.07
^{238}U	200 ± 60

Neutrinoless double beta decay (0νββ)

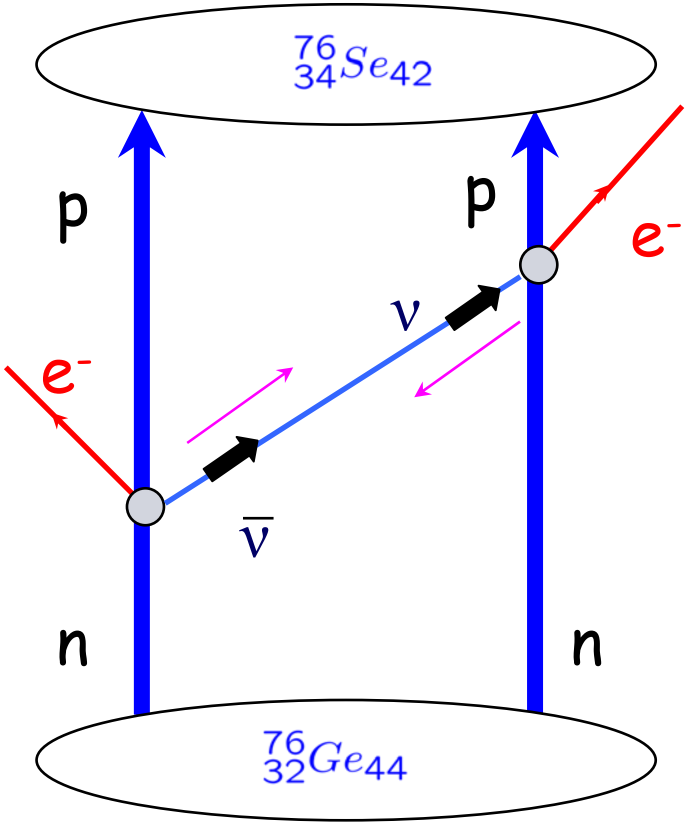
$$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$$



Neutrinoless double beta decay (0νββ)

$$(A,Z) \rightarrow (A,Z+2) + 2\,e^{-}$$

Forbidden in SM electroweak interaction and it may occur if lepton number conservation is not an exact symmetry of nature .



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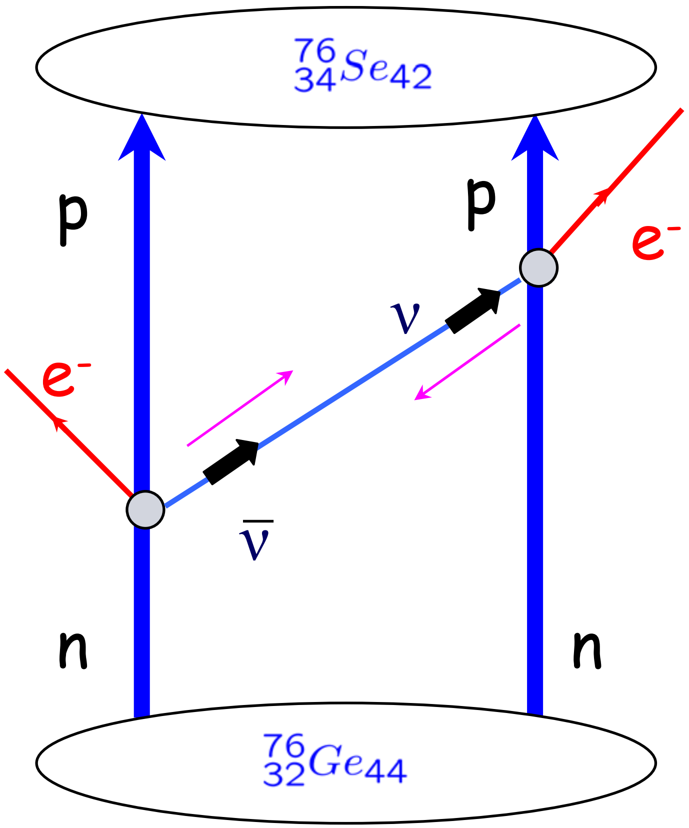
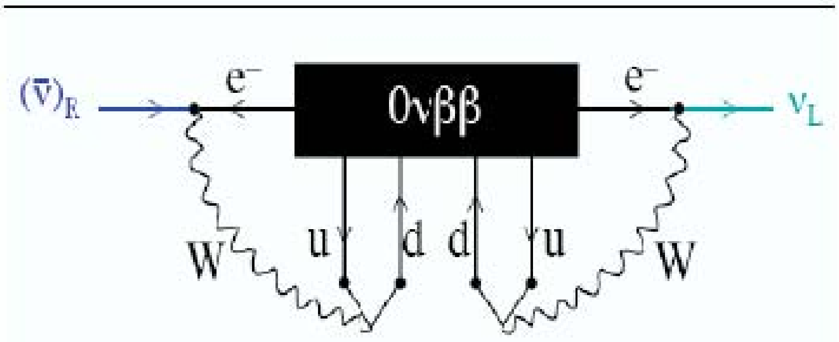
If it is observed ⇒ **neutrino is massive Majorana particle**



Majorana Mass

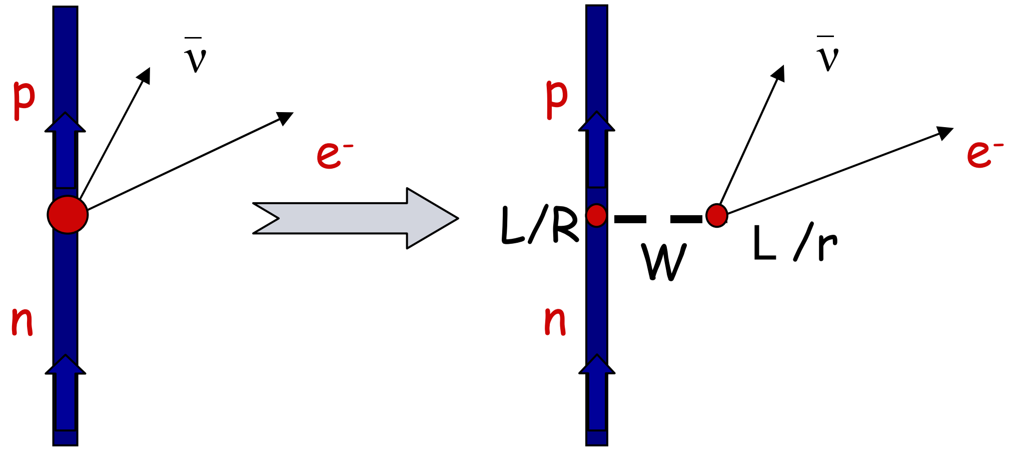
$$\mathcal{L}_M = m_D \overline{\nu}\nu + m_M \overline{\nu}\nu^c + m_M^* \overline{\nu^c}\nu$$

Schechter-Valle theorem



Grand Unification

Left-right symmetric SO(10) Models



W_1(81 GeV) $= W_L \cos\theta + W_R \sin\theta$

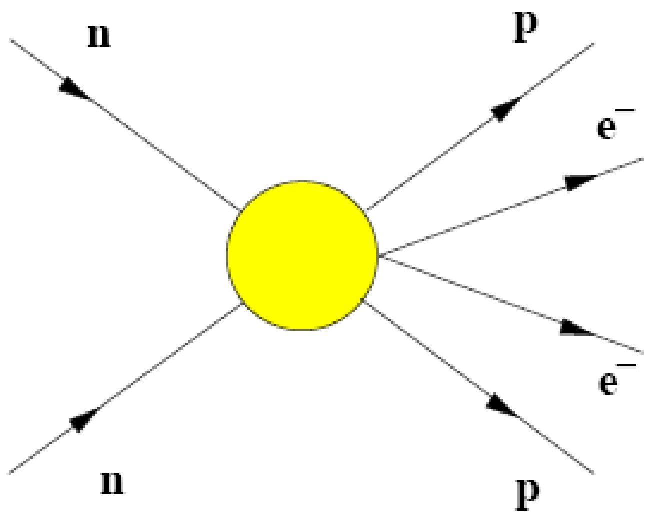
W_2(? GeV) $= W_R \cos\theta - W_L \sin\theta$

$$j^{\mu}_{l/r} = \bar{e}\,\gamma^{\mu}(1 \mp \gamma_5)\nu\,, \quad J^{\mu}_{L/R} = \bar{n}\,\gamma^{\mu}(g_V \mp g_A\gamma_5)p$$

