

Neutrinoless double beta decay studied with configuration mixing methods

Tomás R. Rodríguez



Outline

1. Introduction

**2. Method:
GCM
+PNAMP**

**3. Results:
GCM+PNAMP**

**4. Summary
and
Conclusions**

CONTENTS

1. Introduction

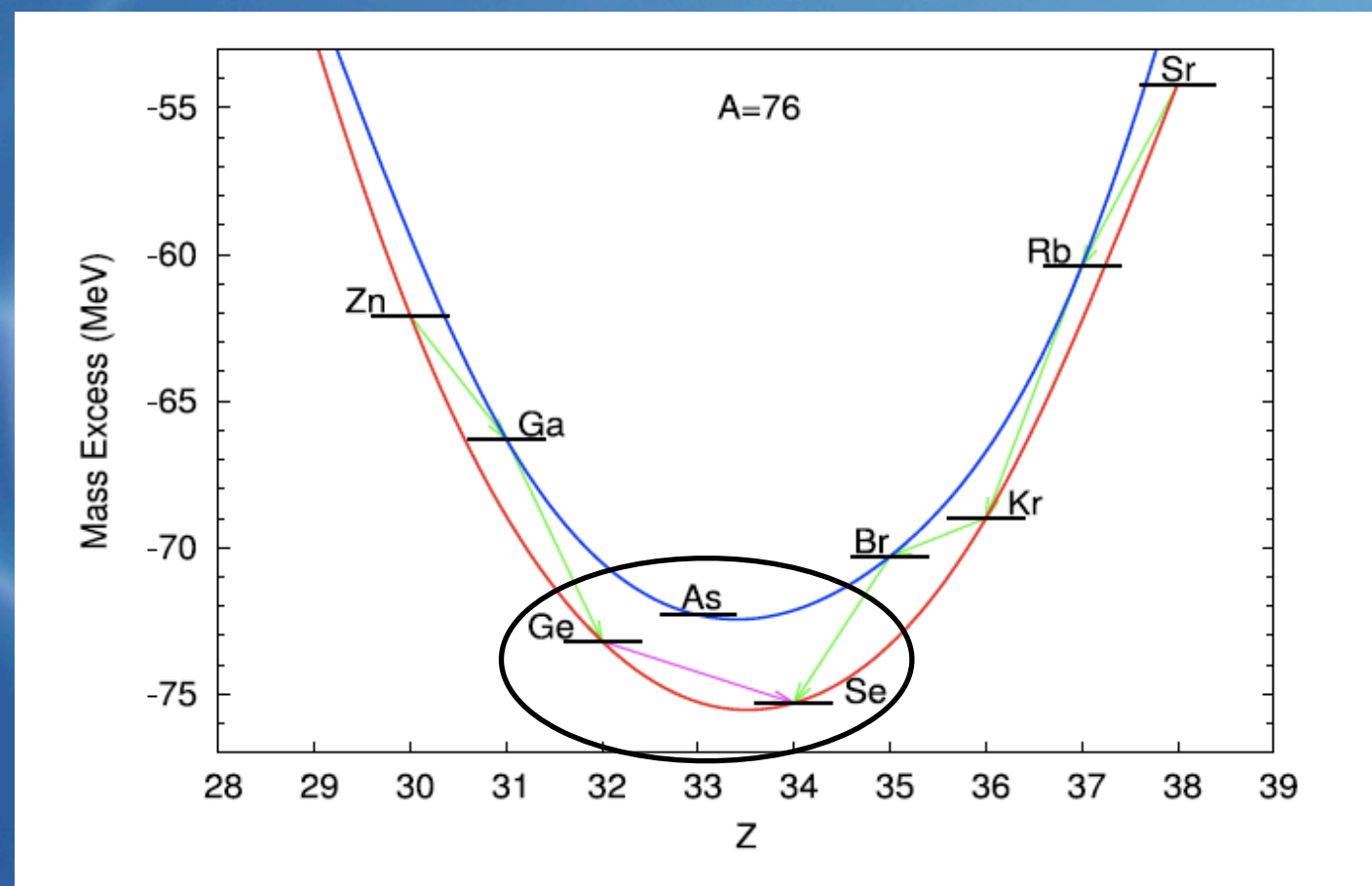
2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Double beta (-) decay: Process mediated by the weak interaction which occurs in those even-even nuclei where the single beta decay is energetically forbidden.



CONTENTS

1. Introduction

2. Method: GCM +PNAMP

3. Results: GCM +PNAMP

4. Summary and Conclusions

Introduction

Double beta (-) decay: P

oc
fo

Rb78 17.66 m 0(+)	Rb79 22.9 m 5/2+	Rb80 34 s 1+	Rb81 4.576 h 3/2-	Rb82 1.273 m 1+	Rb83 86.2 d 5/2-	Rb84 32.77 d 2-
Kr77 74.4 m 5/2+	Kr78 0+	Kr79 35.04 h 1/2-	Kr80 0+	Kr81 2.29E+5 y 7/2+	Kr82 0+	Kr83 9/2+
Br76 16.2 h 1-	Br77 57.036 h 3/2-	Br78 6.46 m 1+	Br79 3/2-	Br80 17.68 m 1+	Br81 3/2-	Br82 3/2-
Se75 119.779 d 5/2+	Se76 0+	Se77 1/2-	Se78 0+	Se79 1.13E6 y 7/2+	Se80 0+	Se81 18.45 m 1/2-
As74 17.77 d 2-	As75 3/2-	As76 1.0778 d 1/2-	As77 38.83 h 3/2-	As78 90.7 m 2-	As79 9.01 m 3/2-	As80 15.2 s 1+
Ge73 9/2+	Ge74 0+	Ge75 82.78 m 1/2-	Ge76 0+	Ge77 11.30 h 7/2+	Ge78 88.0 m 0+	Ge79 0+
Ga72 14.10 h 3-	Ga73 4.86 h 3/2-	Ga74 8.12 m (3-)	Ga75 126 s 3/2-	Ga76 32.6 s (2+,3+)	Ga77 13.2 s (3/2-)	Ga78 0+

Mass

-70

-75

28

29

30

V48 15.9735 d 4+	V49 338 d 7/2-	V50 1.48E+17 y 6+	V51 7/2-	V52 3.743 m 3+	V53 1.61 m 7/2-
Ti47 5/2-	Ti48 0+	Ti49 7/2-	Ti50 0+	Ti51 5.76 m 3/2-	Ti52 1.7 m 0+
Sc46 83.79 d 4+	Sc47 3.3492 d 7/2-	Sc48 43.67 h 6+	Sc49 57.2 m 7/2-	Sc50 182.5 s 5+	Sc51 12.4 s (7/2-)
Ca45 162.61 d 7/2-	Ca46 0+	Ca47 4.536 d 7/2-	Ca48 6B+18 y 0+	Ca49 8.718 m 3/2-	Ca50 13.9 s 0+
K44 22.13 m 2-	K45 17.3 m 3/2+	K46 185 s (2-)	K47 17.58 s 1/2+	K48 6.8 s (2-)	K49 1.24 s (3/2+)
Ar43 5.37 m	Ar44 11.87 m	Ar45 21.48 s	Ar46 8.4 s	Ar47 799 m	Ar48 0+

Ru99 5/2+	Ru100 0+	Ru101 5/2+	Ru102 0+	Ru103 39.26 d 3/2+	Ru104 35.7 d 1/2-
Tc98 4.2E+6 y (6+)	Tc99 2.111E+5 y 9/2+	Tc100 15.8 s +	Tc101 14.22 m (9/2)+	Tc102 5.28 s 1+	Tc103 54.5 s 5/2+
Mo97 5/2+	Mo98 0+	Mo99 65.94 h 1/2+	Mo100 1.2E19 y 0+	Mo101 14.61 m 1/2+	Mo102 11.1 m 0+
Nb96 23.35 h 6+	Nb97 72.1 m 9/2+	Nb98 2.86 s 1+	Nb99 15.0 s 9/2+	Nb100 1.5 s 1+	Nb101 7.7 s 5/2+
Zr95 0+	Zr96 10.75 m 9/2+	Zr97 0+	Zr98 0+	Zr99 0+	Zr100 0+

ne v
beta

Sml49 2.15 y 7/2-	Sml50 47.8 0+	Sml51 90 y 5/2-	Sml52 52.2 0+	Sml53 46.27 h 3/2+	Sml54 4.1 m 0+
Pml48 370 d 1-	Pml49 53.08 h 7/2+	Pml50 2.68 h (1-)	Pml51 28.40 h 5/2+	Pml52 4.12 m 1+	Pml53 1.1 m 0+
Ndl47 1.98 d 5/2-	Ndl48 0+	Ndl49 1.728 h 5/2-	Ndl50 1.1E19 y 0+	Ndl51 12.44 m (3/2)+	Ndl52 0+
Sr 0+	Sr 0+	Sr 0+	Sr 0+	Sr 0+	Sr 0+

A=76

Rb

Sr

Bal27 12.7 m 1/2+	Bal28 2.43 d 0+	Bal29 2.23 h 1/2+	Bal30 0+	Bal31 11.50 d 1/2+	Bal32 0+	Bal33 10.51 y 1/2+	Bal34 0+	Bal35 3/2+	Bal36 0+	Bal37 3/2+	Bal38 0+	Bal39 7/2+
Cs126 1.64 m 1+	Cs127 6.25 h 1/2+	Cs128 3.66 m 1+	Cs129 32.06 h 1/2+	Cs130 29.21 m 1+	Cs131 9.689 d 5/2+	Cs132 6.479 d 2+	Cs133 100	Cs134 2.0648 y 4+	Cs135 2.3E+6 y 7/2+	Cs136 3.16 d 1/2+	Cs137 30.07 y 7/2+	Cs138 33.4 y 3
Xel125 16.9 h (1/2)+	Xel126 0+	Xel127 36.4 d 1/2+	Xel128 0+	Xel129 1/2+	Xel130 0+	Xel131 3/2+	Xel132 0+	Xel133 5.243 d 3/2+	Xel134 0+	Xel135 9.14 h 3/2+	Xel136 2.36E21 y 0+	Xel137 3.81 m 7/2+
Il124 4.1760 d 2-	Il125 59.408 d 5/2+	Il126 13.11 d 2-	Il127 1.91	Il128 2.99 m 5/2+	Il129 1.57E7 y 7/2+	Il130 12.36 h +	Il131 8.02070 d 7/2+	Il132 2.295 h 4+	Il133 20.8 h 7/2+	Il134 52.5 m (4)+	Il135 6.57 h 7/2+	Il136 83.0 h (1)
Tel23 1E+13 y 1/2+	Tel24 0+	Tel25 1/2+	Tel26 0+	Tel27 9.35 h 3/2+	Tel28 2.2E24 y 0+	Tel29 69.6 m 3/2+	Tel30 7.9E20 y 0+	Tel31 25.0 m 3/2+	Tel32 3.204 d 0+	Tel33 12.5 m (3/2+)	Tel34 41.8 m 0+	Tel35 19.1 m (7/2)
Sb122 2.7238 d 2-	Sb123 7/2+	Sb124 6.00 d 3-	Sb125 2.7582 y 7/2+	Sb126 12.46 d (8)-	Sb127 3.85 d 7/2+	Sb128 9.01 h 8-	Sb129 4.40 h 7/2+	Sb130 39.5 m (8)-	Sb131 23.03 m (7/2+)	Sb132 2.79 m (4+)	Sb133 2.5 m (7/2+)	Sb134 0.7 m (0)
Sn121 27.06 h 3/2+	Sn122 0+	Sn123 129.2 d 11/2-	Sn124 0+	Sn125 9.64 d 11/2-	Sn126 1E+5 y 0+	Sn127 2.10 h (11/2)-	Sn128 59.07 m 0+	Sn129 2.23 m (3/2+)	Sn130 3.72 m 0+	Sn131 56.0 s (3/2+)	Sn132 39.7 s 0+	Sn133 1.4 s (7/2)
In120 2.08 m	In121 23.1 s	In122 1.5 s	In123 5.08 s	In124 2.11 s	In125 2.35 s	In126 1.60 s	In127 1.00 s	In128 0.84 s	In129 0.61 s	In130 0.33 s	In131 0.28 s	In132 0.20 s

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

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

$${}^A_Z X_N \Rightarrow {}^A_{Z+2} Y_{N-2} + 2e^- + 2\bar{\nu}_e$$

- Conserves the leptonic number
- Compatible with massive or massless Dirac/Majorana neutrinos
- Experimentally observed ($T_{1/2} \sim 10^{19-21}$ y)
- Within the Standard Model

Neutrinoless double beta decay $0\nu\beta\beta$

$${}^A_Z X_N \Rightarrow {}^A_{Z+2} Y_{N-2} + 2e^-$$

- Violates the leptonic number conservation
- Neutrinos are massive Majorana particles
- Except one controversial claim (Klapdor-Kleingrothaus et al. PLB 586, 198, 2004) has not been experimentally observed ($T_{1/2} \sim 10^{25}$ y)
- Beyond the Standard Model

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Relevance of neutrinoless double beta decay

- Neutrino oscillation observations (solar, atmospheric and reactors) establish that the neutrinos have a finite mass $\longrightarrow$ NEW PHYSICS BEYOND THE SM.
- From neutrino oscillation the absolute mass scale cannot be measured (only differences and mixing angles)
- Neutrinoless double beta decay rates depend directly on the effective neutrino mass so there are several experiments running or projected devoted to search for this process

252

H. Ejiri / Progress in Particle and Nuclear Physics 64 (2010) 249–257

Table 1

Limits on neutrino-less double β^- decays. $Q_{\beta\beta}$: Q value for the $0^+ \rightarrow 0^+$ ground state transition. $G^{0\nu}$: kinematical factor (phase space volume) in units of 10^{-14} y^{-1} , $T_{1/2}^{0\nu}$: half-life limits in units of 10^{24} y and $\langle m_\nu \rangle$: limit on the effective ν mass in units of eV.

Isotope	$Q_{\beta\beta}$ (MeV)	$G^{0\nu}$	$T_{1/2}^{0\nu}$ (10^{24})	$\langle m_\nu \rangle$ (eV)	Future experiments
^{48}Ca	4.276	4.46	>0.014	$<7.2\text{--}45$	CANDLES
^{76}Ge	2.039	0.44	$>19(22)$	$<0.35(0.32)$	GERDA
^{76}Ge	2.039	0.44	>16	$<0.33\text{--}1.35$	MAJORANA
^{82}Se	2.992	1.89	>0.36	$<0.9\text{--}1.6$	S-NEMO MOON
^{100}Mo	3.034	3.17	>1.1	$<0.45\text{--}0.93$	MOON CaMoO_4
^{116}Cd	2.804	3.24	>0.17	<1.7	COBRA CdWO_4
^{130}Te	2.529	2.86	>3	<0.46	CUORE
^{136}Xe	2.467	3.03	>0.44	$<1.8\text{--}5.2$	EXO KamLAND BOREXINO
^{150}Nd	3.368	13.4	>0.018	$<1.7\text{--}2.4$	S-NEMO SNO+ DCBA

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Half-life neutrinoless double beta decay (Doi et al (1985))

$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = G_{01} |M^{0\nu\beta\beta}|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2$$

light-neutrino exchange mechanism

- Kinematic phase space factor:

$$G_{01} = \frac{(Gg_A(0))^4 m_e^4}{64\pi^5 \ln 2} \int F_0(Z, \varepsilon_1) F_0(Z, \varepsilon_2) \times p_1 p_2 \delta(\varepsilon_1 + \varepsilon_2 - E_f - E_i) d\varepsilon_1 d\varepsilon_2 d(\hat{\vec{p}}_1 \cdot \hat{\vec{p}}_1)$$

- Effective neutrino mass:

$$\langle m_\nu \rangle = \sum_j U_{ej}^2 m_j$$

- Nuclear Matrix Element (NME):

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

Fermi

Gamow-Teller

Tensor

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Nuclear Matrix Elements

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

- Each term can be written as the expectation value of a transition operator acting on the ground states of the mother and granddaughter nuclei:

$$M_{\xi}^{0\nu\beta\beta} = \langle 0_f^+ | \hat{O}_{\xi}^{0\nu\beta\beta} | 0_i^+ \rangle$$

- Nuclear structure methods for calculating these NME:
 - Quasiparticle Random Phase Approximation in different versions: QRPA, RQRPA, SRQRPA. (Tübingen group, Jyväskylä group)
 - Interacting Shell Model -ISM- (Strasbourg-Madrid collaboration)
 - Interacting Boson Model -IBM- (Yale group)
 - Projected Hartree-Fock-Bogoliubov -PHFB- (Lucknow-UNAM group)

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Nuclear Matrix Elements

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

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$$M_{\xi}^{0\nu\beta\beta} = \langle 0_f^+ | \hat{O}_{\xi}^{0\nu\beta\beta} | 0_i^+ \rangle$$

- Nuclear structure methods for calculating these NME:

Different ways to deal with:

- Quasiparticle Random Phase Approximation in different versions:
QRPA, RQRPA, SRQRPA. (Tübingen group, Jyväskylä group)
- Finding the best initial and final ground states.
- Handling the transition operator (inclusion of most relevant terms, corrections, approximations, etc.).
- Interacting Shell Model -ISM- (Strasbourg-Madrid collaboration)

Some remarks about these methods:

- Interacting Boson Model -IBM- (Yale group)
- Calculations with limited single particle bases.
- Interactions fitted to the specific region (ISM) or to each nucleus individually (rest).
- Projected Hartree-Fock-Bogoliubov -PHFB- (Lucknow-UNAM group)
- Difficulties to include collective degrees of freedom.
- Problems with particle number conservation.

CONTENTS

1. Introduction

2. Method: GCM +PNAMP

3. Results: GCM +PNAMP

4. Summary and Conclusions

Introduction

Nuclear Matrix Elements

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

- Neglect the tensor term.
- Closure approximation (10% error at most)

$$M_F^{0\nu\beta\beta} = \left(\frac{g_A(0)}{g_V(0)} \right)^2 \langle 0_f^+ | \hat{V}_F(1, 2) \hat{\tau}_-^{(1)} \hat{\tau}_-^{(2)} | 0_i^+ \rangle$$

$$M_{GT}^{0\nu\beta\beta} = \langle 0_f^+ | \hat{V}_{GT}(1, 2) \hat{\tau}_-^{(1)} \hat{\tau}_-^{(2)} | 0_i^+ \rangle$$

$$\langle \vec{r}_1 \vec{r}_2 | \hat{V}_F(1, 2) | \vec{r}'_1 \vec{r}'_2 \rangle = v_F(|\vec{r}_1 - \vec{r}_2|) \delta(\vec{r}_1 - \vec{r}'_1) \delta(\vec{r}_2 - \vec{r}'_2)$$

$$\langle \vec{r}_1 \vec{r}_2 | \hat{V}_{GT}(1, 2) | \vec{r}'_1 \vec{r}'_2 \rangle = v_{GT}(|\vec{r}_1 - \vec{r}_2|) \delta(\vec{r}_1 - \vec{r}'_1) \delta(\vec{r}_2 - \vec{r}'_2) \hat{\vec{\sigma}}^{(1)} \cdot \hat{\vec{\sigma}}^{(2)}$$

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Nuclear Matrix Elements

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

- Neglect the tensor term.
- Closure approximation (10% error at most)

$$M_F^{0\nu\beta\beta} = \left(\frac{g_A(0)}{g_V(0)} \right)^2 \langle 0_f^+ | \hat{V}_F(1, 2) \hat{\tau}_-^{(1)} \hat{\tau}_-^{(2)} | 0_i^+ \rangle$$

$$M_{GT}^{0\nu\beta\beta} = \langle 0_f^+ | \hat{V}_{GT}(1, 2) \hat{\tau}_-^{(1)} \hat{\tau}_-^{(2)} | 0_i^+ \rangle$$

$$\begin{aligned} \langle \vec{r}_1 \vec{r}_2 | \hat{V}_F(1, 2) | \vec{r}'_1 \vec{r}'_2 \rangle &= v_F(|\vec{r}_1 - \vec{r}_2|) \delta(\vec{r}_1 - \vec{r}'_1) \delta(\vec{r}_2 - \vec{r}'_2) \\ \langle \vec{r}_1 \vec{r}_2 | \hat{V}_{GT}(1, 2) | \vec{r}'_1 \vec{r}'_2 \rangle &= v_{GT}(|\vec{r}_1 - \vec{r}_2|) \delta(\vec{r}_1 - \vec{r}'_1) \delta(\vec{r}_2 - \vec{r}'_2) \hat{\vec{\sigma}}^{(1)} \cdot \hat{\vec{\sigma}}^{(2)} \end{aligned}$$

Neutrino potentials

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Neutrino potentials

Starting from the weak lagrangian that describes the process some approximations are made:

1. Non-relativistic approach in the hadronic part.
2. Closure approximation in the virtual intermediate state
3. Nucleon form factors taken in the dipolar approximation.
4. Tensor contribution is neglected.
5. High order currents are included (HOC).
6. Short range correlations are included with an UCOM correlator.

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Introduction

Neutrino potentials

Starting from the weak lagrangian that describes the process some approximations are made:

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4. Tensor contribution is neglected.
5. High order currents are included (HOC).
6. Short range correlations are included with an UCOM correlator.

- Find the initial and final 0^+ states within the GCM+PNAMP method (axial calculations)
- Evaluate the transition operators between these states

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

See also P.-H. Heenen's talk (Sunday afternoon)

 **Effective nucleon-nucleon interaction (Density Dependent): Gogny force (D1S)** that is able to describe properly many phenomena along the whole nuclear chart.

$$V(1,2) = \sum_{i=1}^2 e^{-(\vec{r}_1 - \vec{r}_2)^2 / \mu_i^2} (W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau) \\ + iW_0(\sigma_1 + \sigma_2) \vec{k} \times \delta(\vec{r}_1 - \vec{r}_2) \vec{k} + t_3(1 + x_0 P^\sigma) \delta(\vec{r}_1 - \vec{r}_2) \rho^\alpha ((\vec{r}_1 + \vec{r}_2)/2) \\ + V_{\text{Coulomb}}(\vec{r}_1, \vec{r}_2)$$

 **Method of solving the many-body problem:**

First step: Particle Number Projection (before the variation) of HFB-type wave functions.

Second step: Simultaneous Particle Number and Angular Momentum Projection (after the variation).

Third step: Configuration mixing within the framework of the Generator Coordinate Method (GCM).

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Determination of mother and granddaughter states (I)

Intrinsic state: Solve the PN-VAP equations with the Gogny DIS interaction

$$|\Phi\rangle \text{ HFB states} \longrightarrow \delta \left(E^{N,Z} [|\bar{\Phi}(q)\rangle] \right)_{|\bar{\Phi}\rangle=|\Phi\rangle} = 0$$

$$E^{N,Z} [|\Phi\rangle] = \frac{\langle \Phi | \hat{H} \hat{P}^N \hat{P}^Z | \Phi \rangle}{\langle \Phi | \hat{P}^N \hat{P}^Z | \Phi \rangle} + \varepsilon_{DD}^{N,Z} (|\Phi\rangle) - \lambda_q \langle \Phi | \hat{Q} | \Phi \rangle$$

Particle number and angular momentum projected state:

$$|IMK; NZ; q\rangle = \frac{2I+1}{8\pi^2} \int \mathcal{D}_{MK}^{I*}(\Omega) \hat{R}(\Omega) \hat{P}^N \hat{P}^Z |\Phi(q)\rangle d\Omega$$

General form (GCM state):

$$|IM; NZ\sigma\rangle = \sum_{Kq} f_{Kq}^{I;NZ,\sigma} |IMK; NZ; q\rangle$$

Hill-Wheeler-Griffin equation (GCM)

$$\sum_{K'q'} \left(\mathcal{H}_{KqK'q'}^{I;NZ} - E^{I;NZ;\sigma} \mathcal{N}_{KqK'q'}^{I;NZ} \right) f_{K'q'}^{I;NZ;\sigma} = 0$$

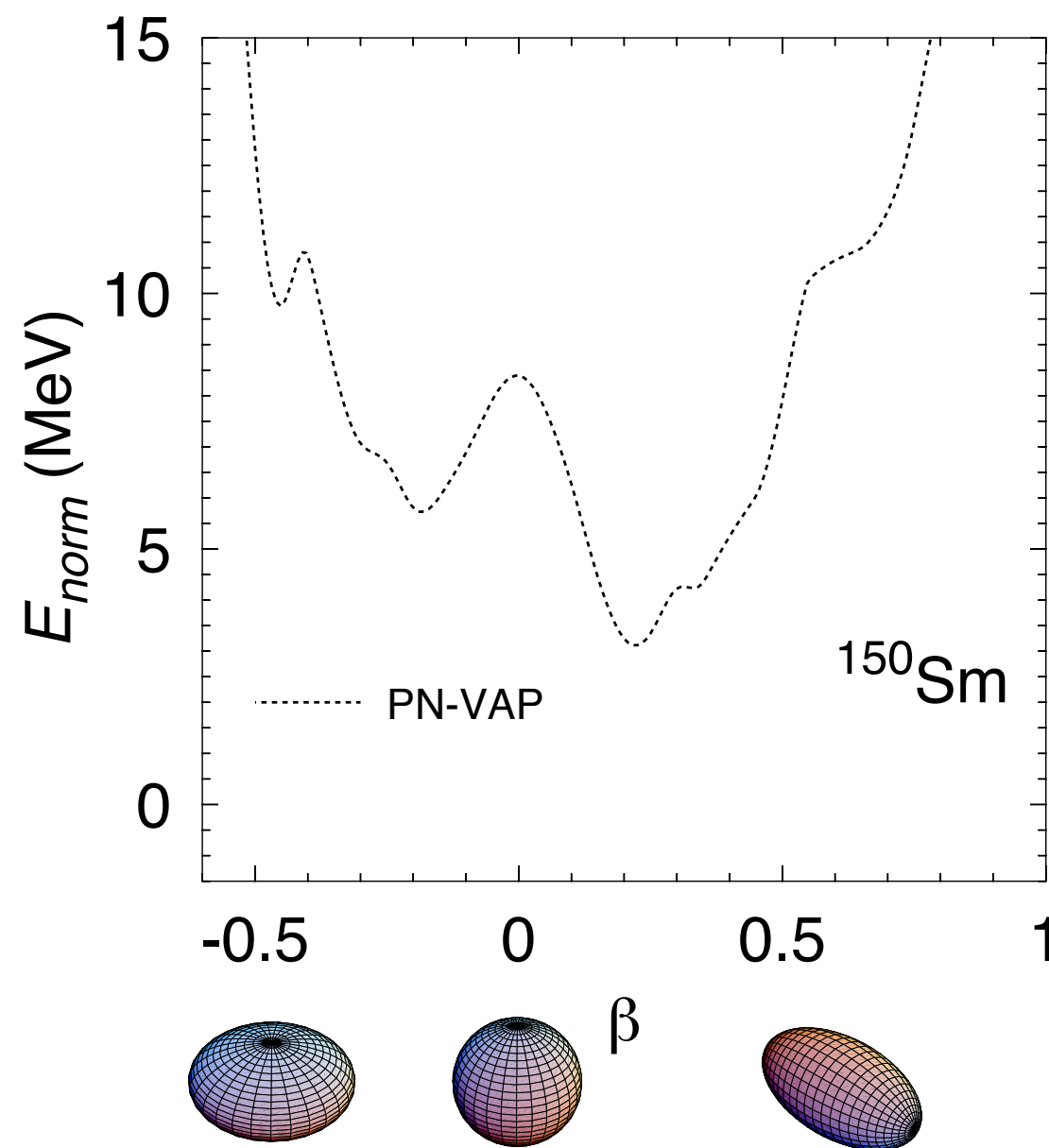
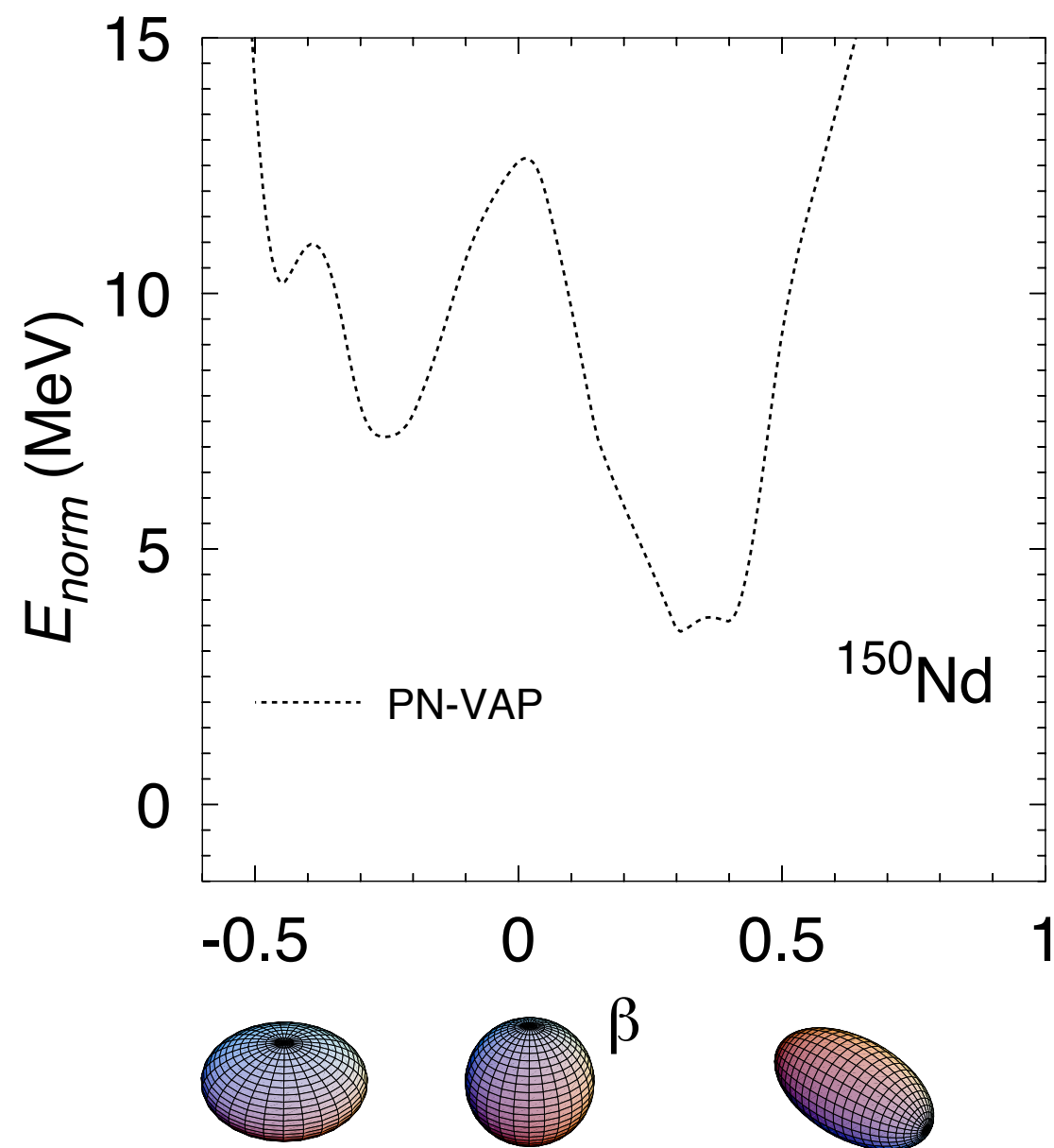
$$\mathcal{N}_{KqK'q'}^{I;NZ} \equiv \langle IMK; NZ; q | IMK'; NZ; q' \rangle$$

$$\mathcal{H}_{KqK'q'}^{I;NZ} \equiv \langle IMK; NZ; q | \hat{H} | IMK'; NZ; q' \rangle + \varepsilon_{DD}^{IKK';NZ} [|\Phi(q)\rangle, |\Phi(q')\rangle]$$

—————→ generalized eigenvalue problem

Method: GCM+PNAMP

Determination of mother and granddaughter states (I)



CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Determination of mother and granddaughter states (II)

Intrinsic state: Solve the VAP-PN equations with the Gogny DIS interaction

$$|\Phi\rangle \text{ HFB states} \longrightarrow \delta \left(E^{N,Z} [|\bar{\Phi}(q)\rangle] \right)_{|\bar{\Phi}\rangle=|\Phi\rangle} = 0$$

$$E^{N,Z} [|\Phi\rangle] = \frac{\langle \Phi | \hat{H} \hat{P}^N \hat{P}^Z | \Phi \rangle}{\langle \Phi | \hat{P}^N \hat{P}^Z | \Phi \rangle} + \varepsilon_{DD}^{N,Z} (|\Phi\rangle) - \lambda_q \langle \Phi | \hat{Q} | \Phi \rangle$$

Particle number and angular momentum projected state:

$$|IMK; NZ; q\rangle = \frac{2I+1}{8\pi^2} \int \mathcal{D}_{MK}^{I*}(\Omega) \hat{R}(\Omega) \hat{P}^N \hat{P}^Z |\Phi(q)\rangle d\Omega$$