$g_V=1$, $g_A=1.25$

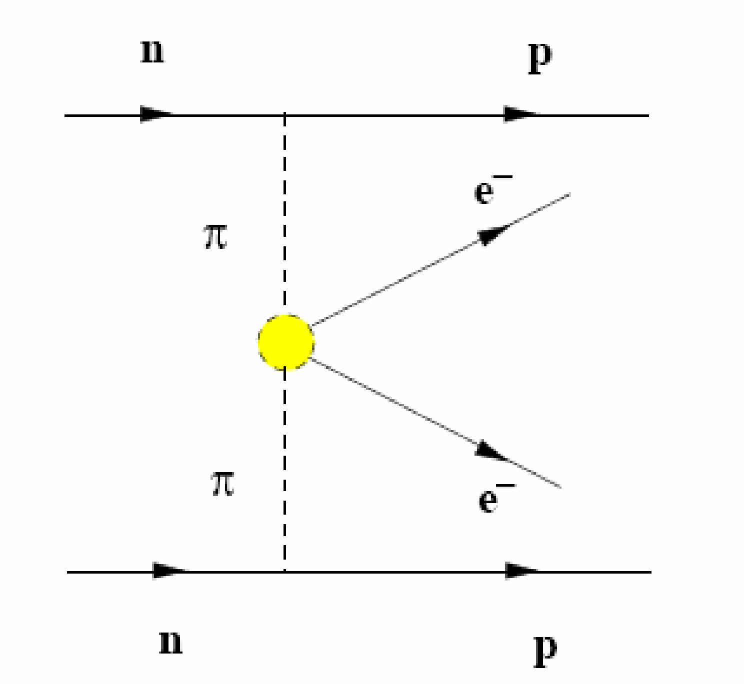
Heavy particle exchange

Two-nucleon mechanism



Can be neglected

Pion-exchnge mechanism



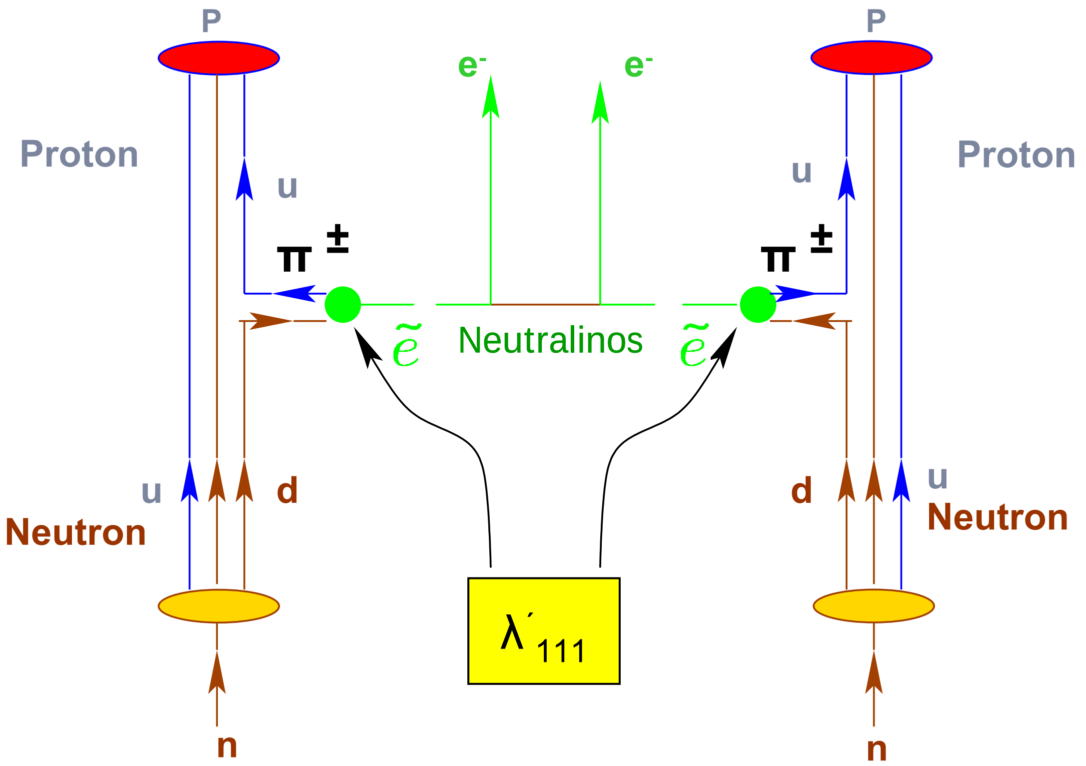
The dominant contribution

R-parity violating SUSY

Bosons ↔ Fermions

$$\tilde{\chi} = \tilde{\gamma}, \tilde{Z}^0, \tilde{h}_1^0, \tilde{h}_2^0$$

Neutralinos

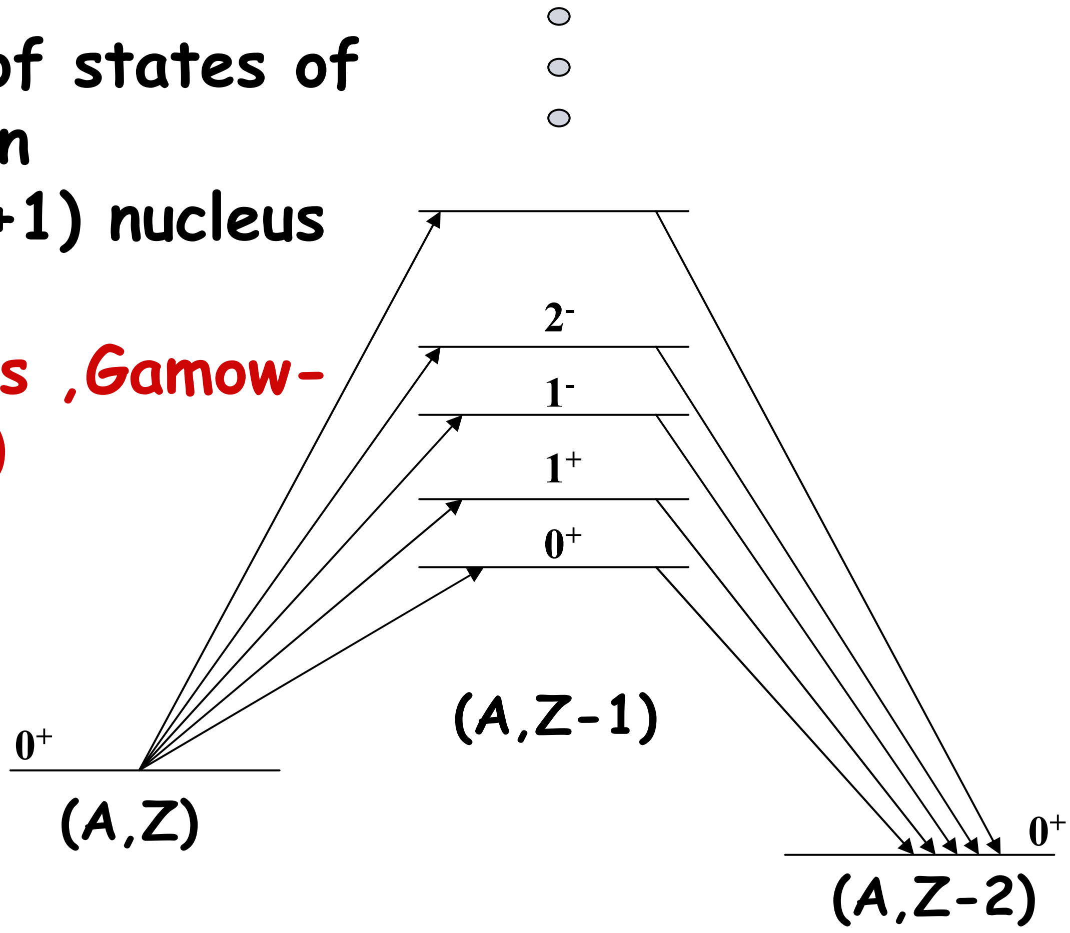


Faessler, Kovalenko, Simkovic, PRL(1997): coupling to pions can increase the SUSY 0-decay probability by a factor 10000!

Nuclear Dynamics of ββ Decay

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

(2νββ only 1^+ states ,Gamow-Teller transitions)



Matrix Elements

Frank Avignone: "Nuclear matrix elements for Double Beta Decay are as important as the data to determine Neutrino Mass" (Erice'05)

Matrix Elements

The rate of $2\nu\beta\beta$ decay is

$$1/T_{1/2}^{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

The rate of $0\nu\beta\beta$ decay is

$$1/T_{1/2}^{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 \langle m_\nu \rangle^2$$

The leptonic phase space factors G are accurately calculable.

The fundamental particle physics parameter $\langle m_\nu \rangle$ can be determined with the same accuracy as the nuclear matrix elements

2νββ decay : Description of the Gamow-Teller amplitudes

The double Gamow-Teller transition from g.s.to g.s.:

$$M_{GT}^{2\nu} = \sum_{m_i m_f} \frac{\langle 0_f^+ \| \beta^- \| 1_{m_f}^+ \rangle \langle 1_{m_i}^+ \| \beta^- \| 0_i^+ \rangle}{(E^{m_f} + E^{m_i})/2}$$

0ν decay :

All multipoles contribute(0^+,1^-, ……), enhanced role of nucleon short range correlations.

$$|M_{0\nu}| \equiv M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} = \left\langle f \left| \sum_{lk} H(r_{lk}, \overline{A}) \tau_l^+ \tau_k^+ (\vec{\sigma}_l . \vec{\sigma}_k - \frac{g_V^2}{g_A^2}) \right| i \right\rangle$$

Neutrino Potential

Why to focus on the nuclear deformation?

Nuclear transition	$\langle M'^{0\nu} \rangle$ RQRPA	$\langle M'^{0\nu} \rangle$ QRPA	$T_{1/2}^{0\nu}(\langle m_{\beta\beta} \rangle = 50 meV)$ [yrs]
$^{76}Ge \to {}^{76}Se$	3.92	4.51	8.60 X 10^{26}
$^{100}Mo \to {}^{100}Ru$	2.78	3.34	2.37 X 10^{26}
$^{130}Te \to {}^{130}Xe$	2.95	3.66	2.16 X 10^{26}
$^{150}Nd \to {}^{150}Sm$	4.16	4.74	2.23 X 10^{25}

V.Rodin, A. Faessler, F. Šimkovic., P. Vogel, nucl-th/07006.4304

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V.Rodin, A. Faessler, F. Šimkovic., P. Vogel, nucl-th/07006.4304

Decay rate dependance:

	1. Q-value (MeV)	2. Coulomb Effects * Z
$^{76}Ge \rightarrow {}^{76}Se$	2.039	32
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	42
$^{130}Te \rightarrow {}^{130}Xe$	2.533	52
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	60

* Coulomb Effects α $(Z/1-\exp(-cZ))^4$

measured $T^{2\nu}_{1/2}$ (A. Barabash, 2005)

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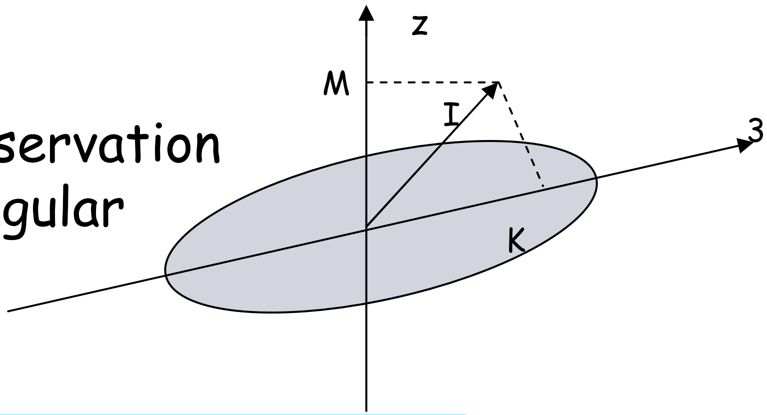
Deformed Nuclei:

Use of deformed single particle basis

⇨ the s.p. wave function without conservation of the total angular momentum, only angular momentum projection (K) is conserved.



$$M_{GT}^{2\nu} = \sum_{m_i m_f} \sum_{K=0,\pm1} \frac{\langle 0_f^+ \| \beta_K^- \| 1_{m_i}^+(K) \rangle \langle 1_{m_f}^+(K) | 1_{m_i}^+(K) \rangle \langle 1_{m_i}^+(K) \| \beta_K^- \| 0_i^+ \rangle}{(E_K^{m_f} + E_K^{m_i})/2}$$

The overlap is necessary since the two sets of intermediate states calculated within the QRPA are not the same.

Where,

$$\beta_K^- = \sum_{pn} \langle p | \tau^+ \sigma_K | n \rangle a_p^+ a_n$$

Quasi Random Phase Approximation

pn QRPA : successfully exploited in nuclear physics to describe the properties of excited states of open shell nuclei and to calculate intensities of various nuclear reaction, including double beta decay but Violates PEP by generating too many ground state correlations.

RQRPA: Taking into account the quasiparticle occupation numbers in the QRPA ground state, restore the PEP but violates the model independent ISR .

SCQRPA: Fixing the number of particles in the ground state, but also violates the model independent ISR .

FR-QRPA: Fulfills the model independent ISR.