General form (GCM state):

$$|IM; NZ\sigma\rangle = \sum_{Kq} f_{Kq}^{I;NZ,\sigma} |IMK; NZ; q\rangle$$

Hill-Wheeler-Griffin equation (GCM)

$$\sum_{K'q'} \left(\mathcal{H}_{KqK'q'}^{I;NZ} - E^{I;NZ;\sigma} \mathcal{N}_{KqK'q'}^{I;NZ} \right) f_{K'q'}^{I;NZ;\sigma} = 0$$

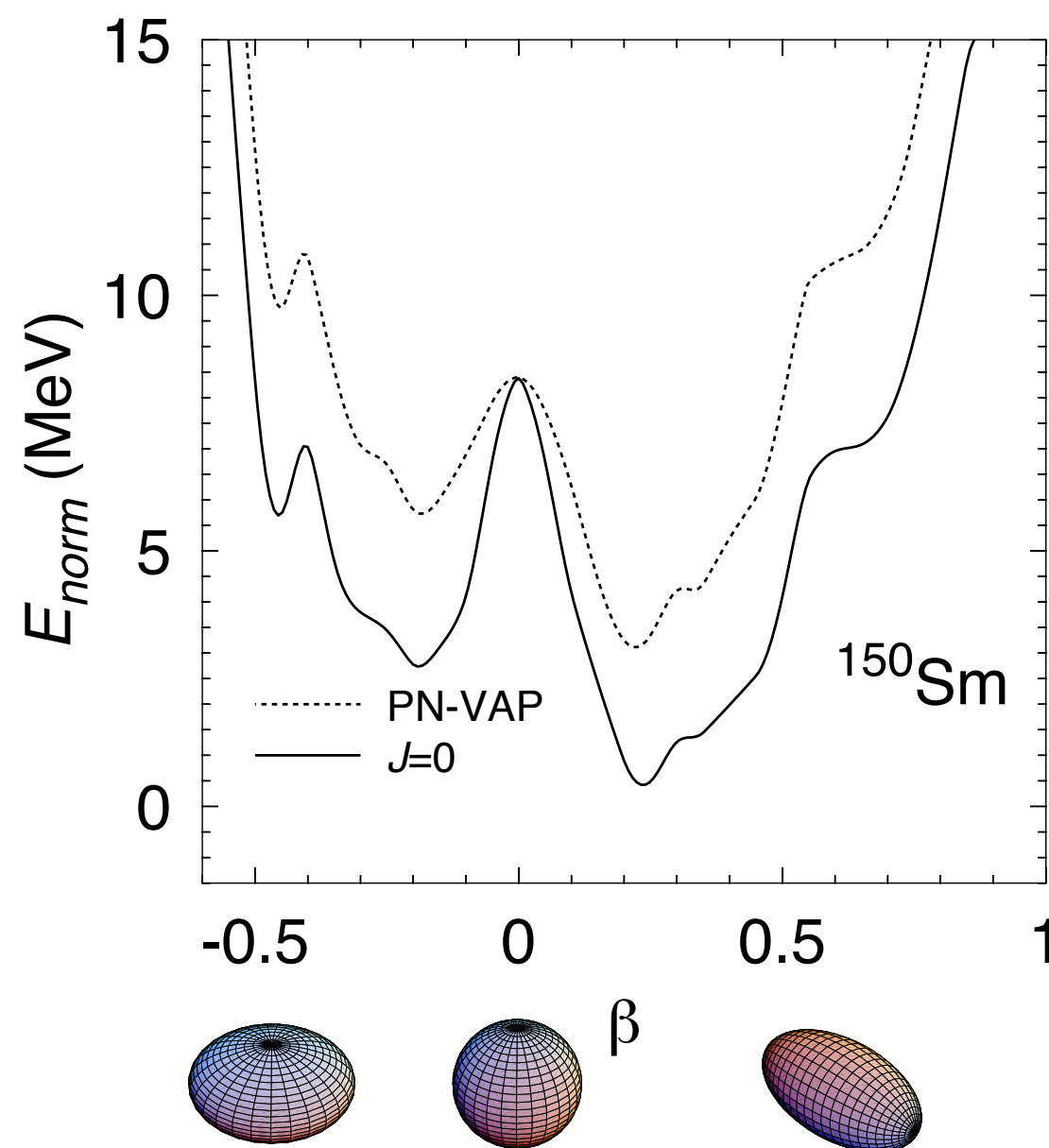
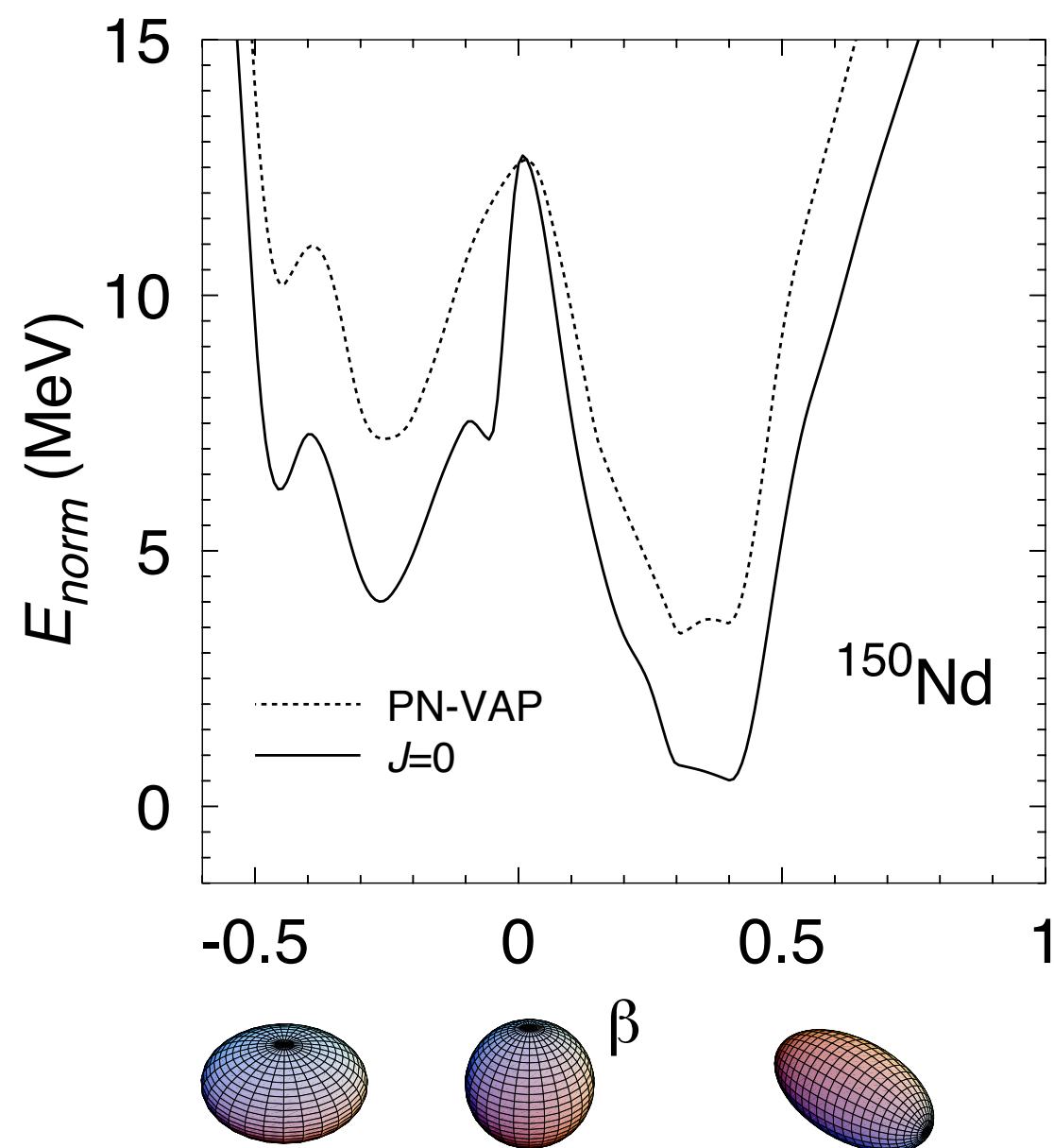
$$\mathcal{N}_{KqK'q'}^{I;NZ} \equiv \langle IMK; NZ; q | IMK'; NZ; q' \rangle$$

$$\mathcal{H}_{KqK'q'}^{I;NZ} \equiv \langle IMK; NZ; q | \hat{H} | IMK'; NZ; q' \rangle + \varepsilon_{DD}^{IKK';NZ} [|\Phi(q)\rangle, |\Phi(q')\rangle]$$

—————→ generalized eigenvalue problem

Method: GCM+PNAMP

Determination of mother and granddaughter states (II)



CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Determination of mother and granddaughter states (III)

Intrinsic state: Solve the VAP-PN equations with the Gogny DIS interaction

$$|\Phi\rangle \text{ HFB states } \longrightarrow \delta \left(E^{N,Z} [|\bar{\Phi}(q)\rangle] \right)_{|\bar{\Phi}\rangle=|\Phi\rangle} = 0$$

$$E^{N,Z} [|\Phi\rangle] = \frac{\langle \Phi | \hat{H} \hat{P}^N \hat{P}^Z | \Phi \rangle}{\langle \Phi | \hat{P}^N \hat{P}^Z | \Phi \rangle} + \varepsilon_{DD}^{N,Z} (|\Phi\rangle) - \lambda_q \langle \Phi | \hat{Q} | \Phi \rangle$$

Particle number and angular momentum projected state:

$$|IMK; NZ; q\rangle = \frac{2I+1}{8\pi^2} \int \mathcal{D}_{MK}^{I*}(\Omega) \hat{R}(\Omega) \hat{P}^N \hat{P}^Z |\Phi(q)\rangle d\Omega$$

General form (GCM state):

$$|IM; NZ\sigma\rangle = \sum_{Kq} f_{Kq}^{I;NZ,\sigma} |IMK; NZ; q\rangle$$

Hill-Wheeler-Griffin equation (GCM)

$$\sum_{K'q'} \left(\mathcal{H}_{KqK'q'}^{I;NZ} - E^{I;NZ;\sigma} \mathcal{N}_{KqK'q'}^{I;NZ} \right) f_{K'q'}^{I;NZ;\sigma} = 0$$

$$\mathcal{N}_{KqK'q'}^{I;NZ} \equiv \langle IMK; NZ; q | IMK'; NZ; q' \rangle$$

$$\mathcal{H}_{KqK'q'}^{I;NZ} \equiv \langle IMK; NZ; q | \hat{H} | IMK'; NZ; q' \rangle + \varepsilon_{DD}^{IKK';NZ} [|\Phi(q)\rangle, |\Phi(q')\rangle]$$

$\longrightarrow$ generalized eigenvalue problem

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Determination of mother and granddaughter states (III)

Intrinsic state: Solve the VAP-PN equations with the Gogny DIS interaction

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Solving HWG equation:

1. Diagonalization of the norm overlap:

$$\sum_{K'q'} \mathcal{N}_{KqK'q'}^{I;NZ} u_{K'q';\Lambda}^{I;NZ} = n_{\Lambda}^{I;NZ} u_{Kq;\Lambda}^{I;NZ}$$

2. Natural basis:

$$|\Lambda^{IM;NZ}\rangle = \sum_{Kq} \frac{u_{Kq;\Lambda}^{I;NZ}}{\sqrt{n_{\Lambda}^{I;NZ}}} |IMK; NZ; q\rangle ; n_{\Lambda}^{I;NZ} / n_{max}^{I;NZ} > \zeta$$

3. Normal eigenvalue problem:

$$\sum_{\Lambda'} \langle \Lambda^{I;NZ} | \hat{H} | \Lambda'^{I;NZ} \rangle G_{\Lambda'}^{I;NZ;\sigma} = E^{I;NZ;\sigma} G_{\Lambda}^{I;NZ;\sigma}$$

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Determination of mother and granddaughter states (III)

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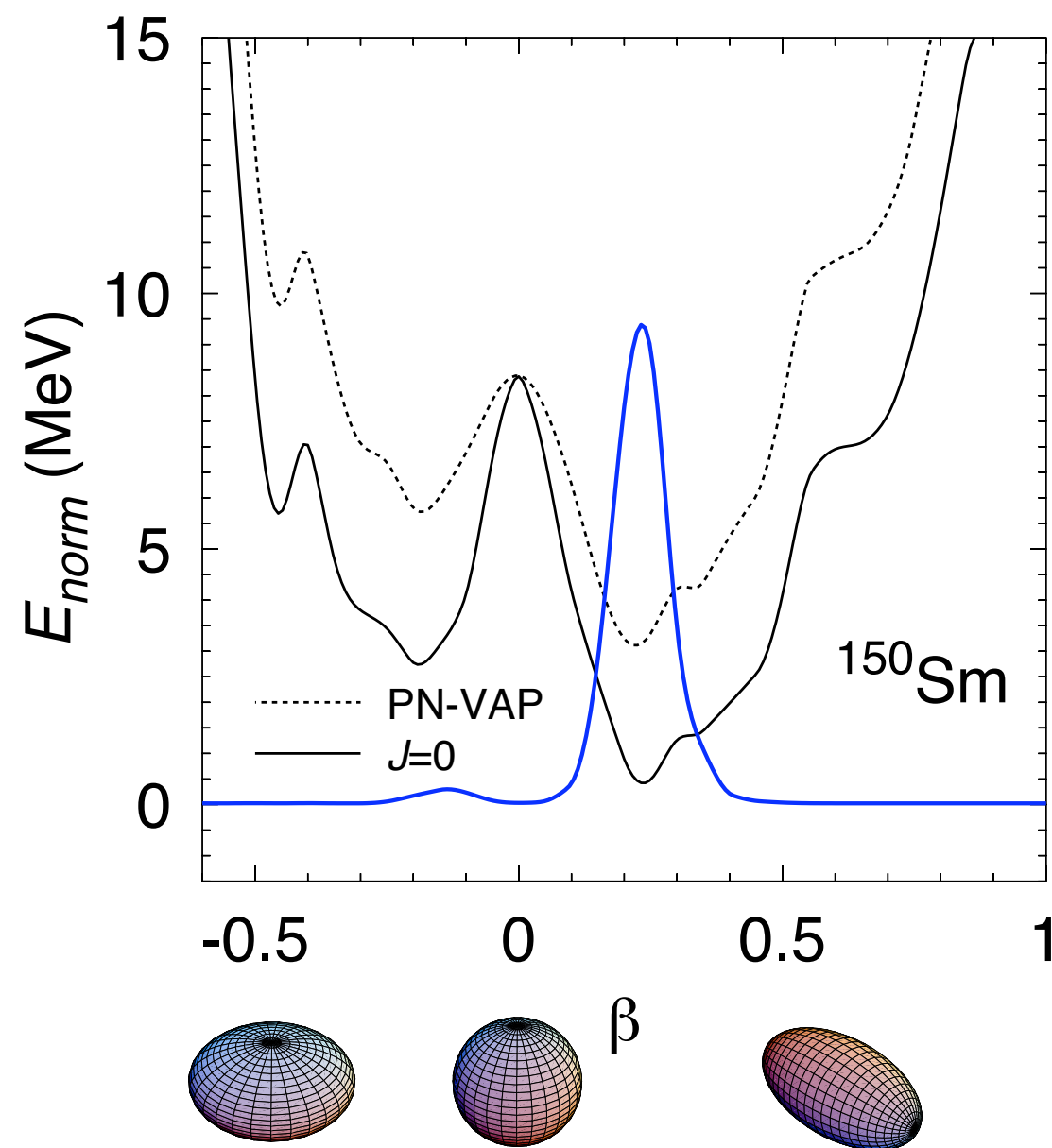
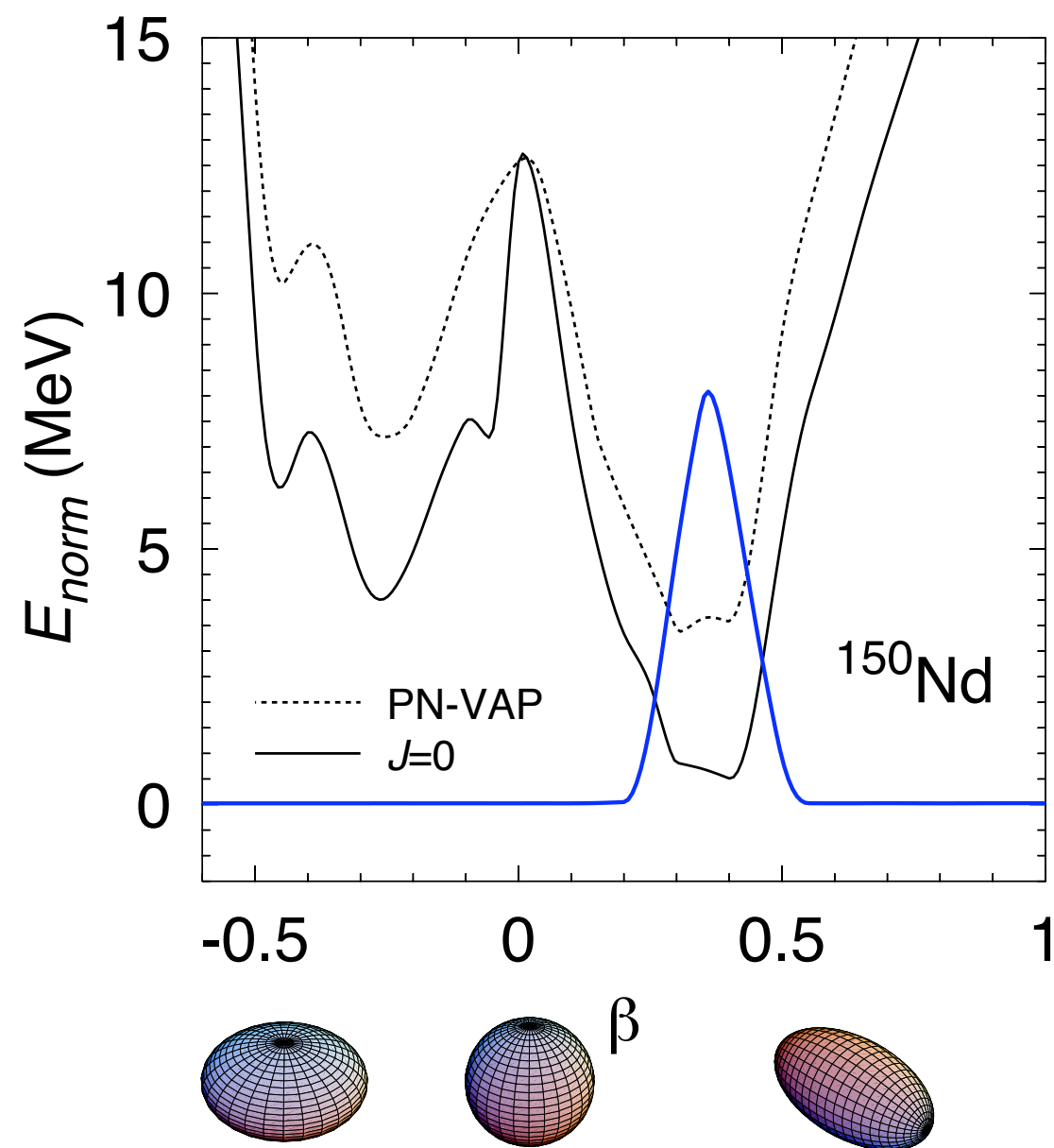
$$|\Lambda^{I;NZ}\rangle = \sum_{Kq} \frac{u_{Kq;\Lambda}^{I;NZ}}{\sqrt{n_{\Lambda}^{I;NZ}}} |IMK; NZ; q\rangle ; n_{\Lambda}^{I;NZ} / n_{max}^{I;NZ} > \zeta$$