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QRPA Formalism (deformed nuclei)

QRPA wave functions of GT excitations for even-even nuclei in the laboratory frame

$$|1M(K),m\rangle = \sqrt{\frac{3}{16\pi^2}}\left[D^1_{MK}(\varphi,\vartheta,\psi)Q^{m^+}_{K} + (-1)^{1+K}D^1_{M-K}(\varphi,\vartheta,\psi)Q^{m^+}_{-K}\right]|RPA\rangle$$

$(K=\pm 1)$

$$|1M(K),\ m\rangle = \sqrt{\frac{3}{8\pi^2}}\left[D^1_{MK}(\varphi,\vartheta,\psi)Q^{m^+}_{K}\right]RPA\rangle$$

$(K=0)$

The intrinsic states are generated by the phonon creation operator

$$Q_K^{m\dagger} = \sum_i (X_{i,K}^m A_i^\dagger(K) - Y_{i,K}^m \tilde{A}_i(K))$$

$$A_{pn}^\dagger(K) = \alpha_{p\rho_p}^\dagger \tilde{\alpha}_{n\rho_n}^\dagger \quad , \quad [A_i, A_j^\dagger] = \delta_{ij} + X$$

The quasi particle creation and annihilation operators can be defined by the Bogolyubov transformation

$$\begin{pmatrix} \alpha_\tau^\dagger \\ \tilde{\alpha}_\tau \end{pmatrix} = \begin{pmatrix} u_\tau & v_\tau \\ -v_\tau & u_\tau \end{pmatrix} \begin{pmatrix} a_\tau^\dagger \\ \tilde{a}_\tau \end{pmatrix}$$

Excitation energy and forward-and backward-going amplitudes - by solving QRPA matrix equation:

$$\begin{pmatrix} \mathcal{A}(K) & \mathcal{B}(K) \\ -\mathcal{B}(K) & -\mathcal{A}(K) \end{pmatrix} \begin{pmatrix} X_K^m \\ Y_K^m \end{pmatrix} = \omega_K^m \begin{pmatrix} X_K^m \\ Y_K^m \end{pmatrix}$$

where

$$\mathcal{A}_{ij}(K) = \langle RPA | [A_i, [H, A_j^\dagger]] | RPA \rangle$$

$$\mathcal{B}_{ij}(K) = -\langle RPA | [A_i, [H, \widetilde{A}_j]] | RPA \rangle$$

Nuclear Hamiltonian

The total Hamiltonian is defined as: $H = H_o + H_{int}$

$$H_o = \sum_{\tau} \varepsilon_{\tau} a_{\tau}^{\dagger} a_{\tau} \quad (\tau = p, n)$$ Single particle part

$$H_{int} = \sum_{pnp'n'} V_{pn\,p'n'} a_p^{\dagger} a_n^{\dagger} a_{n'} a_{p'}$$ Residual two body interaction

Single Particle States

Single-particle wavefunctions in deformed Woods-Saxon potential :

$$\left|\tau\rho_\tau\right\rangle = \sum_{N_d n_z} [b^{(+)}_{N n_z \Omega_\tau} \left|(N_d n_z \Lambda_\tau), \Omega_\tau = \Lambda_\tau + 1/2\right\rangle \left|\Sigma = 1/2\right\rangle$$

$$+ b^{(-)}_{N n_z \Omega_\tau} \left|(N_d n_z \Lambda_\tau + 1), \Omega_\tau = \Lambda_\tau + 1 - 1/2\right\rangle \left|\Sigma = -1/2\right\rangle]$$

Deformed harmonic oscillator wave function

Spin wave function

The selection rules $\Omega_p - \Omega_n = K$ for K= 0, ±1 and $\pi_p \pi_n = 1$

$$\mathcal{A}_{p_1n_1p_2n_2}(K) = (E_{p_1} + E_{n_1})\delta_{p_1p_2}\delta_{n_1n_2} + g_{pp}[V_{p_2\tilde{n}_2p_1\tilde{n}_1}(u_{p_1}u_{n_1}u_{p_2}u_{n_2}) + V_{\tilde{p}_1n_1\tilde{p}_2n_2}(v_{p_1}v_{n_1}v_{p_2}v_{n_2})]$$

$$-g_{ph}[V_{p_2n_1p_1n_2}(u_{p_2}v_{n_2}v_{n_1}u_{p_1}) + V_{p_1n_2p_2n_1}(v_{p_1}u_{n_1}v_{p_2}u_{n_2})]$$

$$\mathcal{B}_{p_1n_1p_2n_2}(K) = -g_{pp}[V_{p_2\tilde{n}_2p_1\tilde{n}_1}(v_{p_1}v_{n_1}u_{p_2}u_{n_2}) + V_{\tilde{p}_1n_1\tilde{p}_2n_2}(u_{p_1}u_{n_1}v_{p_2}v_{n_2})]$$

$$-g_{ph}[V_{p_2n_1p_1n_2}(v_{p_1}u_{n_1}u_{p_2}v_{n_2}) + V_{p_1n_2p_2n_1}(v_{p_2}u_{n_2}u_{p_1}v_{n_1})]$$

where $E_\tau = \sqrt{\varepsilon_\tau^2 + \Delta_\tau^2}$

Separable Interaction

$$H_{int} = \chi \sum_{K=0,\pm 1} (-1)^K (\beta^-_{1K}\beta^+_{1-K} + \beta^+_{1-K}\beta^-_{1K})$$

$$- \kappa \sum_{K=0,\pm 1} (-1)^K (P^-_{1K}\ P^+_{1-K} + P^+_{1-K}\ P^-_{1K})$$

The operators β^- and P^- are ph and pp components of the spin-isospin $\tau^+\sigma$, namely,

$$\beta^-_K = \sum_{pn} \langle p | \tau^+\sigma_K | n \rangle a^\dagger_p a_n, \qquad \beta^+_K = (\beta^-_K)^\dagger$$

$$P^-_K = \sum_{pn} \langle p | \tau^+\sigma_K | n \rangle a^\dagger_p \tilde{a}^\dagger_n, \qquad P^+_K = (P^-_K)^\dagger$$

Realistic Interaction:

As a realistic two-body interaction we use the nuclear matter G-matrix.

$$G = V + V \frac{Q}{W - H_o + i\varepsilon} G$$

Bethe-Goldstone equation

The G-matrix in the deformed single particle basis:

$$\left|N_d n_z \Lambda_\tau\right\rangle = \sum_{N_o}\sum_{l} A^{N_o l n_r}_{N_d n_z \Lambda_\tau}\left|N_o l \Lambda_\tau\right\rangle$$

Wave function in deformed basis

overlap integral

Wave function in spherical basis

Single particle state

$$\left|\tau\rho_\tau\right\rangle = \sum_{N_o lj} B^{(\tau)}_{N_o lj}\left|(N_o lj),\Omega_\tau\right\rangle$$

deformed Woods-saxon state

spherical harmonic oscillator state

Two body wavefunction

$$\left|p\rho_p n\rho_n\right\rangle = \sum_{(N_o lj)_p}\sum_{(N_o lj)_n} B^{(p)}_{(N_o lj)_p} B^{(n)}_{(N_o lj)_n}\sum_{J} C^{JK}_{j_p\Omega_p j_n\Omega_n}\left|(N_o lj)_p (N_o lj)_n, JK\right\rangle$$

The G-matrix in the deformed single particle basis:

$$\left\langle p\rho_p \widetilde{n\,\rho_n} \middle| G \middle| p'\rho_{p'} \widetilde{n'\rho_{n'}} \right\rangle = \sum_J \sum_{(N_o lj)_p} \sum_{(N_o lj)_n} \sum_{(N_o lj)_{p'}} \sum_{(N_o lj)_{n'}} B^{(p)}_{(N_o lj)_p} B^{(n)}_{(N_o lj)_n} B^{(p')}_{(N_o lj)_{p'}} B^{(n')}_{(N_o lj)_{n'}}$$

$$\times \quad (-1)^{j_n - \Omega_n} \quad (-1)^{j_n' - \Omega_n'} \; C^{JK}_{j_p \Omega_p j_n \Omega_n} C^{JK}_{j_{p'} \Omega_{p'} j_{n'} \Omega_{n'}}$$

$$\times \quad \left\langle (N_o lj)_p (N_o lj)_n, J \middle| G \middle| (N_o lj)_{p'} (N_o lj)_{n'}, J \right\rangle$$

G-matrix elements in
spherical single particle basis

Bonn CD potential

Nuclear deformation

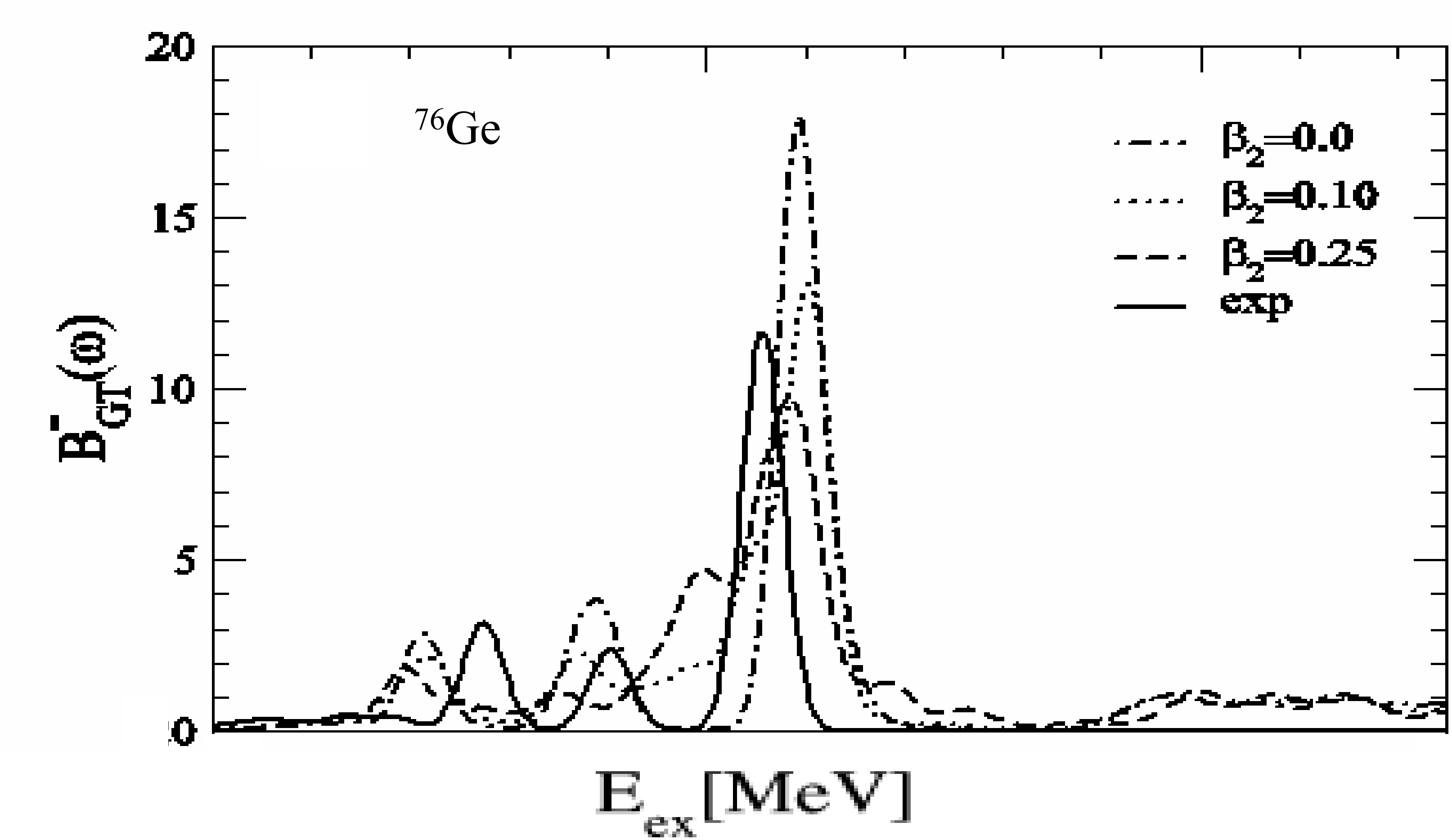
$$\beta = \sqrt{\frac{\pi}{5}} \frac{Q_p}{Z r_c^2}$$