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Method: GCM+PNAMP

Determination of mother and granddaughter states (III)



CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Transitions

1. Axial states $K = 0$
2. Angular momentum $I = 0$
3. Ground states $\sigma = 0$
4. Quadrupole deformations $q = q_{20}$



$$\begin{aligned}
 |0; N_i Z_i; \sigma\rangle &= \sum_{\Lambda_i} G_{\Lambda_i}^{0; N_i Z_i; \sigma} |\Lambda_i^{0; N_i Z_i}\rangle \\
 |0; N_f Z_f; \sigma\rangle &= \sum_{\Lambda_f} G_{\Lambda_f}^{0; N_f Z_f; \sigma} |\Lambda_f^{0; N_f Z_f}\rangle
 \end{aligned}$$

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Transitions

1. Axial states $K = 0$

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$$|0; N_i Z_i; \sigma\rangle = \sum_{\Lambda_i} G_{\Lambda_i}^{0; N_i Z_i; \sigma} |\Lambda_i^{0; N_i Z_i}\rangle$$

$$|0; N_f Z_f; \sigma\rangle = \sum_{\Lambda_f} G_{\Lambda_f}^{0; N_f Z_f; \sigma} |\Lambda_f^{0; N_f Z_f}\rangle$$

TRANSITIONS:

$$M_{\xi}^{0\nu\beta\beta} = \langle 0_f^+ | \hat{O}_{\xi}^{0\nu\beta\beta} | 0_i^+ \rangle = \langle 0; N_f Z_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i \rangle =$$

$$\sum_{\Lambda_f \Lambda_i} \left(G_{\Lambda_f}^{0; N_f Z_f} \right)^* \langle \Lambda_f^{0; N_f Z_f} | \hat{O}_{\xi}^{0\nu\beta\beta} | \Lambda_i^{0; N_i Z_i} \rangle G_{\Lambda_i}^{0; N_i Z_i} = \sum_{q_i q_f; \Lambda_f \Lambda_i}$$

$$\left(\frac{u_{q_f, \Lambda_f}^{0; N_f Z_f}}{\sqrt{n_{\Lambda_f}^{0; N_f Z_f}}} \right)^* \left(G_{\Lambda_f}^{0; N_f Z_f} \right)^* \langle 0; N_f Z_f; q_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i; q_i \rangle \left(G_{\Lambda_i}^{0; N_i Z_i} \right) \left(\frac{u_{q_i, \Lambda_i}^{0; N_i Z_i}}{\sqrt{n_{\Lambda_i}^{0; N_i Z_i}}} \right)$$

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Transitions

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$$\begin{aligned} |0; N_i Z_i; \sigma\rangle &= \sum_{\Lambda_i} G_{\Lambda_i}^{0; N_i Z_i; \sigma} |\Lambda_i^{0; N_i Z_i}\rangle \\ |0; N_f Z_f; \sigma\rangle &= \sum_{\Lambda_f} G_{\Lambda_f}^{0; N_f Z_f; \sigma} |\Lambda_f^{0; N_f Z_f}\rangle \end{aligned}$$

TRANSITIONS:

$$\begin{aligned} M_{\xi}^{0\nu\beta\beta} &= \langle 0_f^+ | \hat{O}_{\xi}^{0\nu\beta\beta} | 0_i^+ \rangle = \langle 0; N_f Z_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i \rangle = \\ &= \sum_{\Lambda_f \Lambda_i} \left(G_{\Lambda_f}^{0; N_f Z_f} \right)^* \langle \Lambda_f^{0; N_f Z_f} | \hat{O}_{\xi}^{0\nu\beta\beta} | \Lambda_i^{0; N_i Z_i} \rangle G_{\Lambda_i}^{0; N_i Z_i} = \sum_{q_i q_f; \Lambda_f \Lambda_i} \\ &= \left(\frac{u_{q_f, \Lambda_f}^{0; N_f Z_f}}{\sqrt{n_{\Lambda_f}^{0; N_f Z_f}}} \right)^* \left(G_{\Lambda_f}^{0; N_f Z_f} \right)^* \langle 0; N_f Z_f; q_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i; q_i \rangle \left(G_{\Lambda_i}^{0; N_i Z_i} \right) \left(\frac{u_{q_i, \Lambda_i}^{0; N_i Z_i}}{\sqrt{n_{\Lambda_i}^{0; N_i Z_i}}} \right) \end{aligned}$$

Matrix elements of the double beta transition operators between particle number and angular momentum projected states

CONTENTS

1. Introduction

**2. Method:
GCM
+PNAMP**

3. Results: GCM
+PNAMP

4. Summary and
Conclusions

Method: GCM+PNAMP

Transitions

$$\begin{array}{ll}
 \begin{array}{l}
 1. \text{ Axial states } K = 0 \\
 2. \text{ Angular momentum } I = 0 \\
 3. \text{ Ground states } \sigma = 0 \\
 4. \text{ Quadrupole deformations } q = q_{20}
 \end{array}
 & \longrightarrow
 \begin{array}{l}
 |0; N_i Z_i; \sigma\rangle = \sum_{\Lambda_i} G_{\Lambda_i}^{0; N_i Z_i; \sigma} |\Lambda_i^{0; N_i Z_i}\rangle \\
 |0; N_f Z_f; \sigma\rangle = \sum_{\Lambda_f} G_{\Lambda_f}^{0; N_f Z_f; \sigma} |\Lambda_f^{0; N_f Z_f}\rangle
 \end{array}
 \end{array}$$

TRANSITIONS:

$$\begin{aligned}
 M_{\xi}^{0\nu\beta\beta} &= \langle 0_f^+ | \hat{O}_{\xi}^{0\nu\beta\beta} | 0_i^+ \rangle = \langle 0; N_f Z_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i \rangle = \\
 &= \sum_{\Lambda_f \Lambda_i} \left(G_{\Lambda_f}^{0; N_f Z_f} \right)^* \langle \Lambda_f^{0; N_f Z_f} | \hat{O}_{\xi}^{0\nu\beta\beta} | \Lambda_i^{0; N_i Z_i} \rangle G_{\Lambda_i}^{0; N_i Z_i} = \sum_{q_i q_f; \Lambda_f \Lambda_i} \\
 &= \left(\frac{u_{q_f, \Lambda_f}^{0; N_f Z_f}}{\sqrt{n_{\Lambda_f}^{0; N_f Z_f}}} \right)^* \left(G_{\Lambda_f}^{0; N_f Z_f} \right)^* \langle 0; N_f Z_f; q_f | \hat{O}_{\xi}^{0\nu\beta\beta} | 0; N_i Z_i; q_i \rangle \left(G_{\Lambda_i}^{0; N_i Z_i} \right) \left(\frac{u_{q_i, \Lambda_i}^{0; N_i Z_i}}{\sqrt{n_{\Lambda_i}^{0; N_i Z_i}}} \right)
 \end{aligned}$$

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

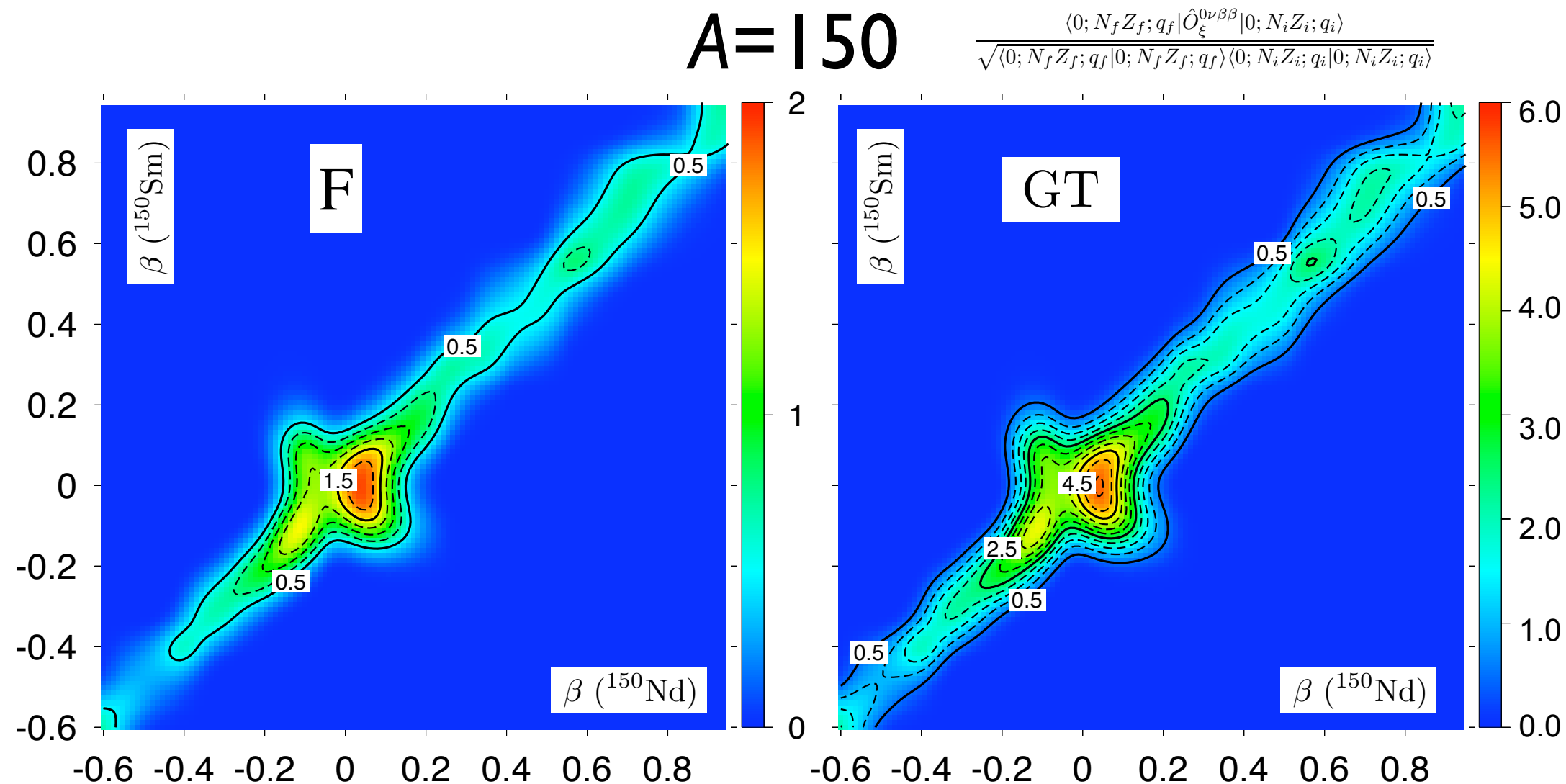
CONTENTS

1. Introduction

2. Method: GCM+PNAMP

3. Results:
GCM+PNAMP

4. Summary and
Conclusions



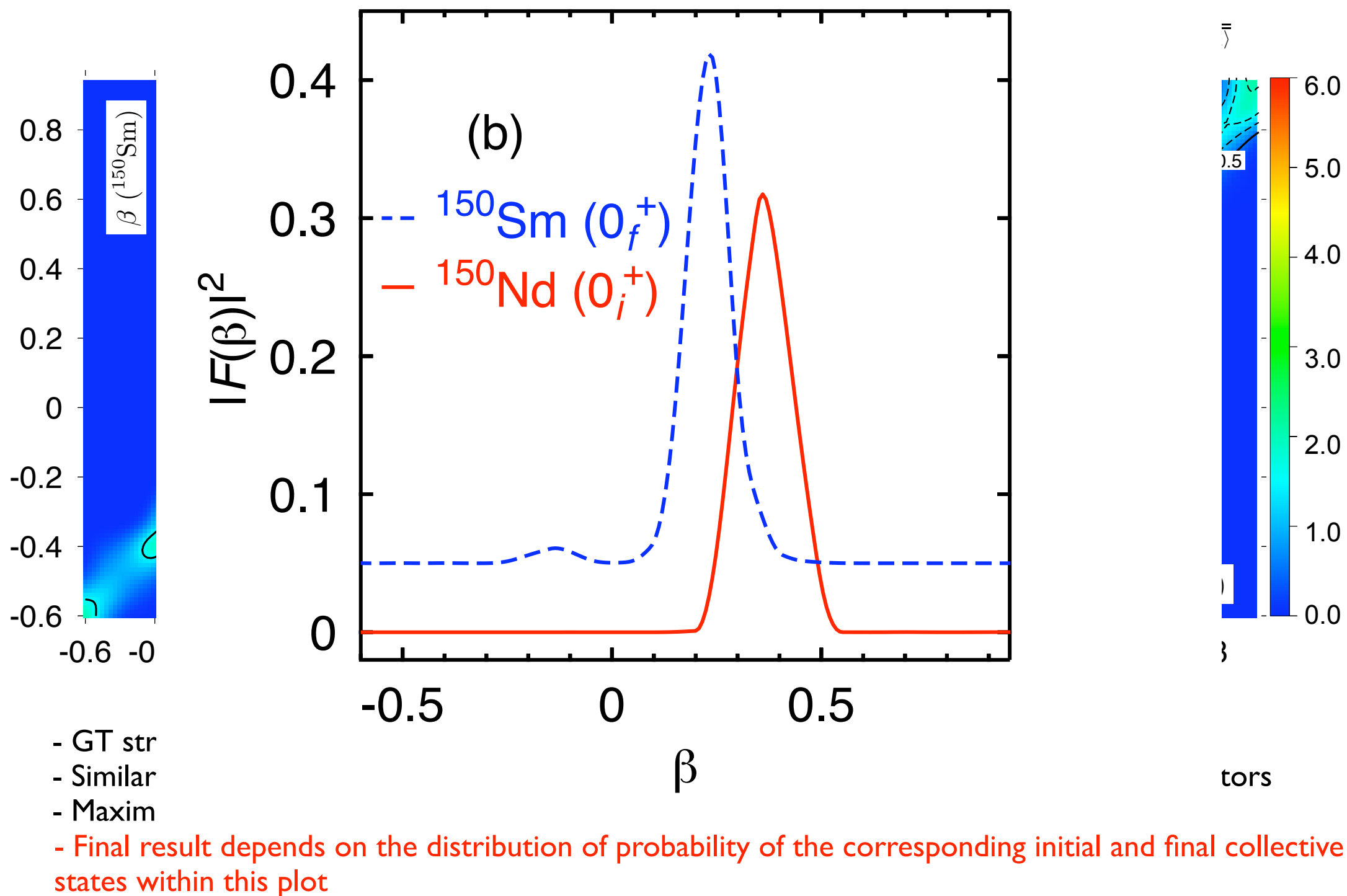
- GT strength greater than Fermi.
- Similar deformation between mother and granddaughter is favored by the transition operators
- Maxima are found close to sphericity although some other local maxima are found