Exp. (nuclear reorientation method)
Theor. I (Rel. mean field theory)
Theor. II (Microsc.-Macrosc. Model of Moeller and Nix)

Nucl.	Exp	Theor. I	Theor. II
^{48}Ca	0.00	0.00	0.00
^{48}Ti	+0.17	-0.01	0.00
^{76}Ge	+0.09	0.16	0.14
^{76}Se	+0.16	-0.24	-0.24
^{82}Se	+0.10	0.13	0.15
^{82}Kr		0.12	0.07
^{96}Zr		0.22	0.22
^{96}Mo	+0.07	0.17	0.08
^{100}Mo	+0.14	0.25	0.24
^{100}Ru	+0.14	0.19	0.16
^{116}Cd	+0.11	-0.26	-0.24
^{116}Sn	+0.04	0.00	0.00
^{128}Te	+0.01	-0.00	0.00
^{128}Xe		0.16	0.14
^{130}Te	+0.03	0.03	0.00
^{130}Xe		0.13	-0.11
^{136}Xe		0.00	0.00
^{136}Ba		0.00	0.00
^{150}Nd	+0.37	0.22	0.24
^{150}Sm	+0.23	0.18	0.21

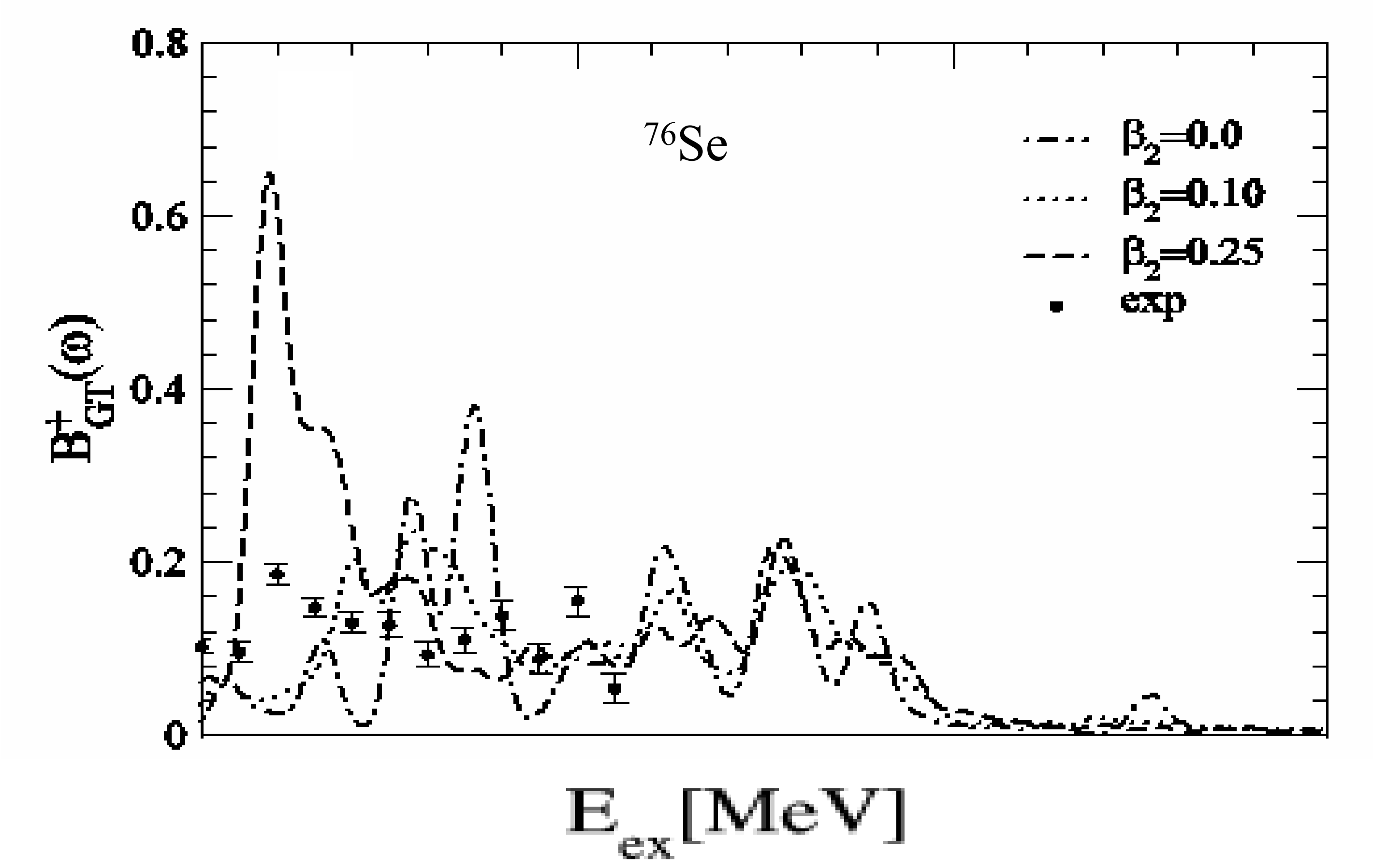
Separable Interaction

β⁻ strength



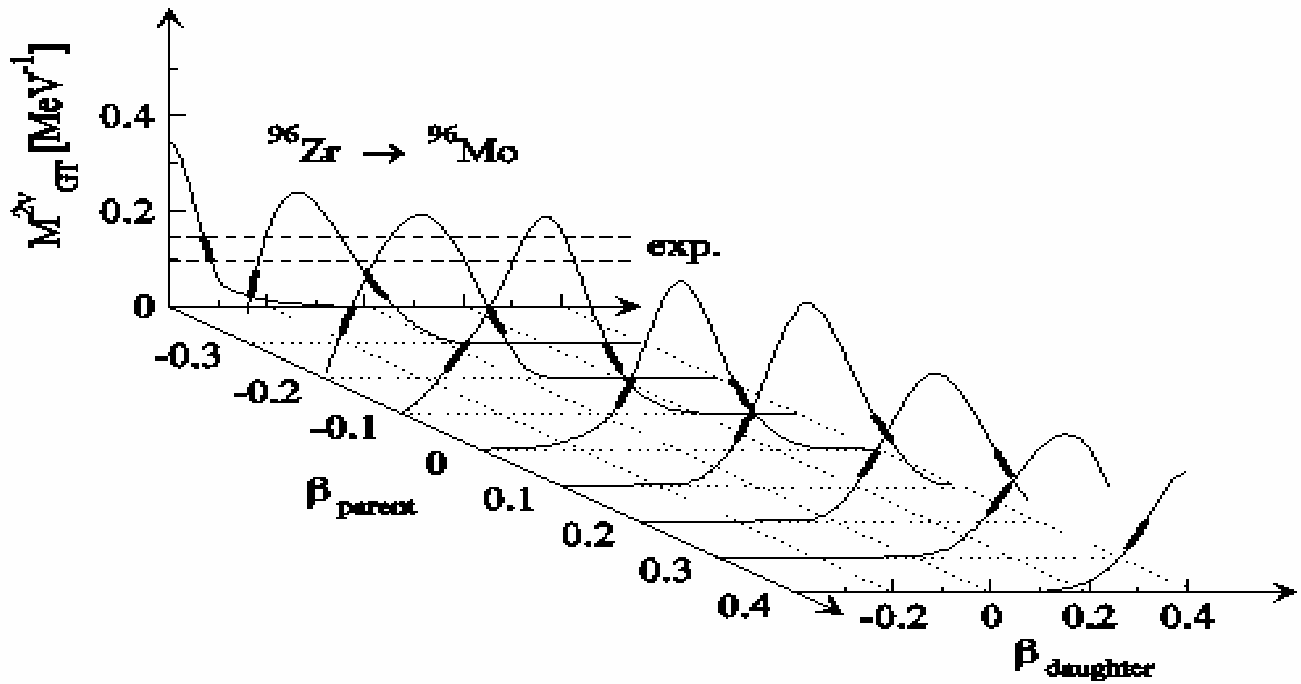
Šimkovic, Pacearescu, Faessler. NPA 733 (2004) 321

β⁺ strength



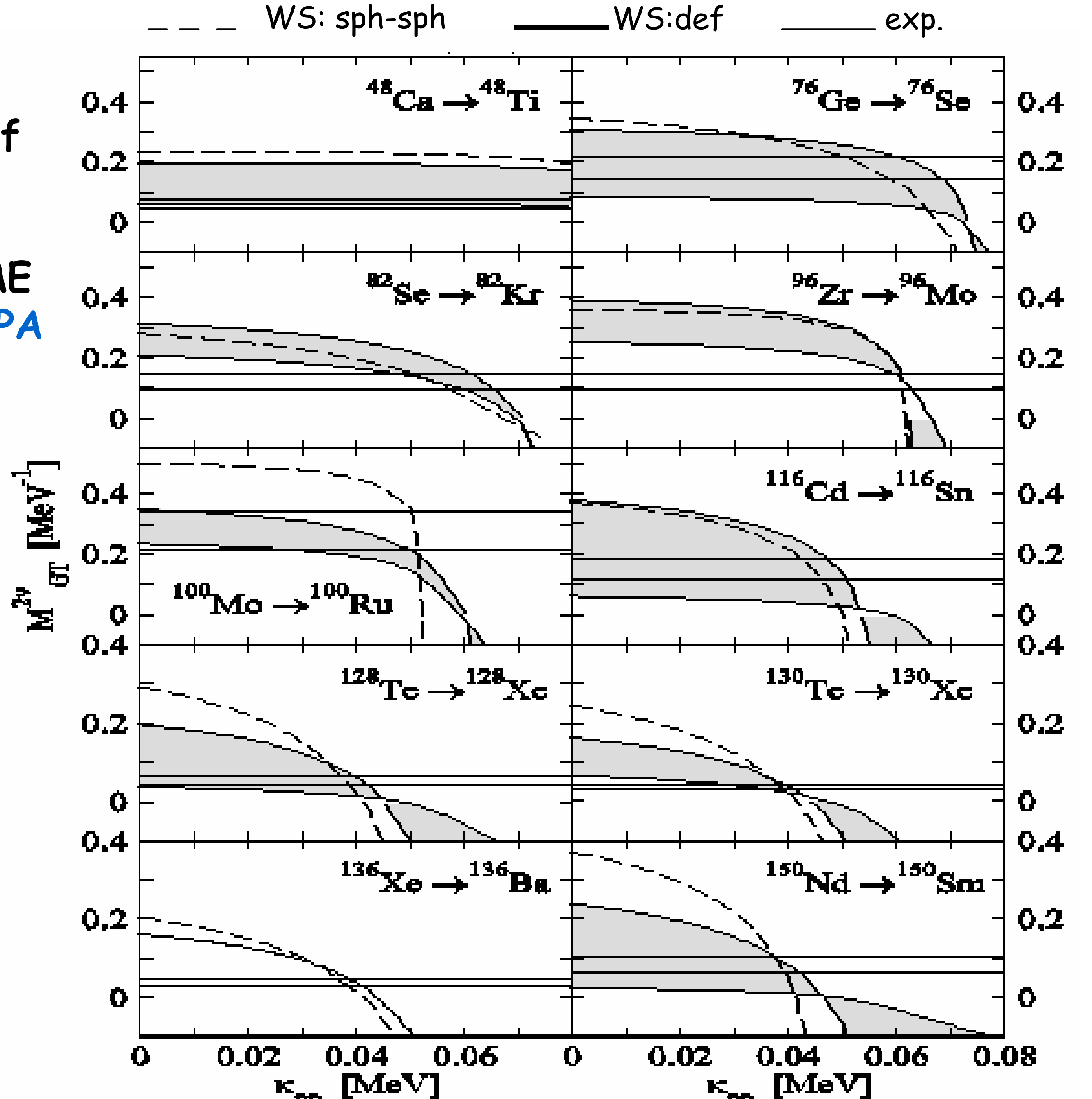
0.8
0.6
0.4
0.2
0
$B^+_{GT}(\omega)$
^{76}Se
β_2=0.0
β_2=0.10
β_2=0.25
exp
E_{ex}[MeV]

The suppression of the NME depends on relative deformation of initial and final nuclei



Alvarez, Sarriguren, Moya, Pacearescu, Faessler, Šimkovic,
Phys. Rev. C 70 (2004) 321

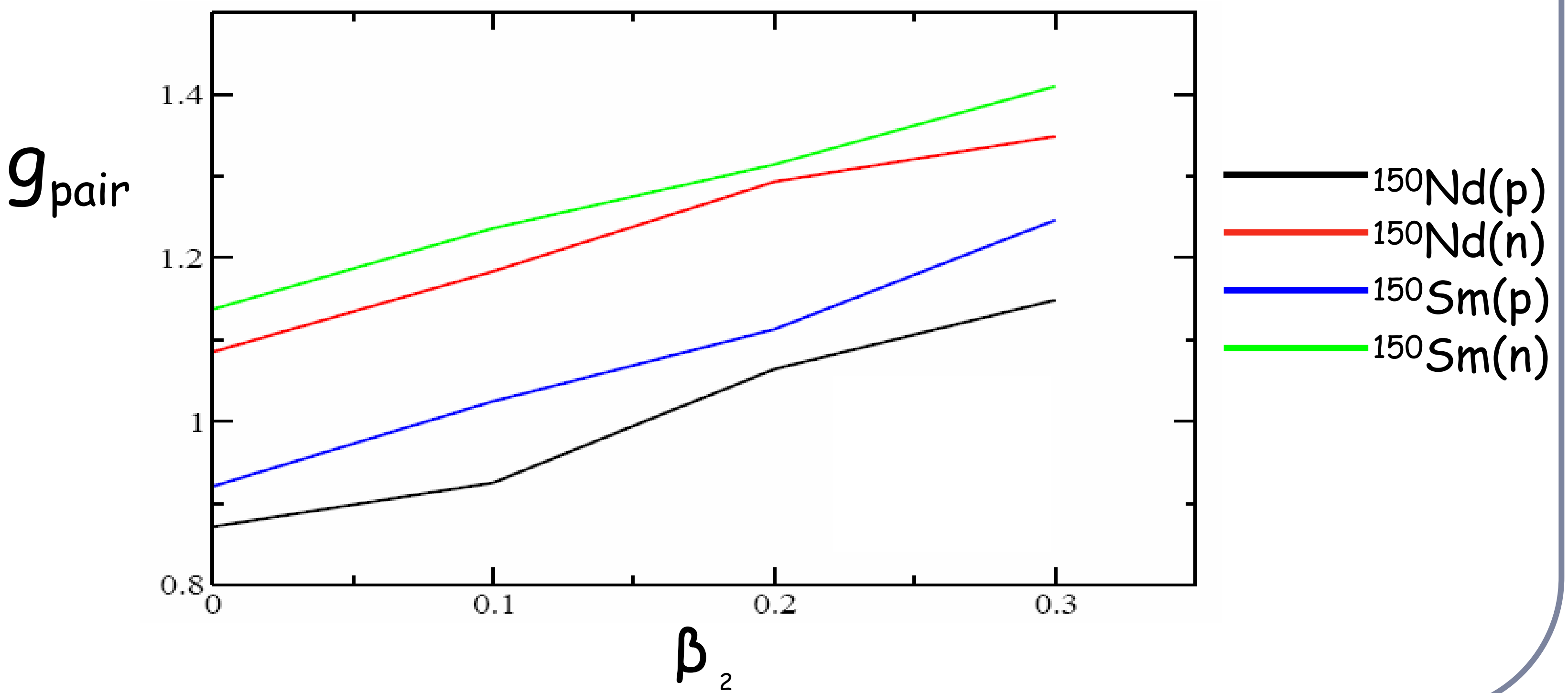
Systematic study of the deformation effect on the 2νββ-decay NME within deformed QRPA

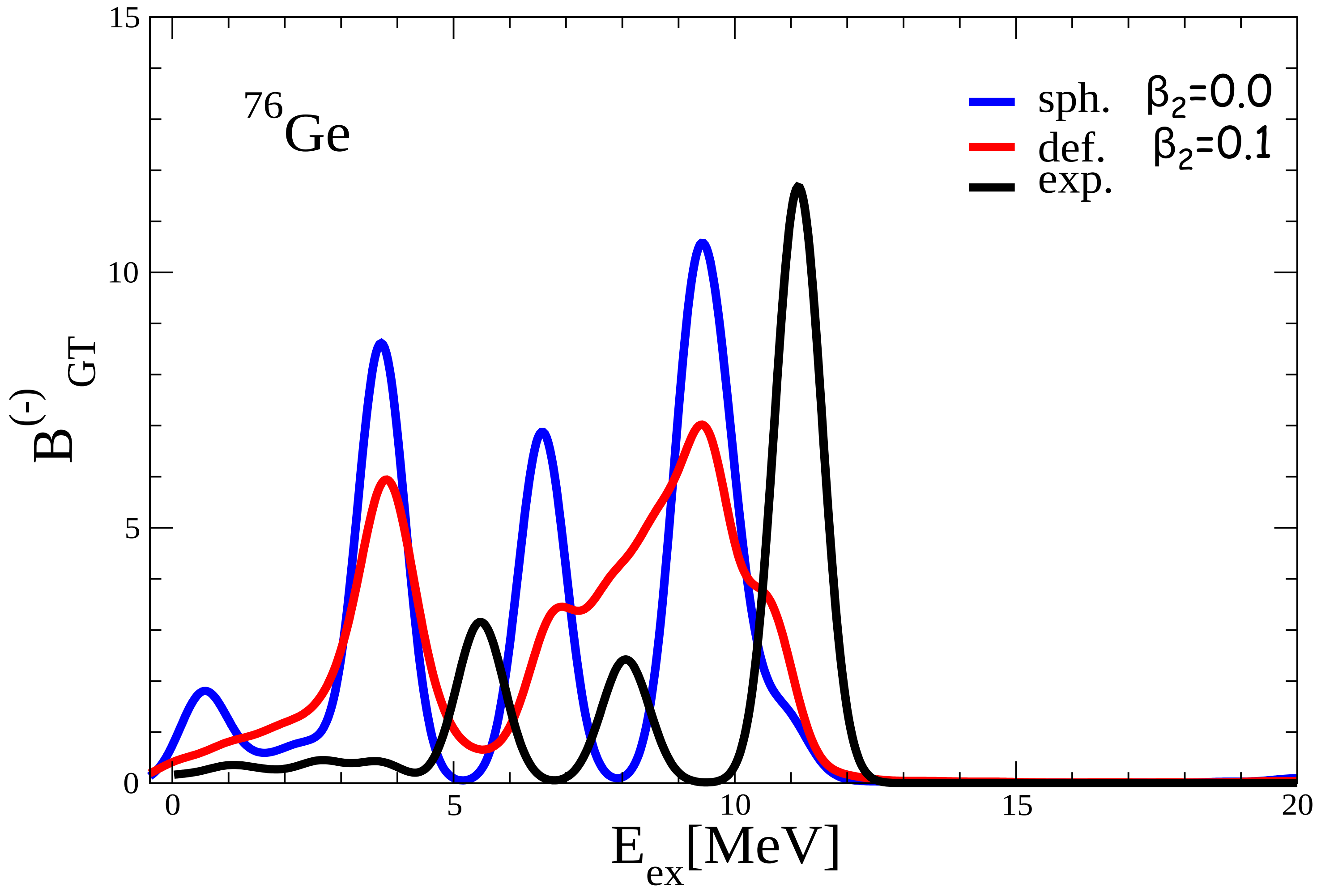


Alvarez,Sarriguren,Moya,Pacearescu, Faessler, Šimkovic, Phys. Rev. C 70 (2004) 321

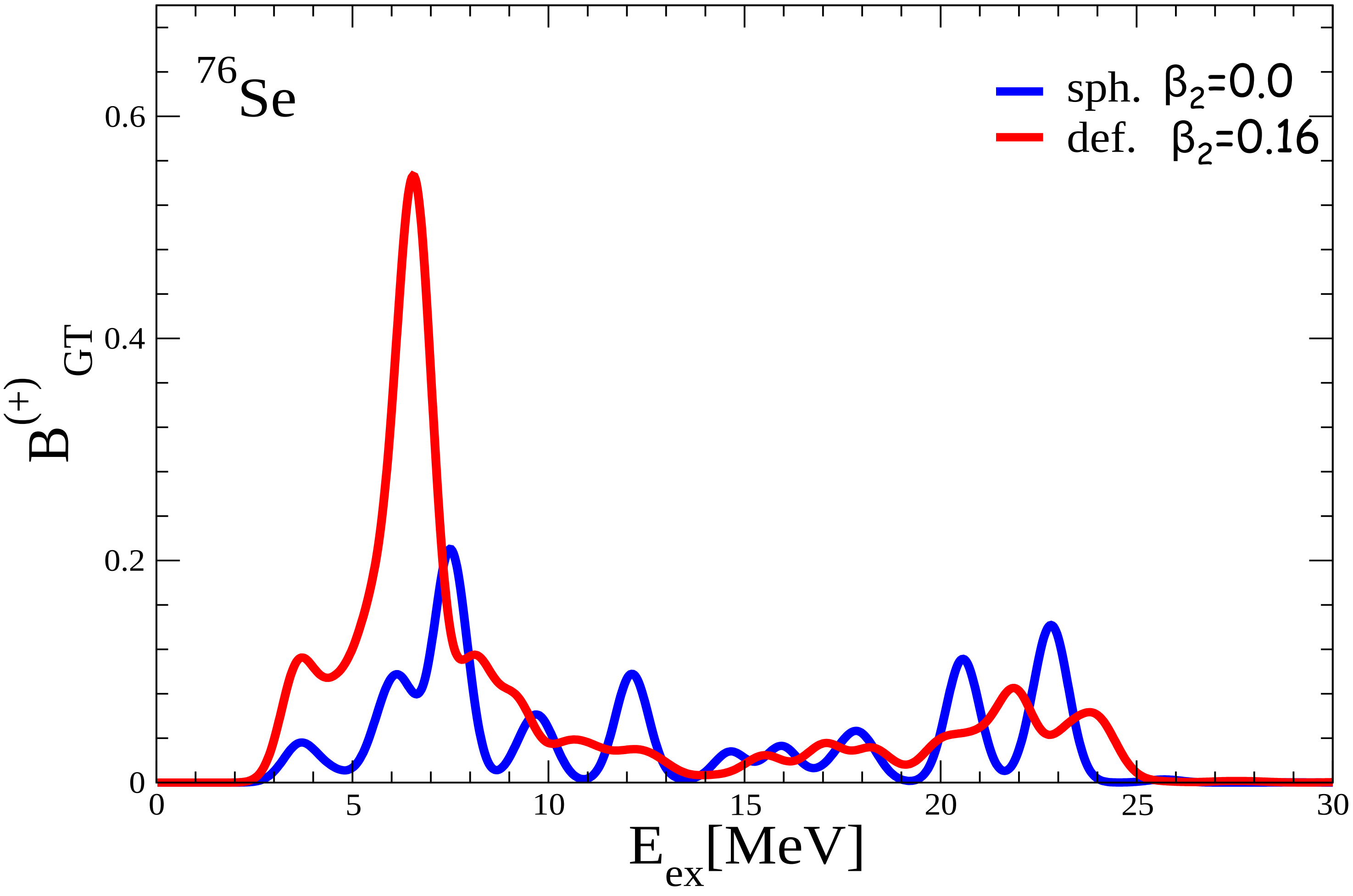
Realistic Forces

- The BCS equation is solved and the strenghts g^p_{pair} and g^n_{pair} are determined to reproduce the experimental odd-even mass difference for each nucleus