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions

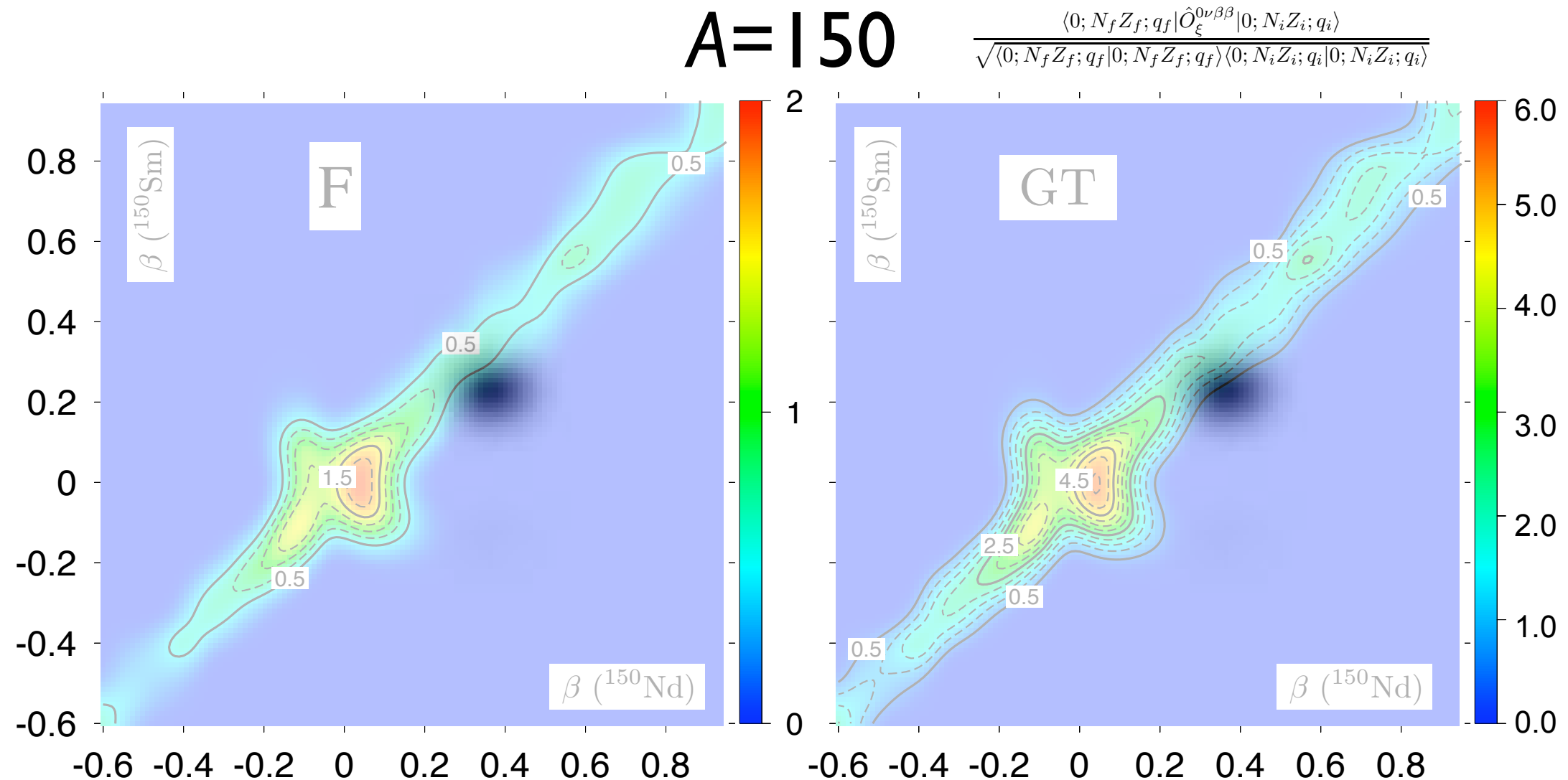


Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions



- GT strength greater than Fermi.
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- Final result depends on the distribution of probability of the corresponding initial and final collective states within this plot

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

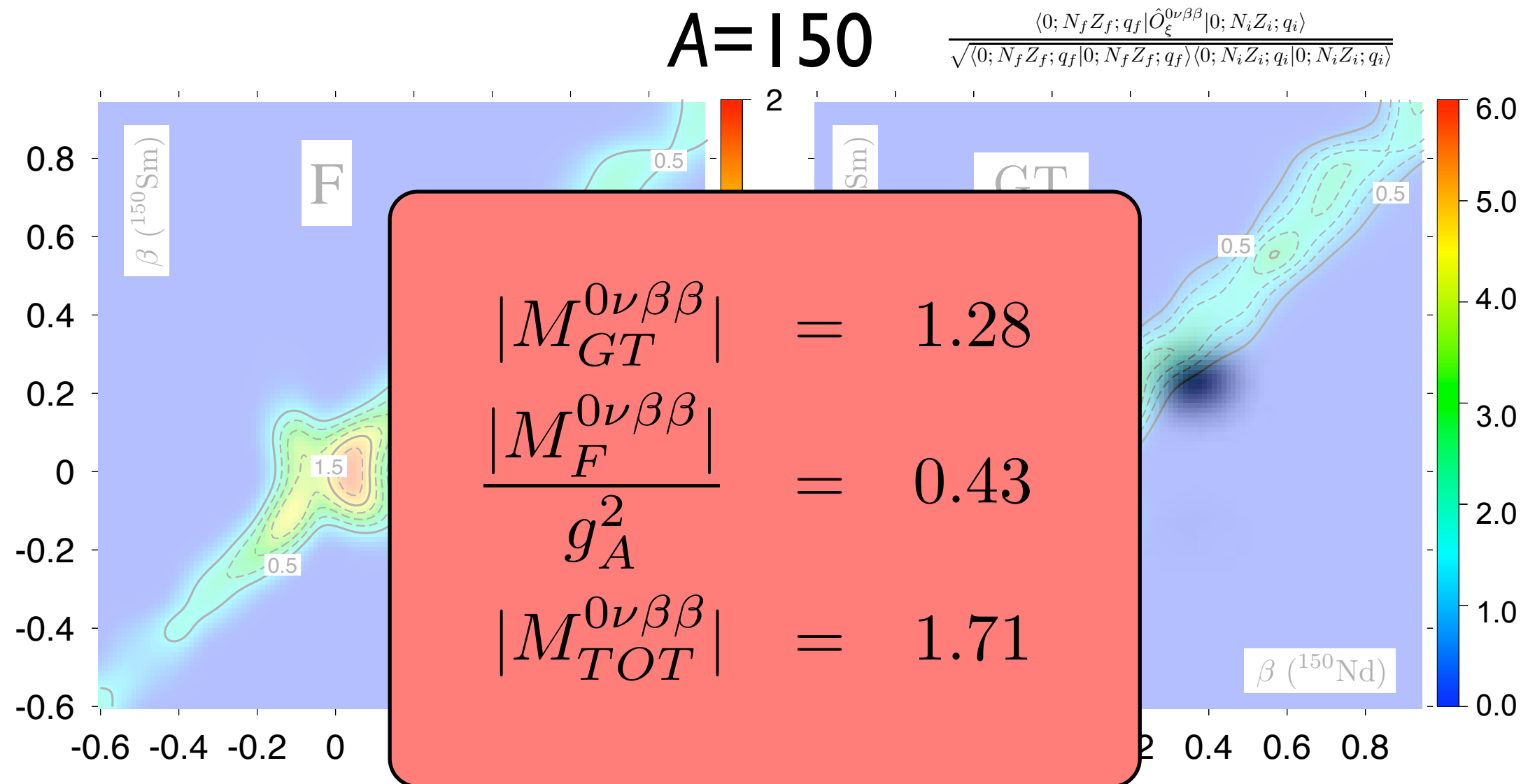
CONTENTS

1. Introduction

2. Method: GCM+PNAMP

3. Results:
GCM+PNAMP

4. Summary and
Conclusions



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- Similar deformation between mother and granddaughter is favored by the transition operators
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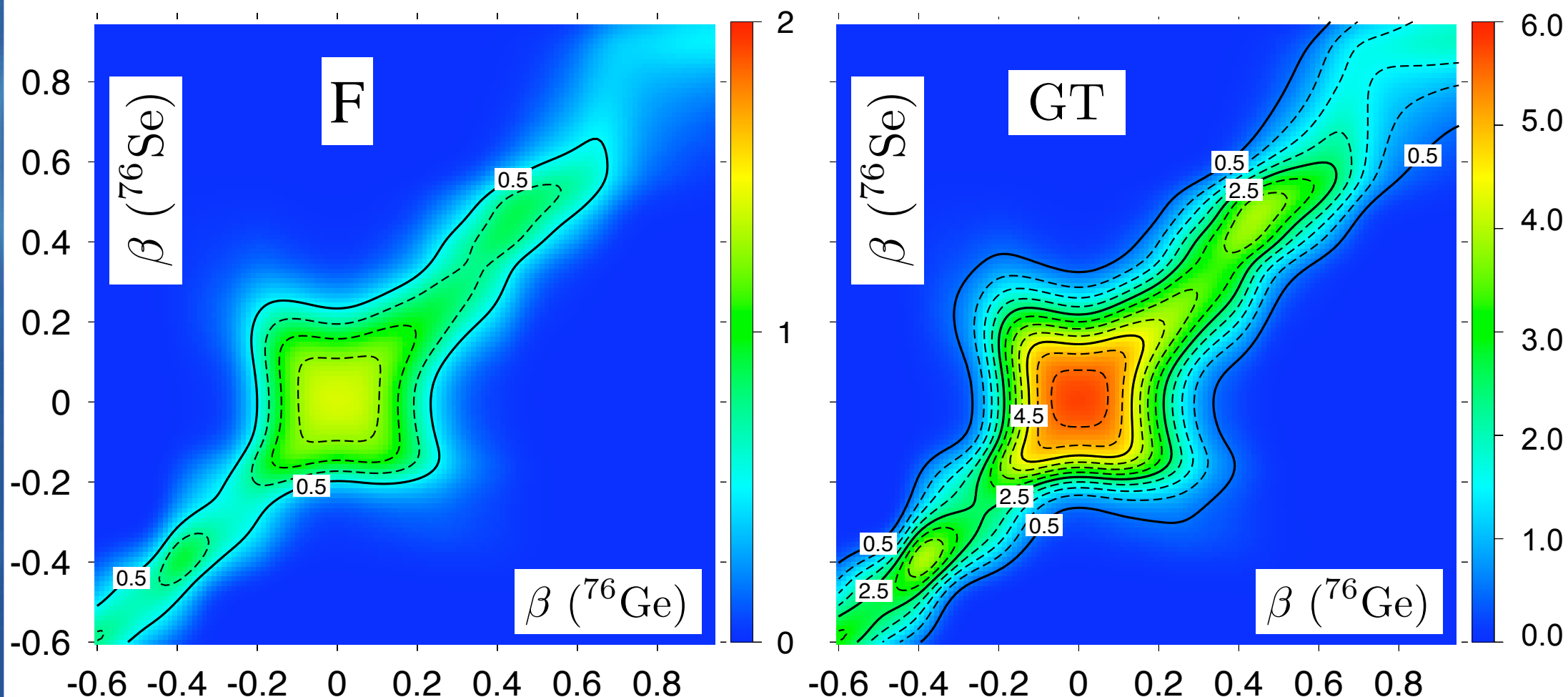
Results: GCM+PNAMP

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions

$A=76$

$$\frac{\langle 0; N_f Z_f; q_f | \hat{O}_\xi^{0\nu\beta\beta} | 0; N_i Z_i; q_i \rangle}{\sqrt{\langle 0; N_f Z_f; q_f | 0; N_f Z_f; q_f \rangle \langle 0; N_i Z_i; q_i | 0; N_i Z_i; q_i \rangle}}$$

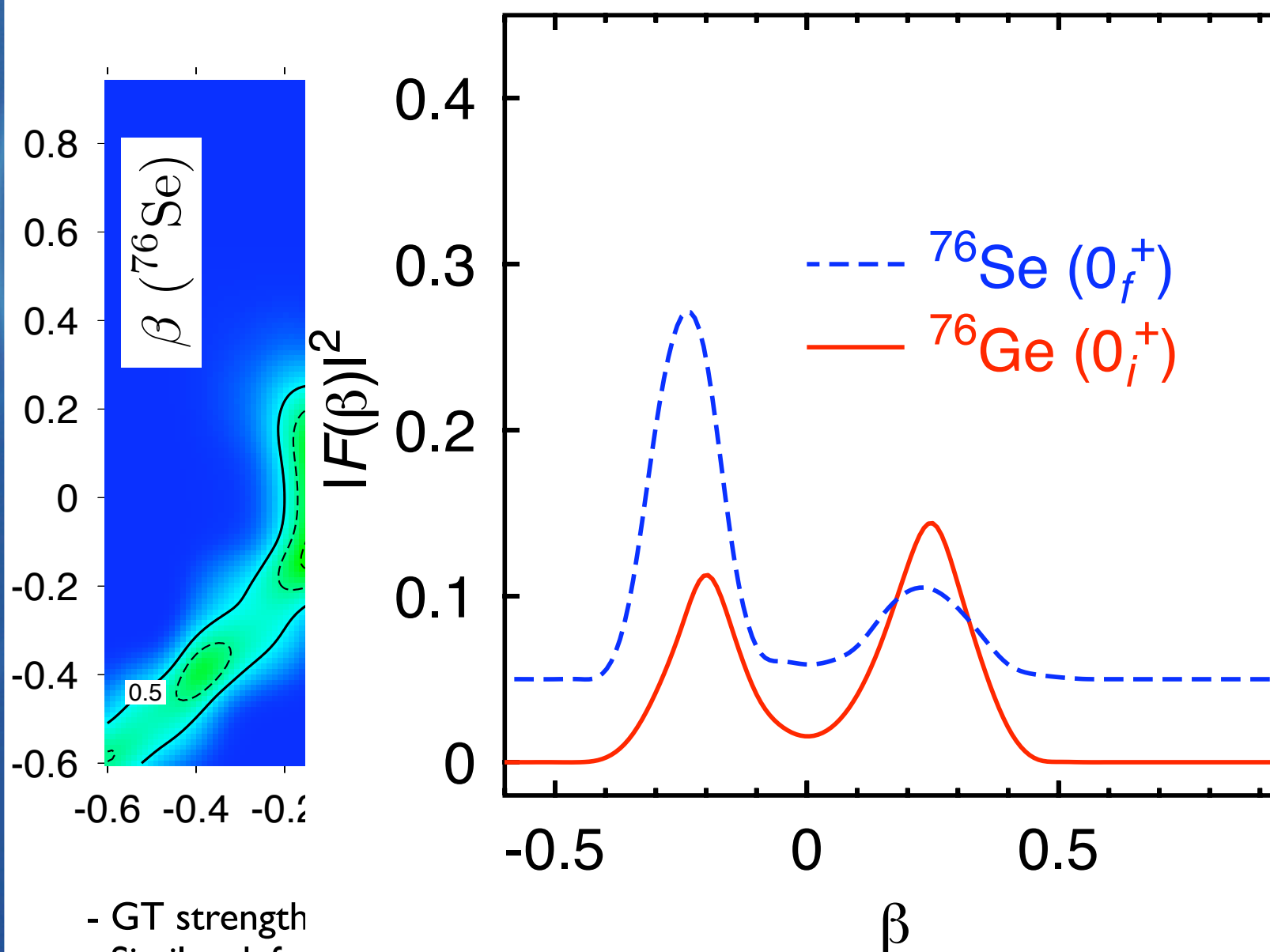


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Results: GCM+PNAMP

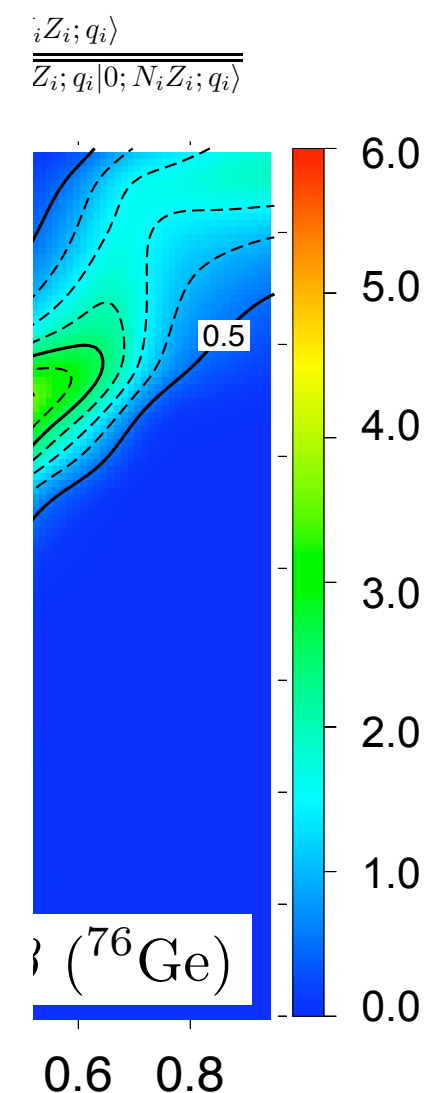
CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions



- GT strength
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ion operators
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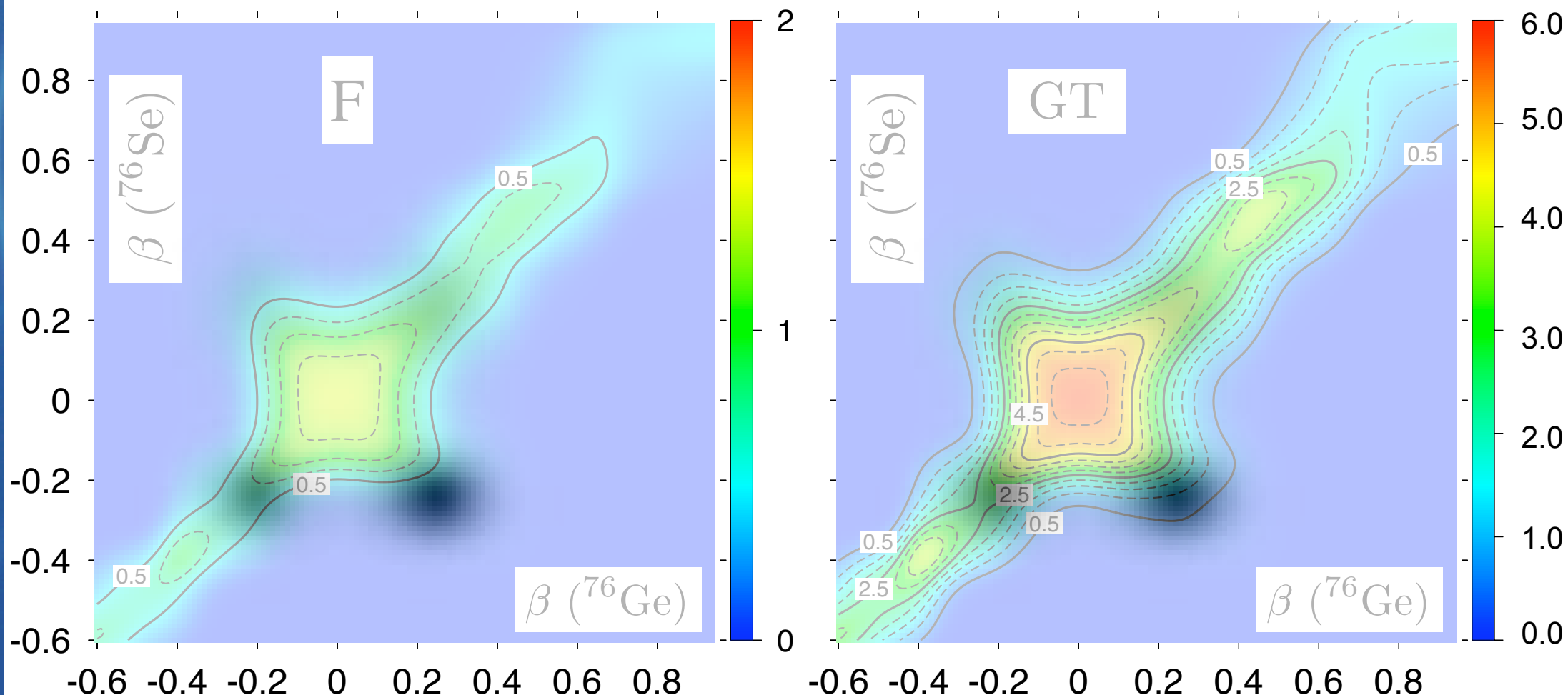
Results: GCM+PNAMP

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions

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CONTENTS

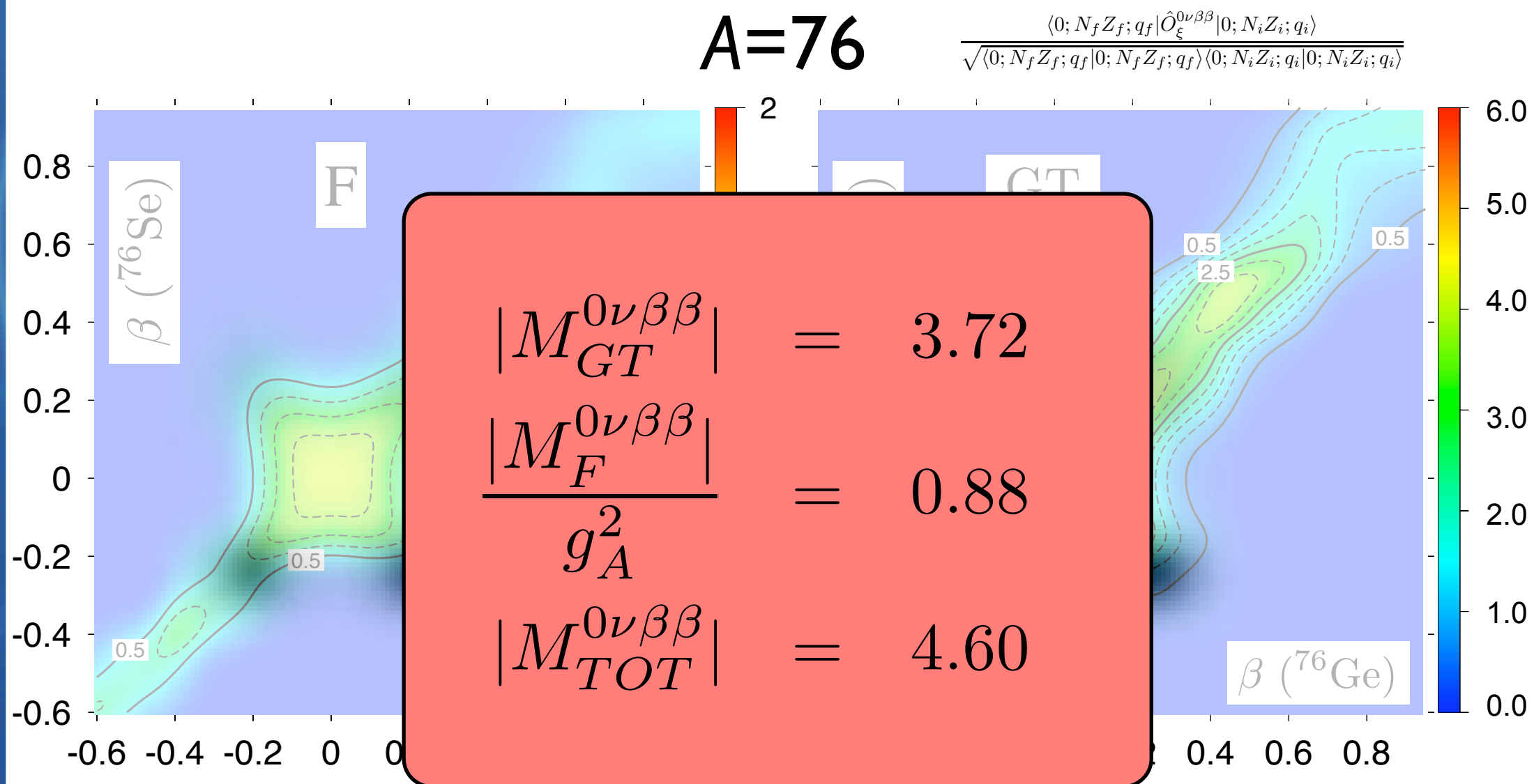
1. Introduction

2. Method: GCM+PNAMP

3. Results:
GCM+PNAMP

4. Summary and
Conclusions

Results: GCM+PNAMP



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CONTENTS

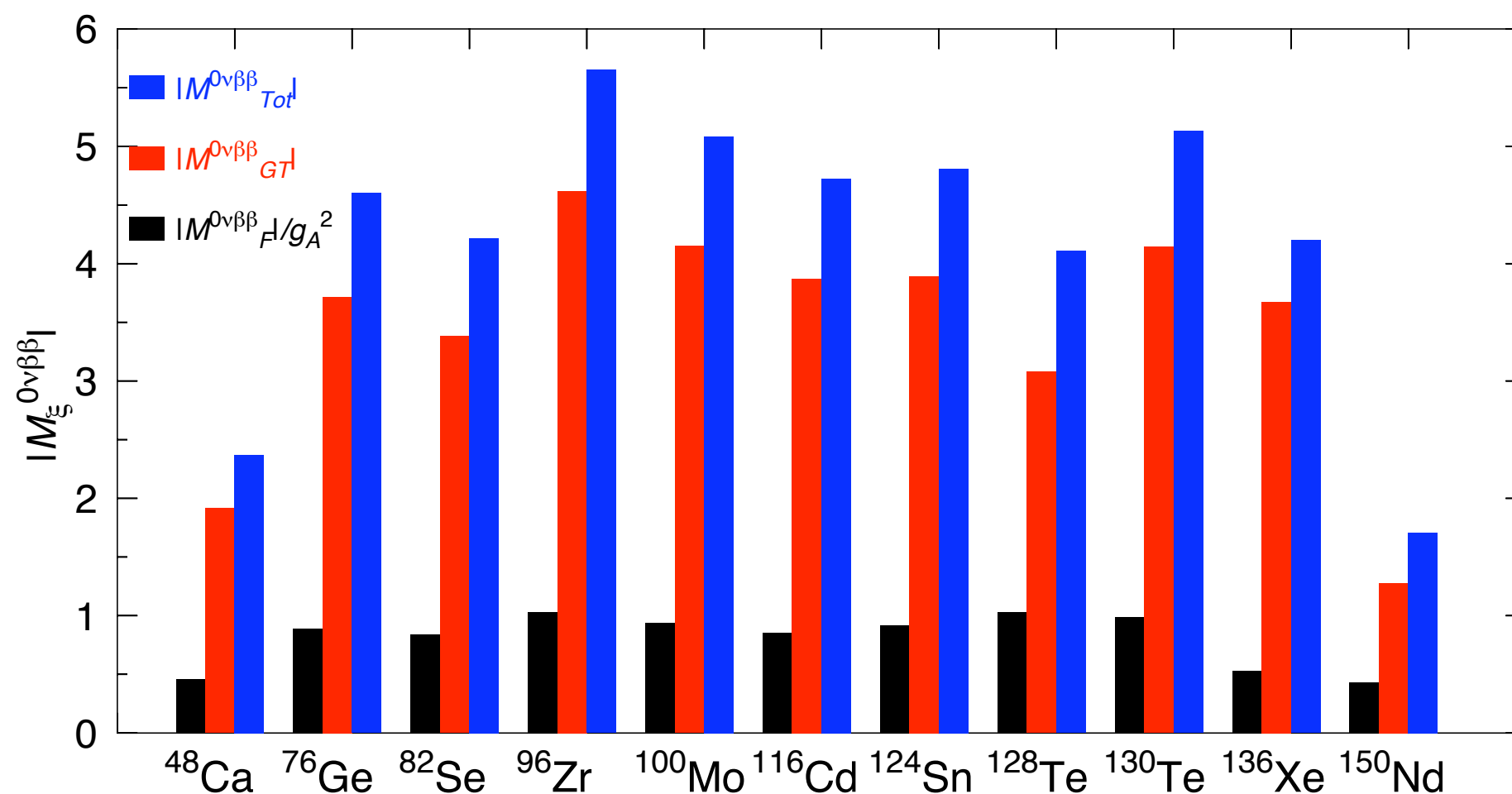
1. Introduction

2. Method: GCM+PNAMP

3. Results:
GCM+PNAMP

4. Summary and
Conclusions

Results: GCM+PNAMP



- Small contribution of Fermi compared to Gamow-Teller.
- Small value for $A=150$ transition due to the difference in deformation.
- Small value for $A=48$ due to the small value of the strength of the operator.

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

CONTENTS

1. Introduction

2. Method: GCM+PNAMP

3. Results: GCM+PNAMP

4. Summary and Conclusions

TABLE I: Difference between theoretical and experimental Q values, kinematical phase space factors, NME and predicted half-lives for several $0\nu\beta\beta$ decaying nuclei assuming $\langle m_{\beta\beta} \rangle = 0.5$ eV.

Nucleus	$Q_{\text{theo}} - Q_{\text{exp}}$ (MeV)	G_{01} ($\times 10^{-14} \text{ y}^{-1}$)	$M^{0\nu}$	$T_{1/2}$ ($\times 10^{23} \text{ y}$)
^{48}Ca	0.265	6.52	2.37	28.5
^{76}Ge	0.271	0.64	4.60	76.9
^{82}Se	-0.366	2.83	4.22	20.8
^{96}Zr	2.580	5.97	5.65	5.48
^{100}Mo	1.879	4.68	5.08	8.64
^{116}Cd	1.365	5.08	4.72	9.24
^{124}Sn	-0.830	2.79	4.81	16.2
^{128}Te	-0.564	0.18	4.11	343.1
^{130}Te	-0.348	4.49	5.13	8.84
^{136}Xe	-1.027	4.68	4.20	12.7
^{150}Nd	-0.380	21.74	1.71	16.5

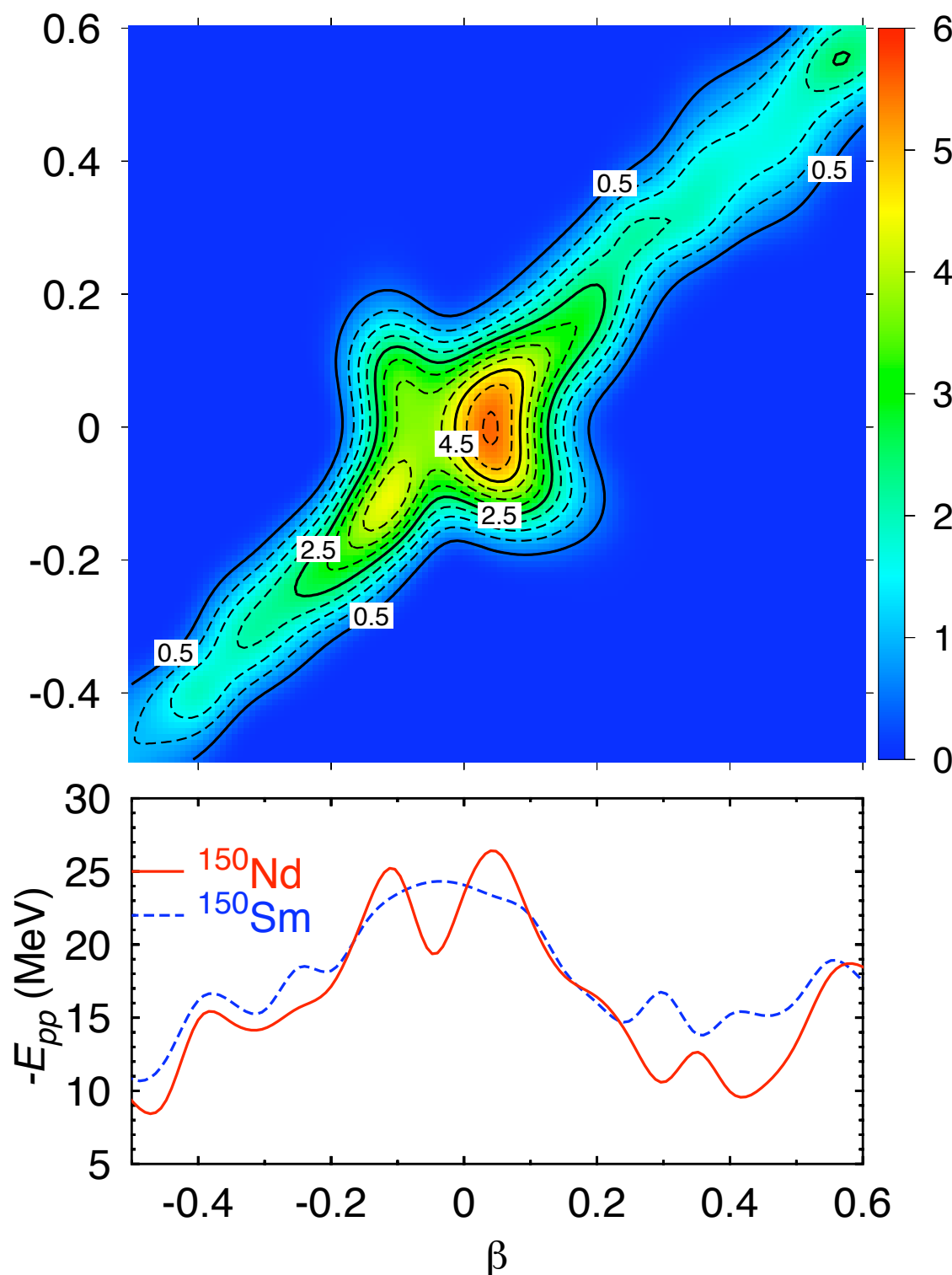
- Good agreement between experimental and theoretical Q -values