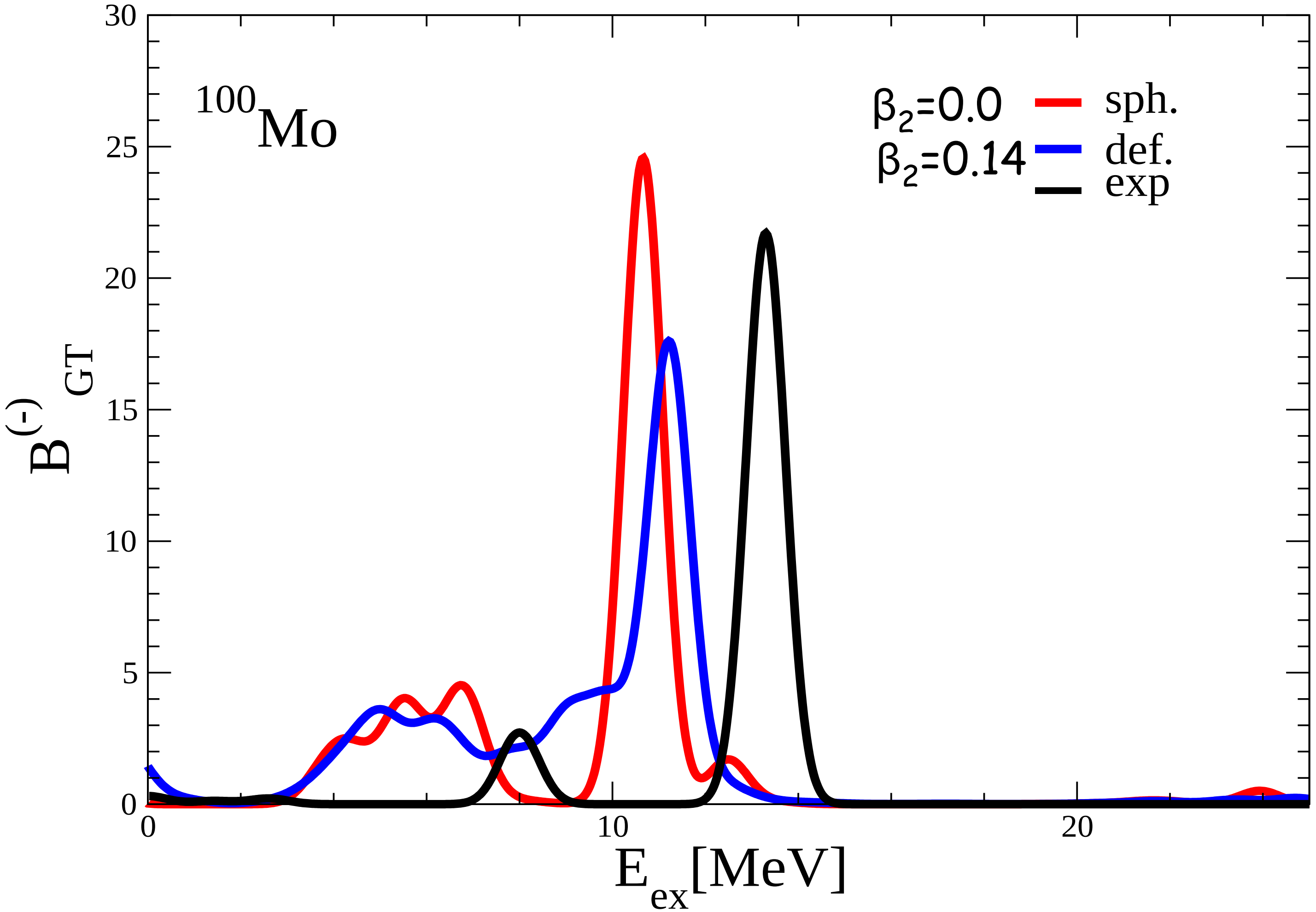




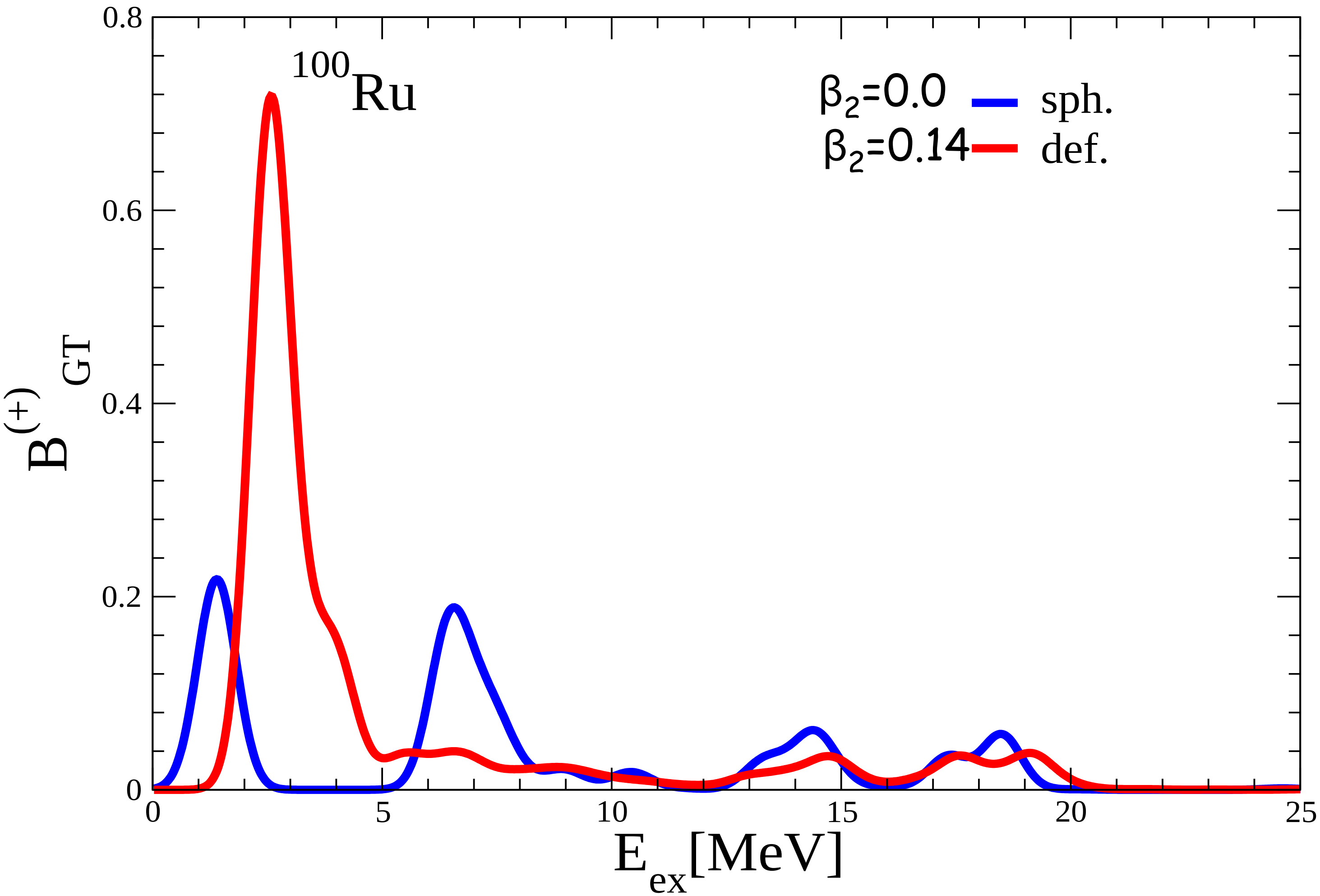
g_{ph}=1



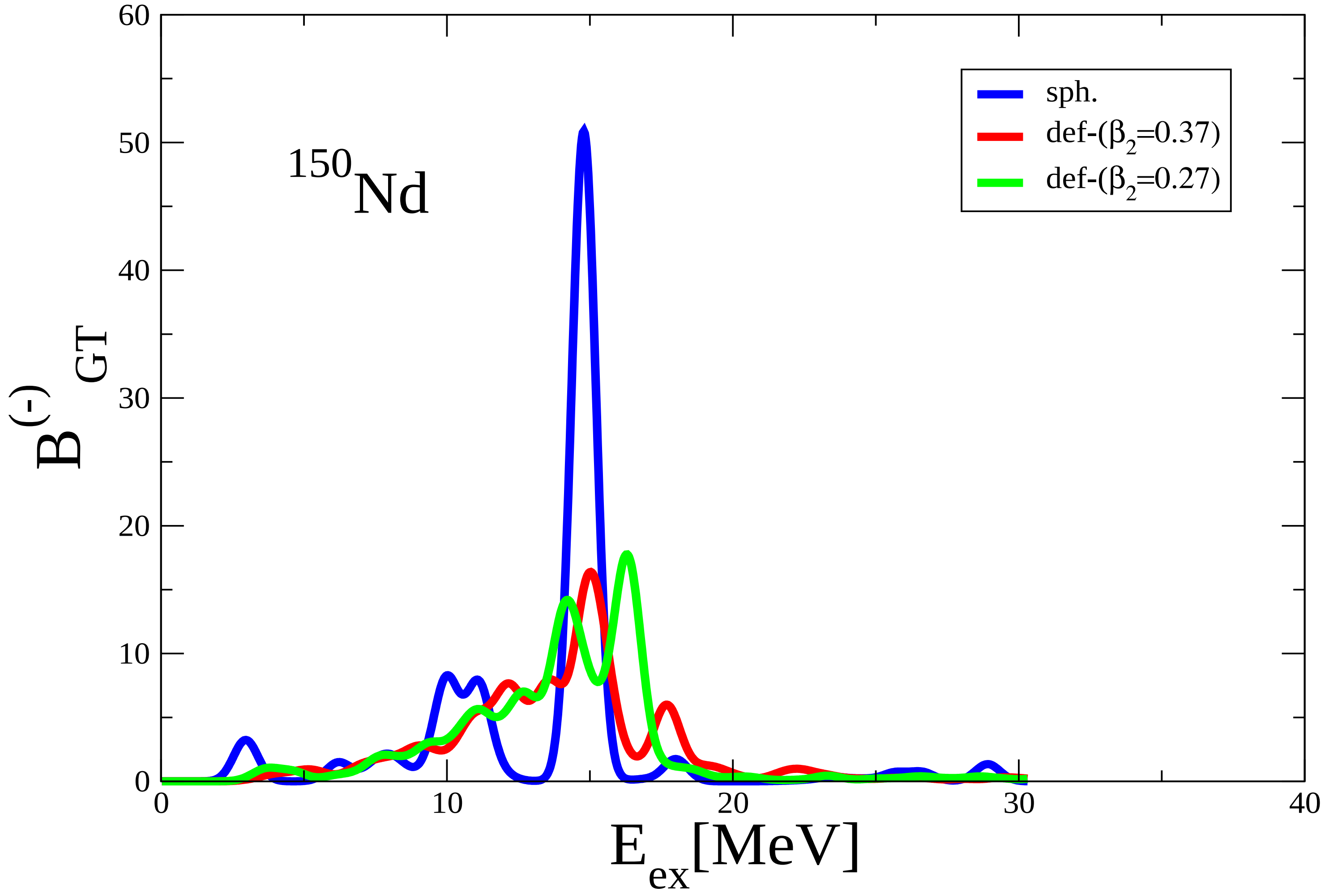
^{76}Se
sph. β_2=0.0
def. β_2=0.16
$B^{(+)}_{GT}$
0
0.2
0.4
0.6
0
5
10
15
20
25
30
E_{ex}[MeV]