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions



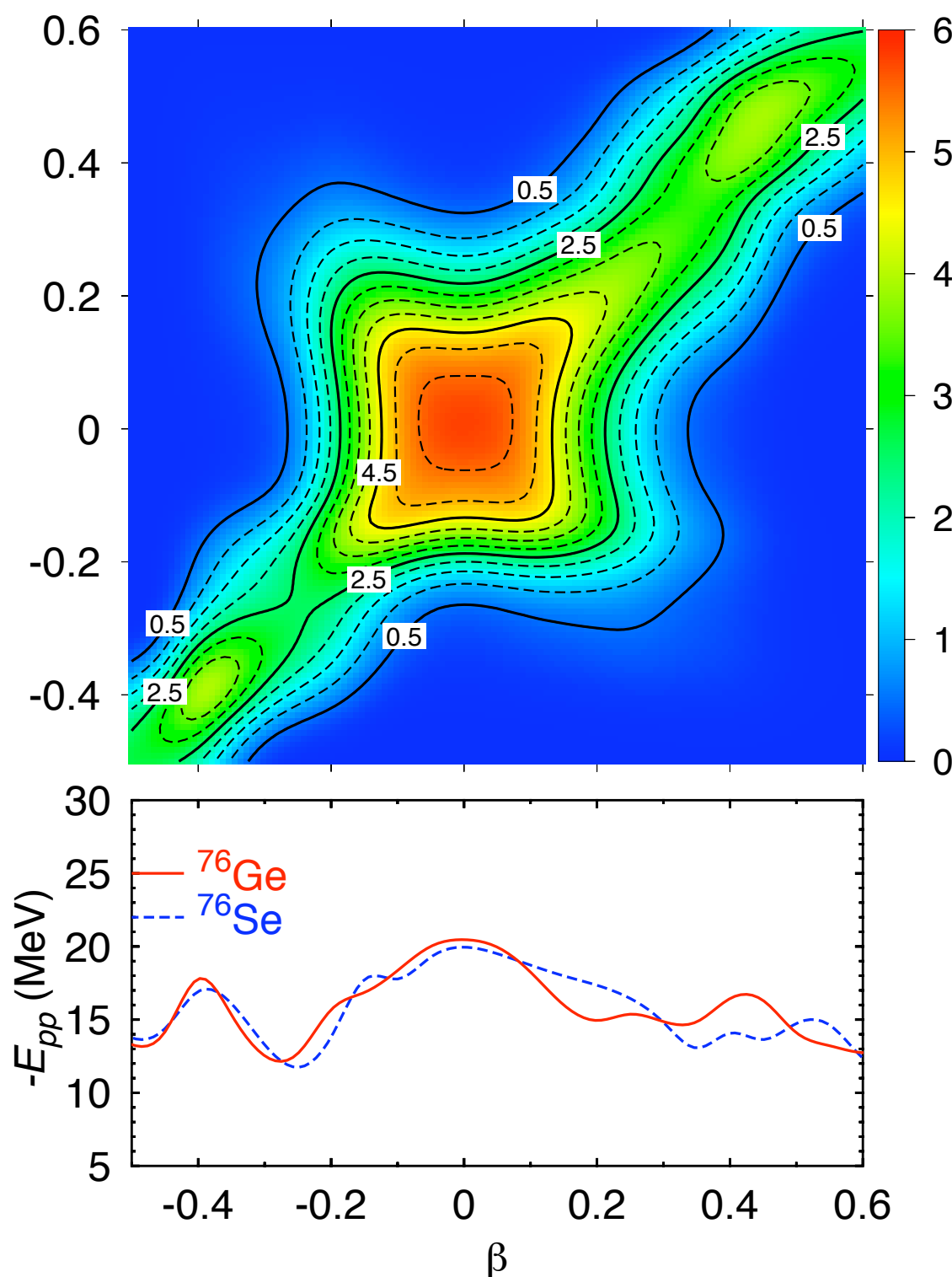
- The structure is related to the pairing energy (particle-particle) of the nuclei involved in the transition
- Maxima of the strength correspond to maxima in pairing energy
- In agreement with seniority arguments (increasing seniority decreases NME)
- Pairing energy and NME involve similar Wick theorem's contractions in this formalism

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260



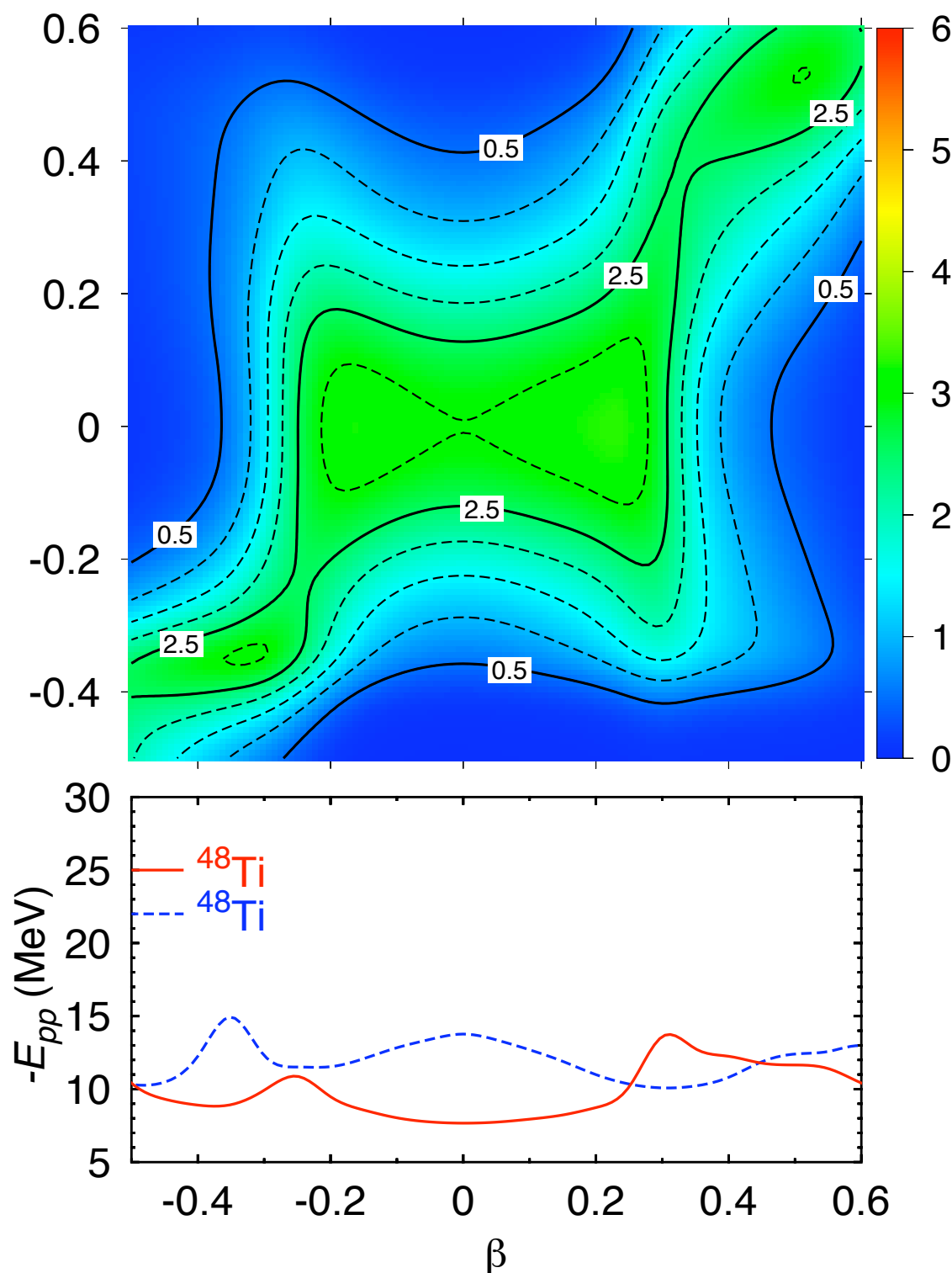
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T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

CONTENTS

1. Introduction
2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions



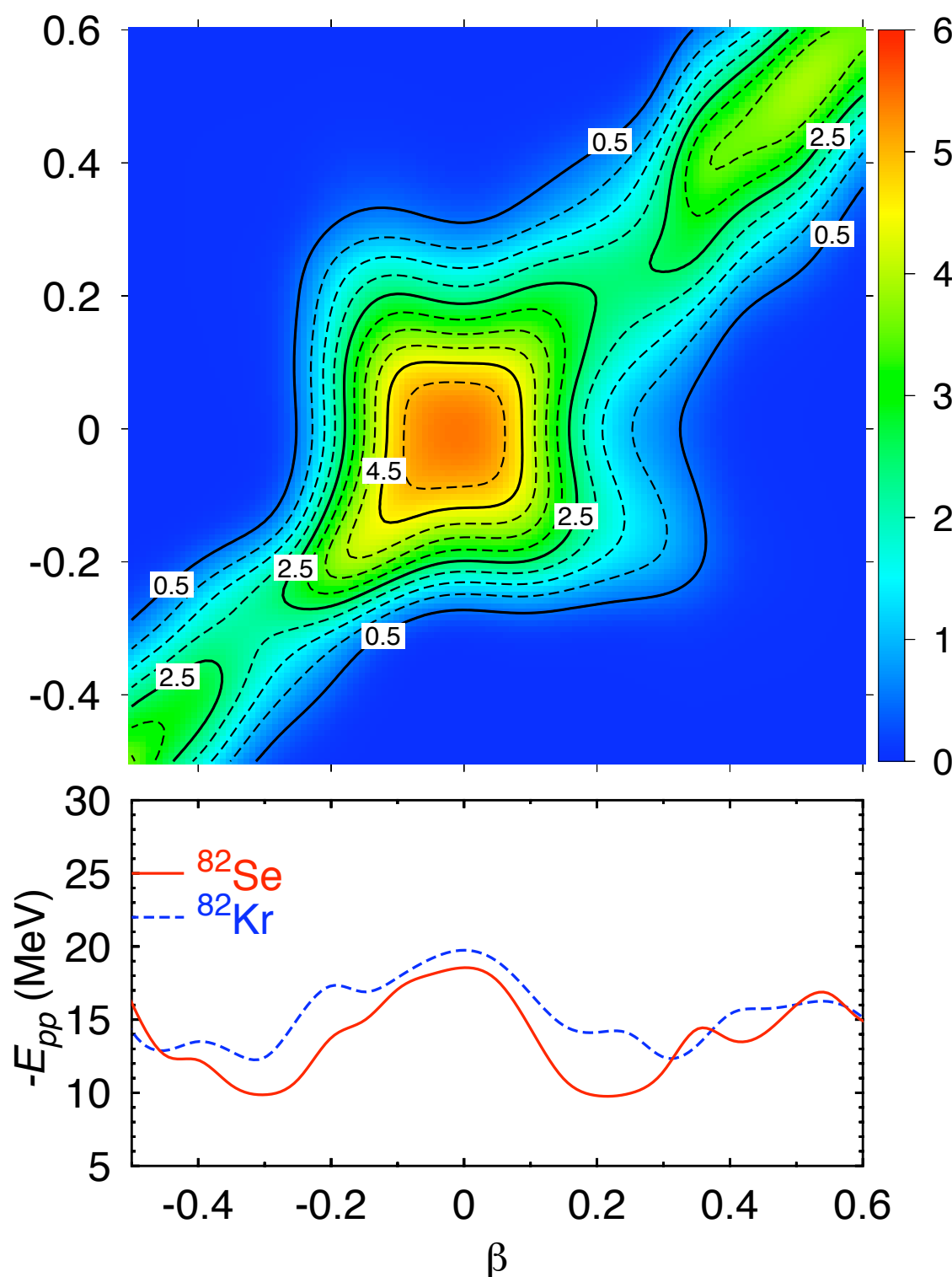
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CONTENTS

1. Introduction
2. Method: GCM+PNAMP
- 3. Results: GCM+PNAMP**
4. Summary and Conclusions

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260



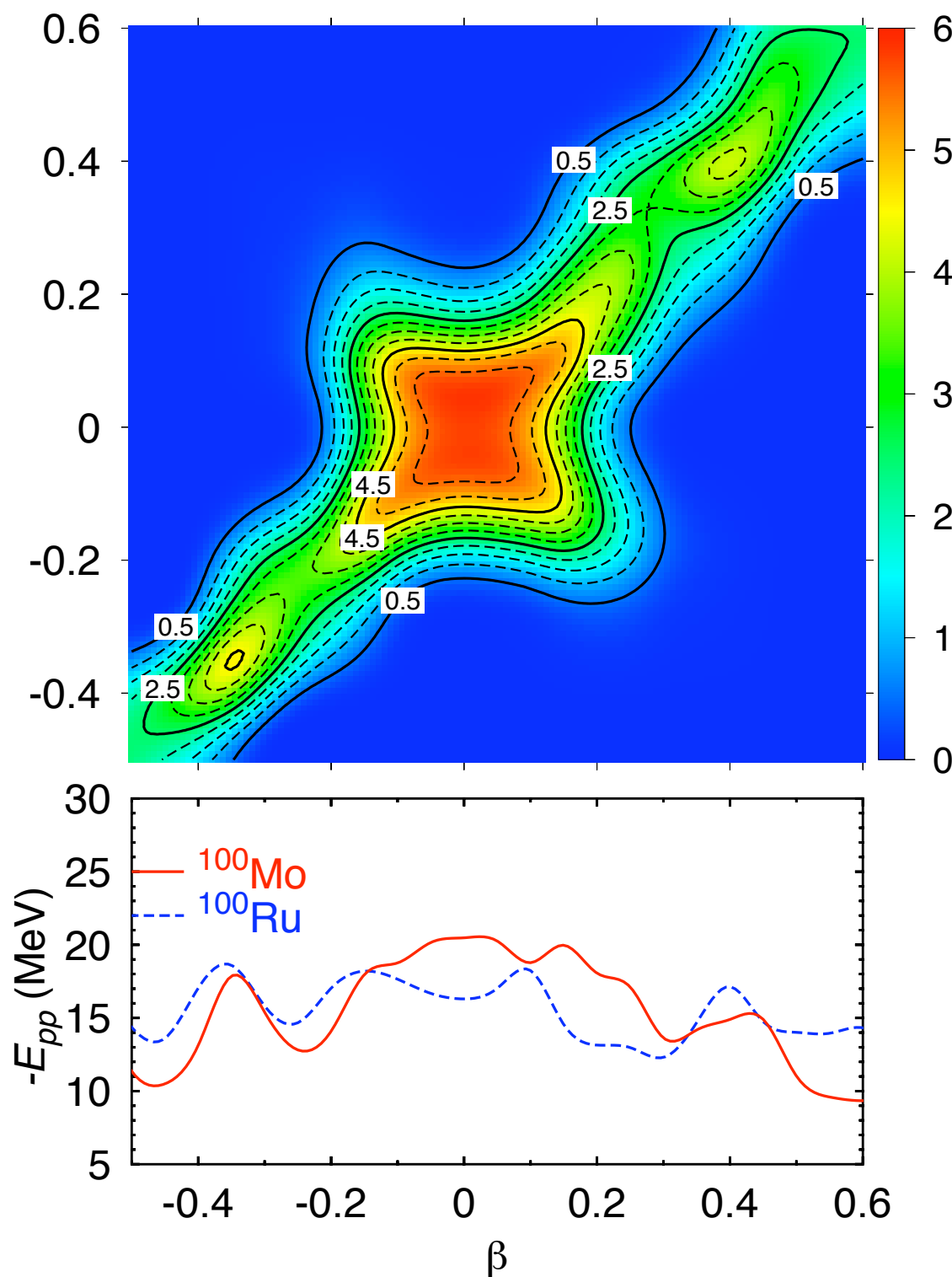
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T.R.R., G. Martinez-Pinedo, arXiv:1008.5260