^{100}Mo
β_2=0.0 sph.
β_2=0.14 def.
exp
$B^{(-)}_{GT}$
E_{ex}[MeV]
0
5
10
15
20
25
30
0
10
20

g_{ph}=1

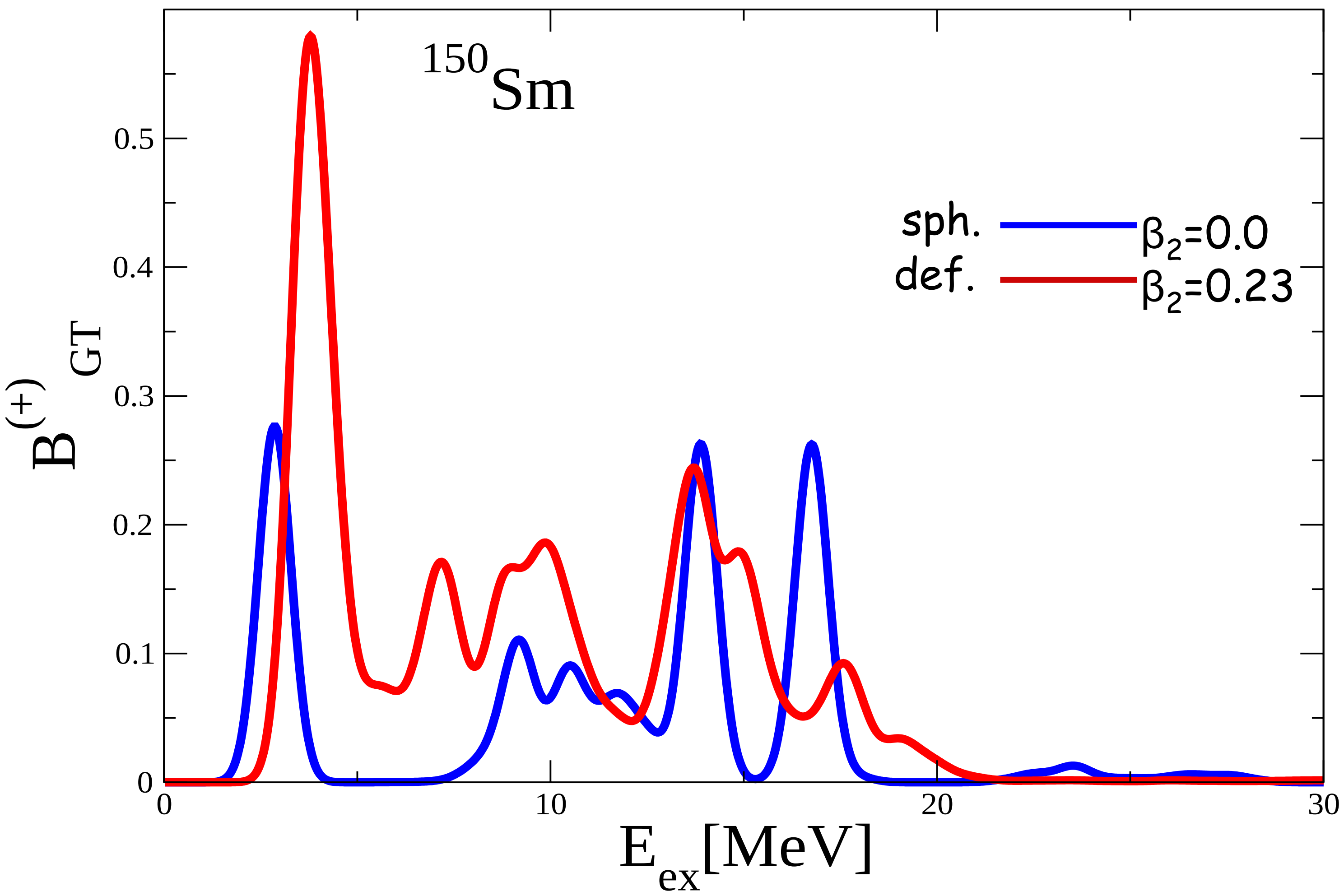


0.8
0.6
0.4
0.2
0
$B^{(+)}_{GT}$
^{100}Ru
β_2=0.0 sph.
β_2=0.14 def.
0
5
10
15
20
25
E_{ex}[MeV]

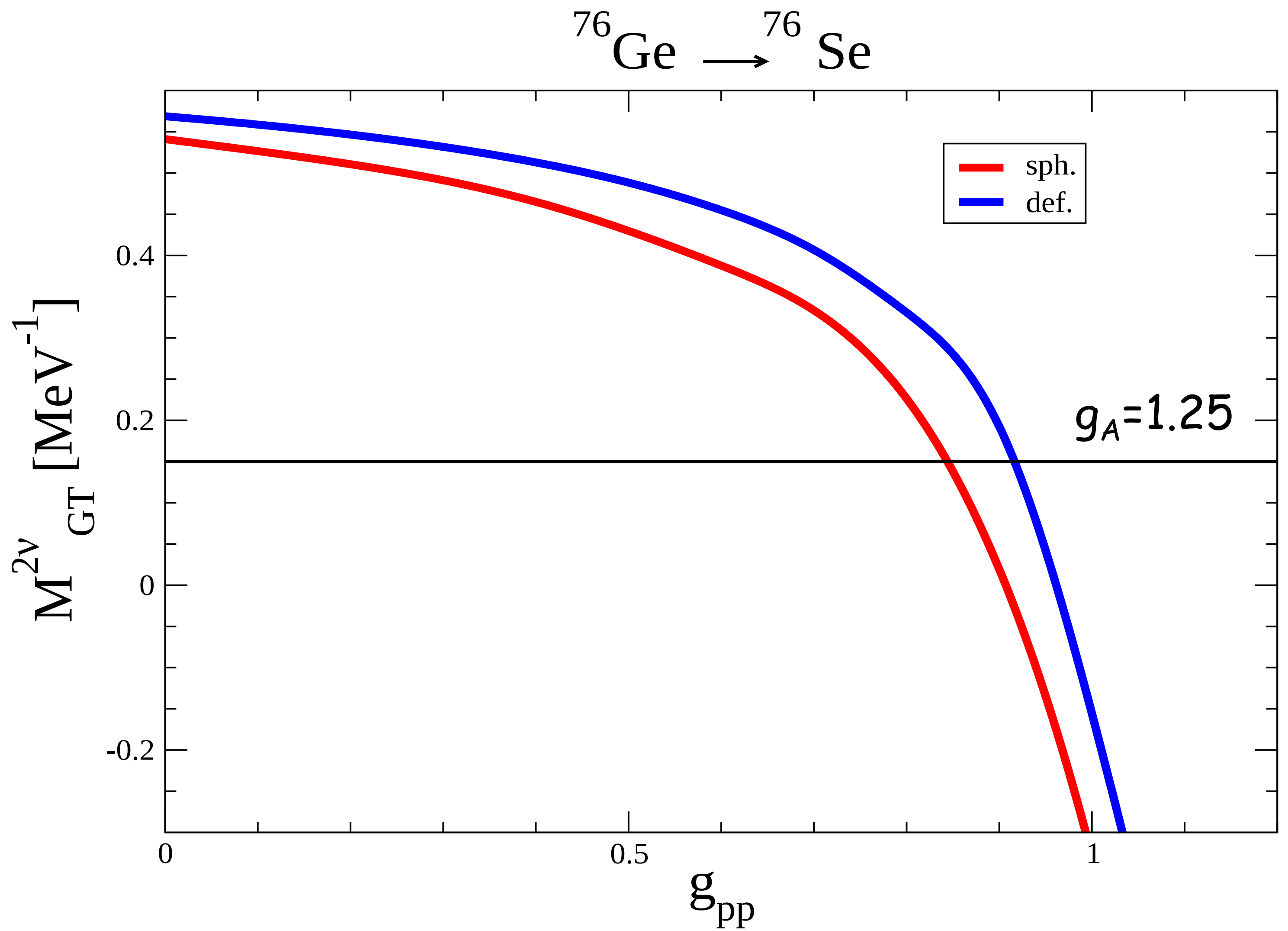


^{150}Nd
sph.
def-(β_2=0.37)
def-(β_2=0.27)
$B^{(-)}_{GT}$
E_{ex}[MeV]
0
10
20
30
40
50
60
0
10
20
30
40

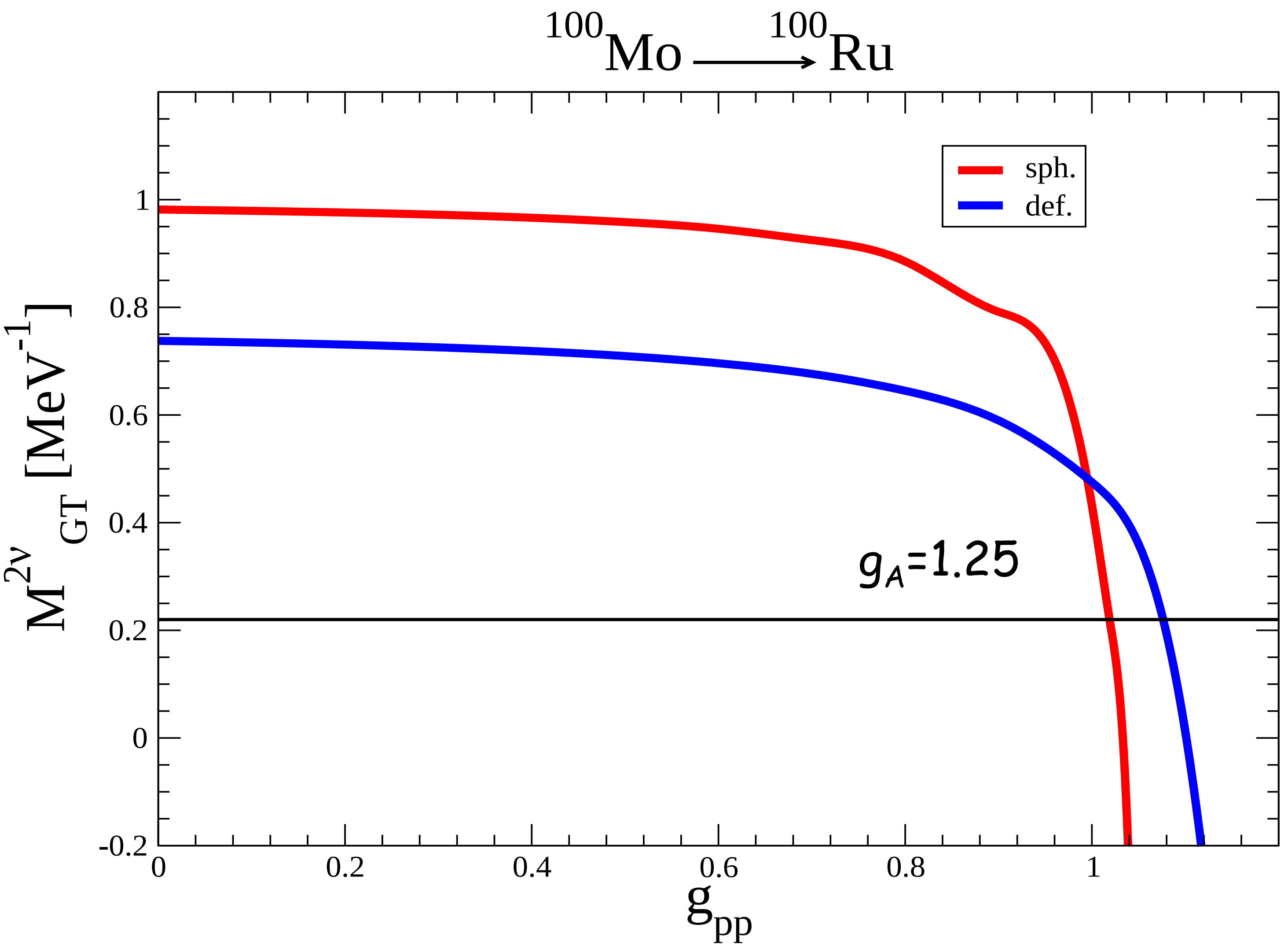
g_{ph}=1



^{150}Sm
sph.
def.
β_2=0.0
β_2=0.23
$B^{(+)}_{GT}$
0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
E_{ex}[MeV]



76Ge → 76 Se
sph.
def.
gA=1.25
0.4
0.2
0
-0.2
0
0.5
1
M2ν GT [MeV-1]
gpp



$^{100}Mo \longrightarrow {}^{100}Ru$
$M^{2\nu}_{GT}$ [MeV^{-1}]
g_{pp}
sph.
def.
g_A=1.25
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1

Summary

- The calculated $0\nu\beta\beta$ decay half life for ^{150}Nd assuming it is a spherical nucleus stimulates a lot of interest to study the effect of deformation on the double beta decay .

For Separable forces:

- $2\nu\beta\beta$ decay matrix elements is obtained for different nuclei within the deformed QRPA.
- The effect of deformation on the $2\nu\beta\beta$ decay matrix elements is large for a significant difference in deformation of the parent and daughter nuclei and is not related with the increasing amount of the ground state correlations close to a collapse of the QRPA solution.

Realistic force

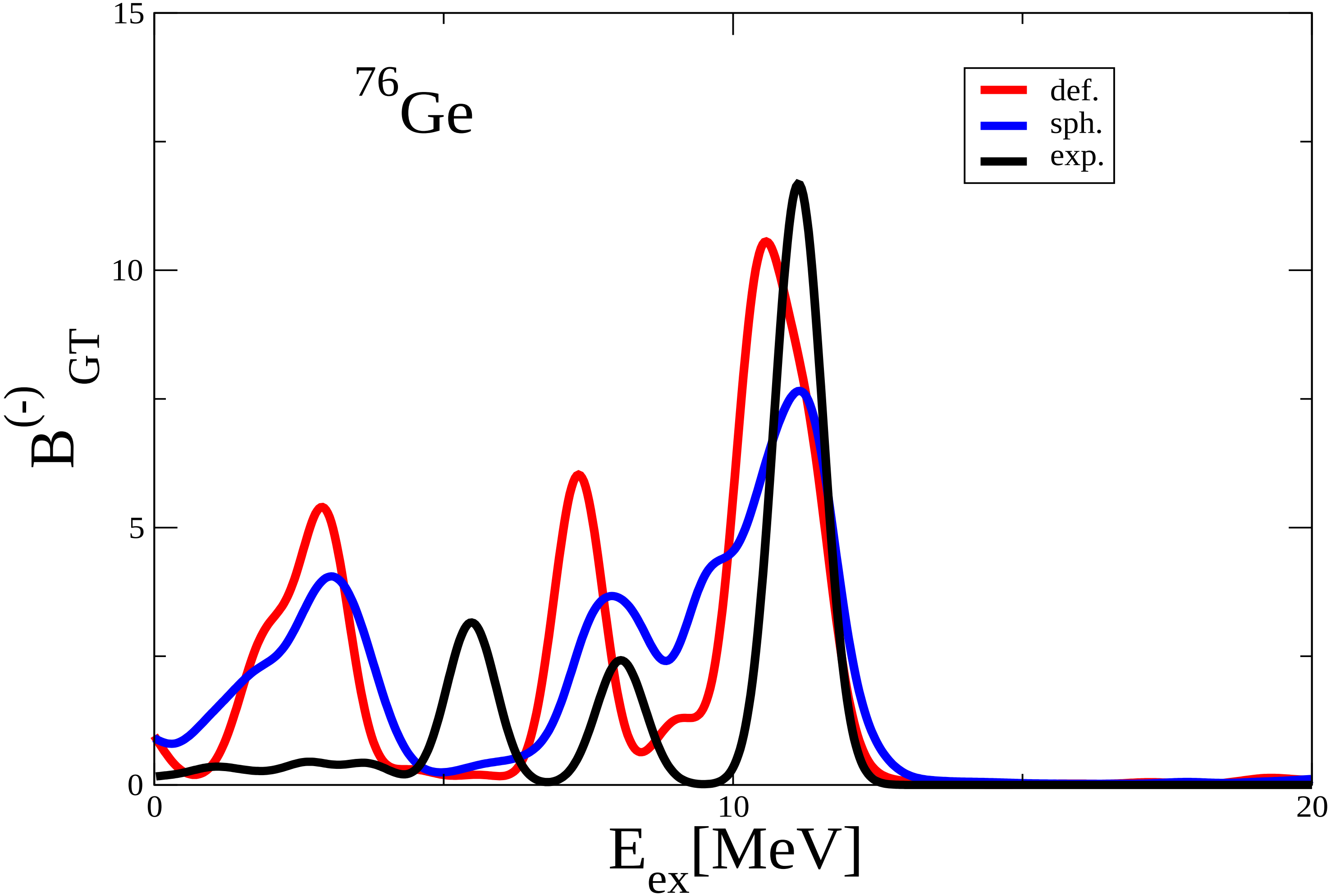
- BCS equations are solved for protons and neutrons. The protons and neutron gaps are determined to reproduce the odd-even mass differences.
- G-matrix in deformed s.p. basis is calculated using that for spherical s.p. basis.
- The QRPA equation is solved using the realistic forces and B(GT) strengths are calculated for ^{76}Ge ,^{76}Se, ^{100}Mo ,^{100}Ru, ^{150}Nd and ^{150}Sm nuclei considering deformation.
- 2νββ matrix element for ^{76}Ge and ^{100}Mo with deformation have been obtained and in progress to calculate Nd.

Outlook

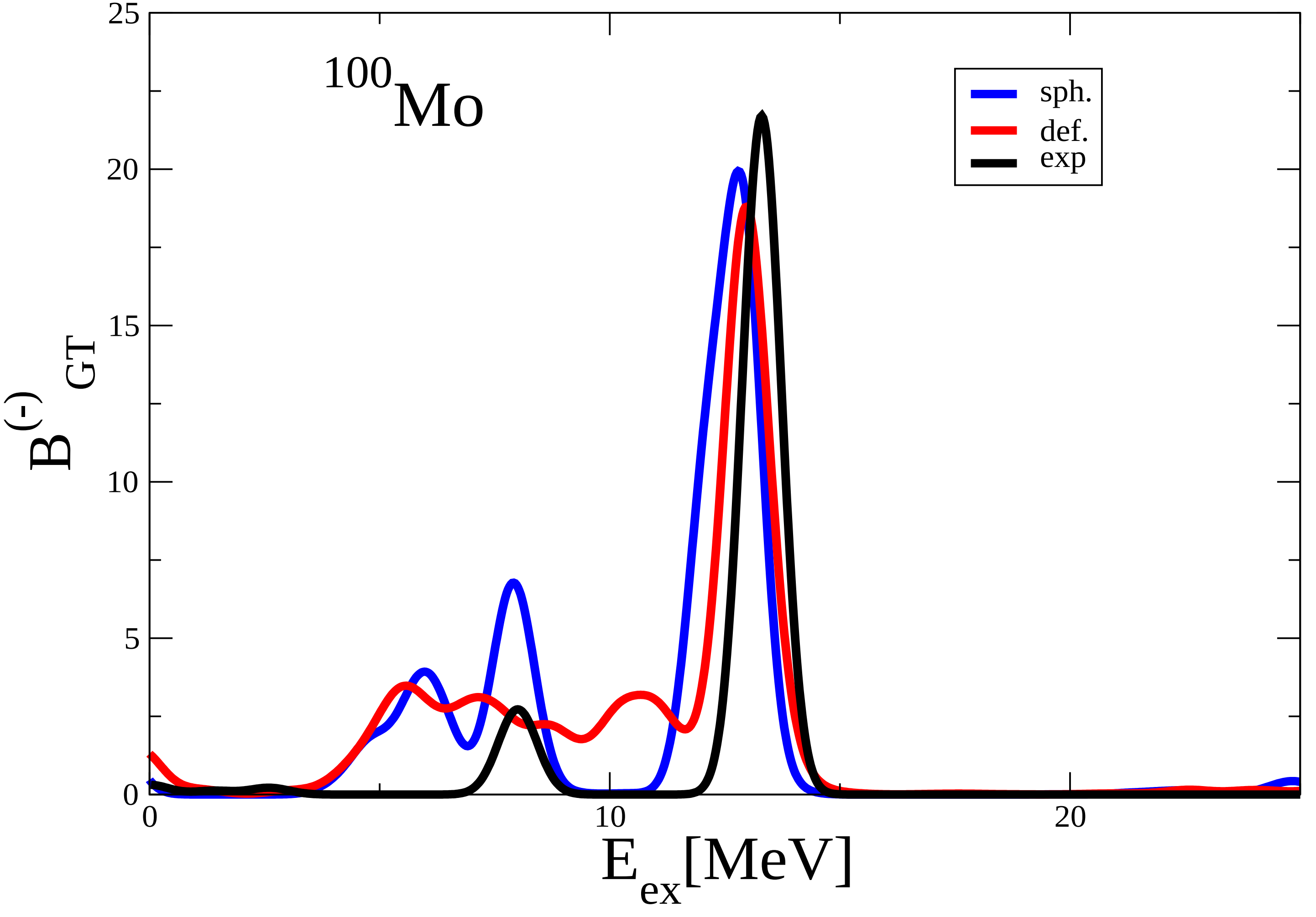
- **Go Further to study the matrix elements of 0νββ decay within deformed QRPA and realistic forces.**

Parameters

- Particle particle strength g_{pp} .
- Particle hole strength g_{ph} .
- Spin orbit coupling constant.



15
10
5
0
0
10
20
76Ge
def.
sph.
exp.
B(-)GT
Eex[MeV]



100Mo
sph.
def.
exp
25
20
15
10
5
0
0
10
20
B(-)GT
Eex[MeV]