CONTENTS

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2. Method: GCM+PNAMP
3. Results: GCM+PNAMP
4. Summary and Conclusions



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CONTENTS

1. Introduction

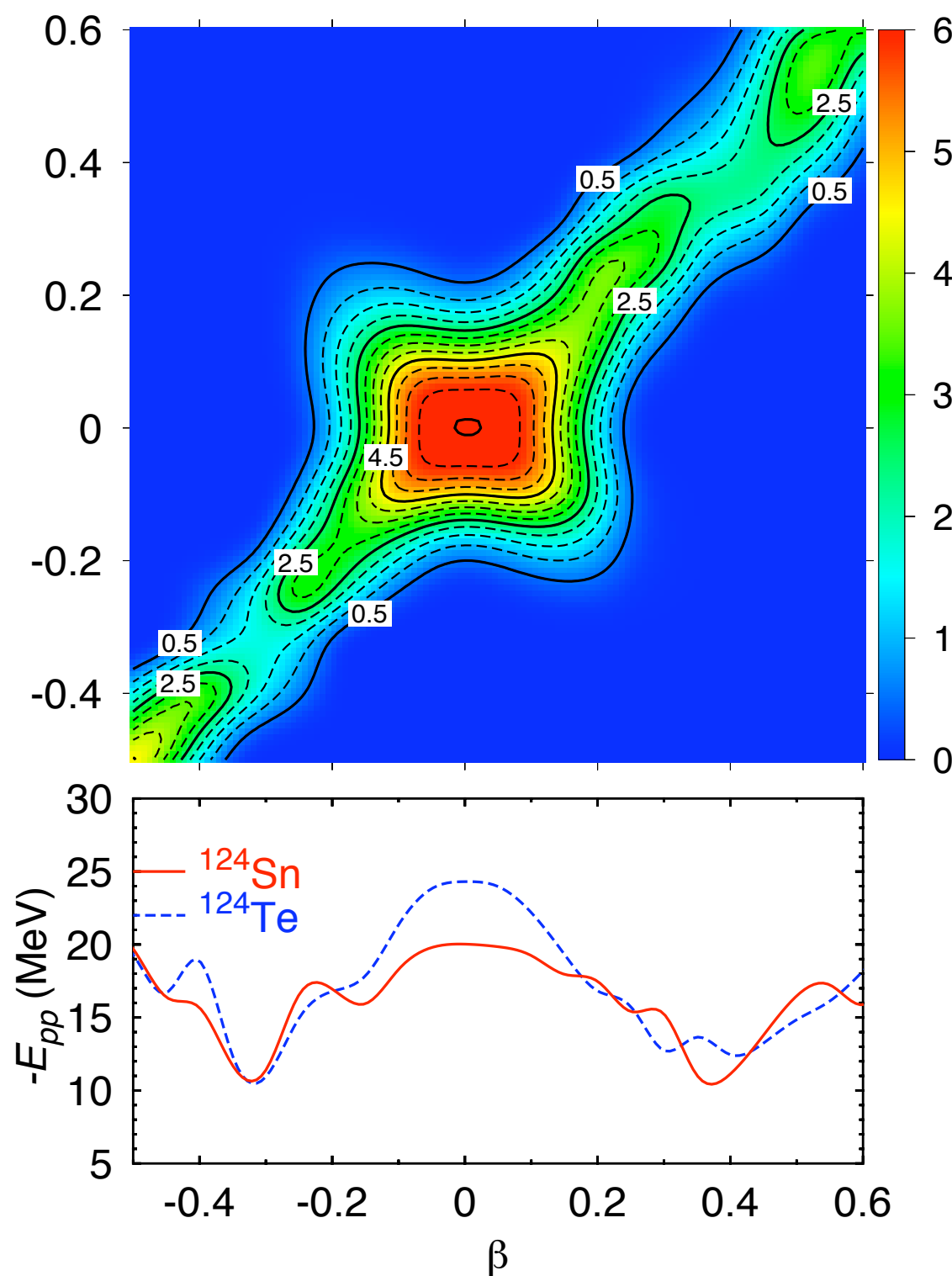
2. Method: GCM+PNAMP

3. Results:
GCM+PNAMP

4. Summary and
Conclusions

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260



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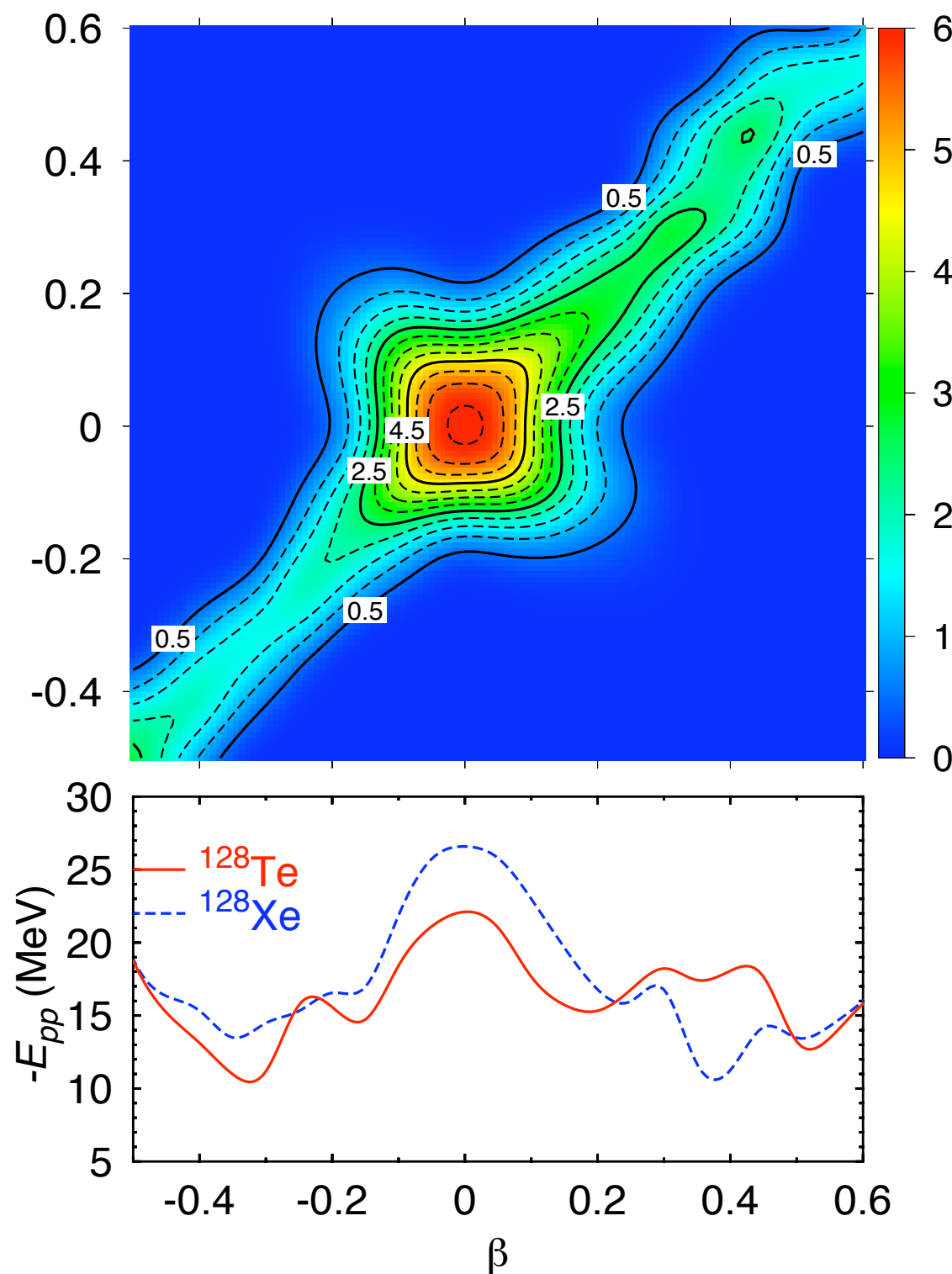
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CONTENTS

1. Introduction
2. Method: GCM+PNAMP
- 3. Results: GCM+PNAMP**
4. Summary and Conclusions

Results: GCM+PNAMP

T.R.R., G. Martinez-Pinedo, arXiv:1008.5260



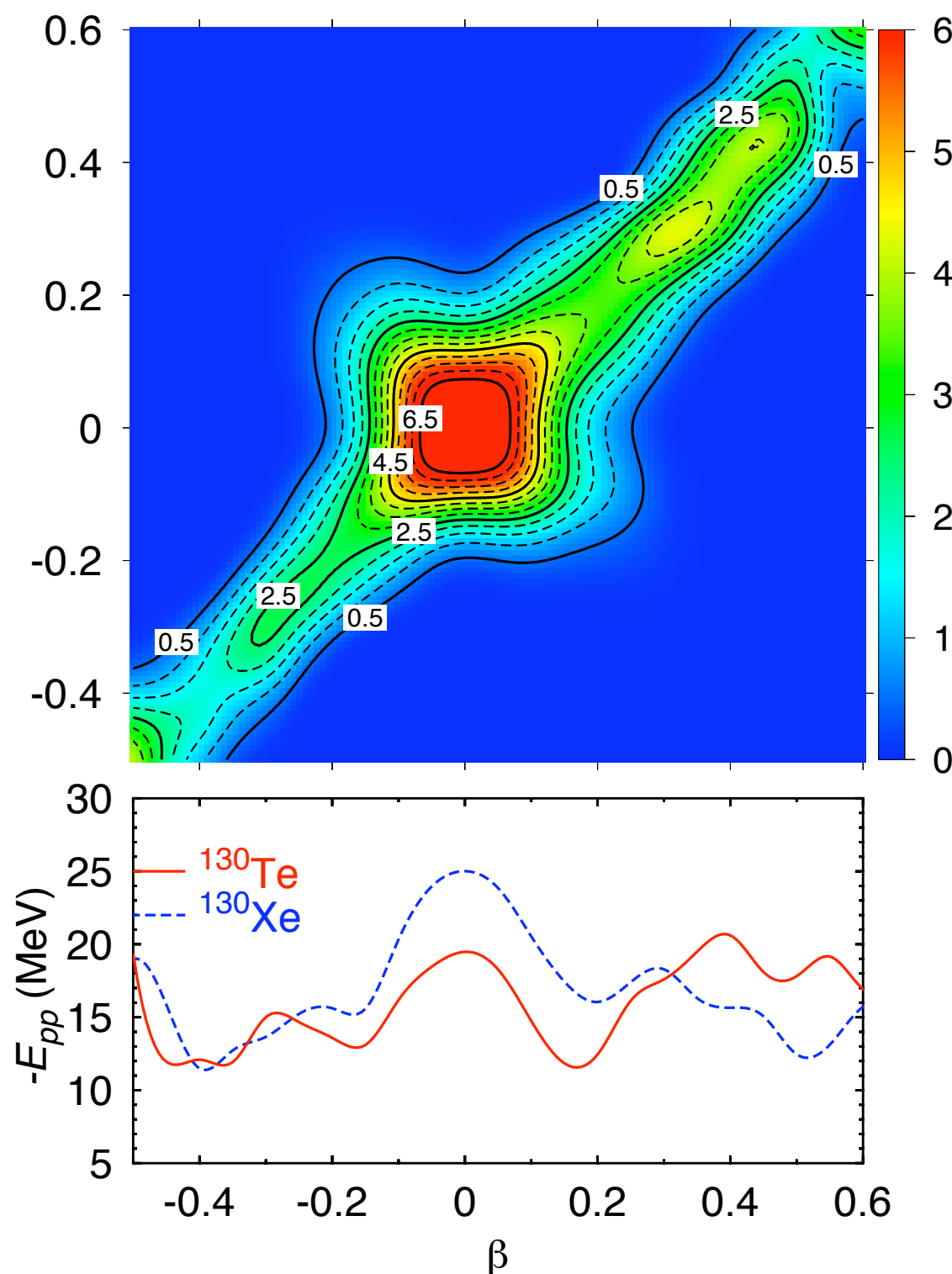
- The structure is related to the pairing energy (particle-particle) of the nuclei involved in the transition
- Maxima of the strength correspond to maxima in pairing energy
- In agreement with seniority arguments (increasing seniority decreases NME)
- Pairing energy and NME involve similar Wick theorem's contractions in this formalism

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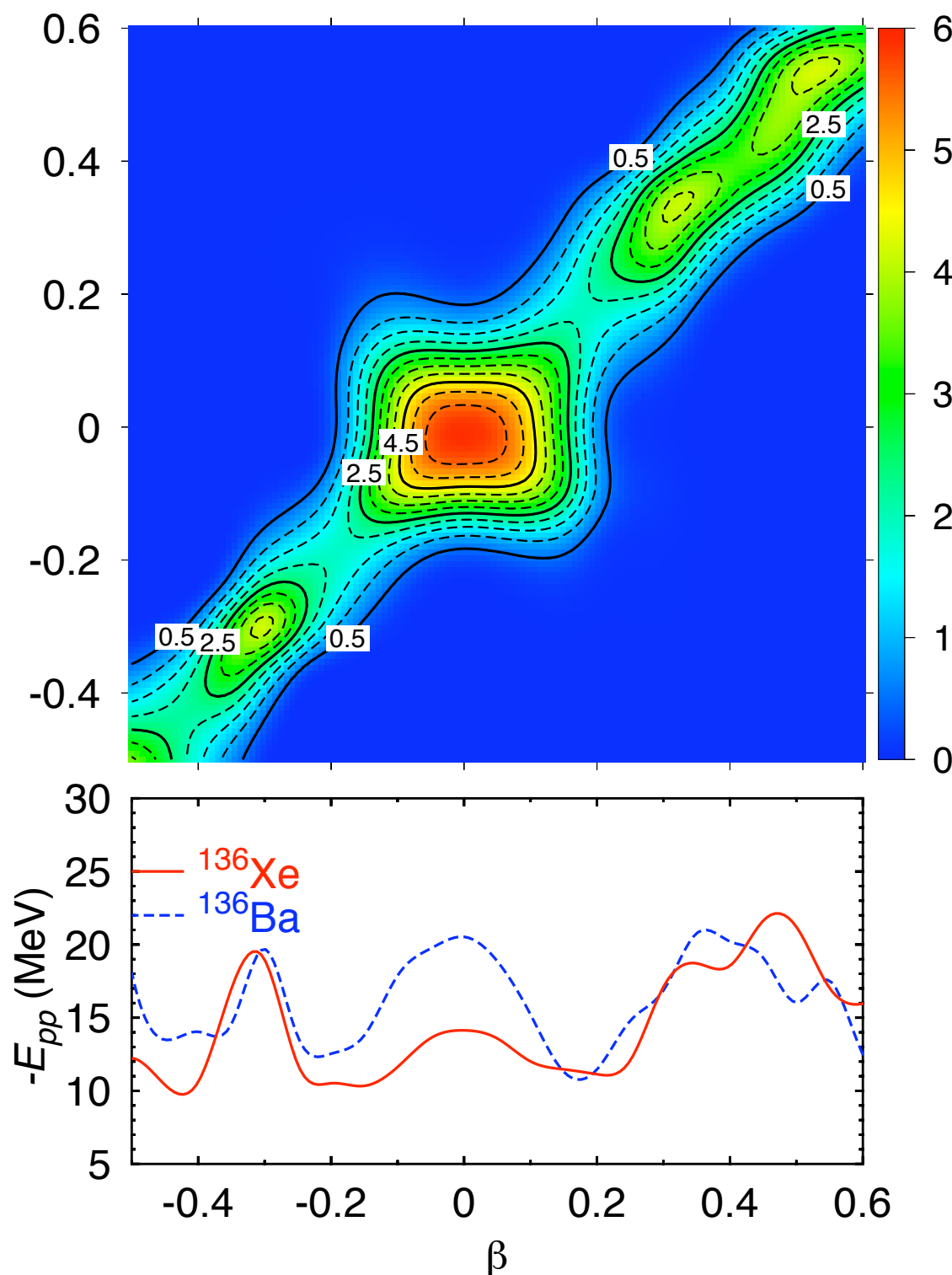
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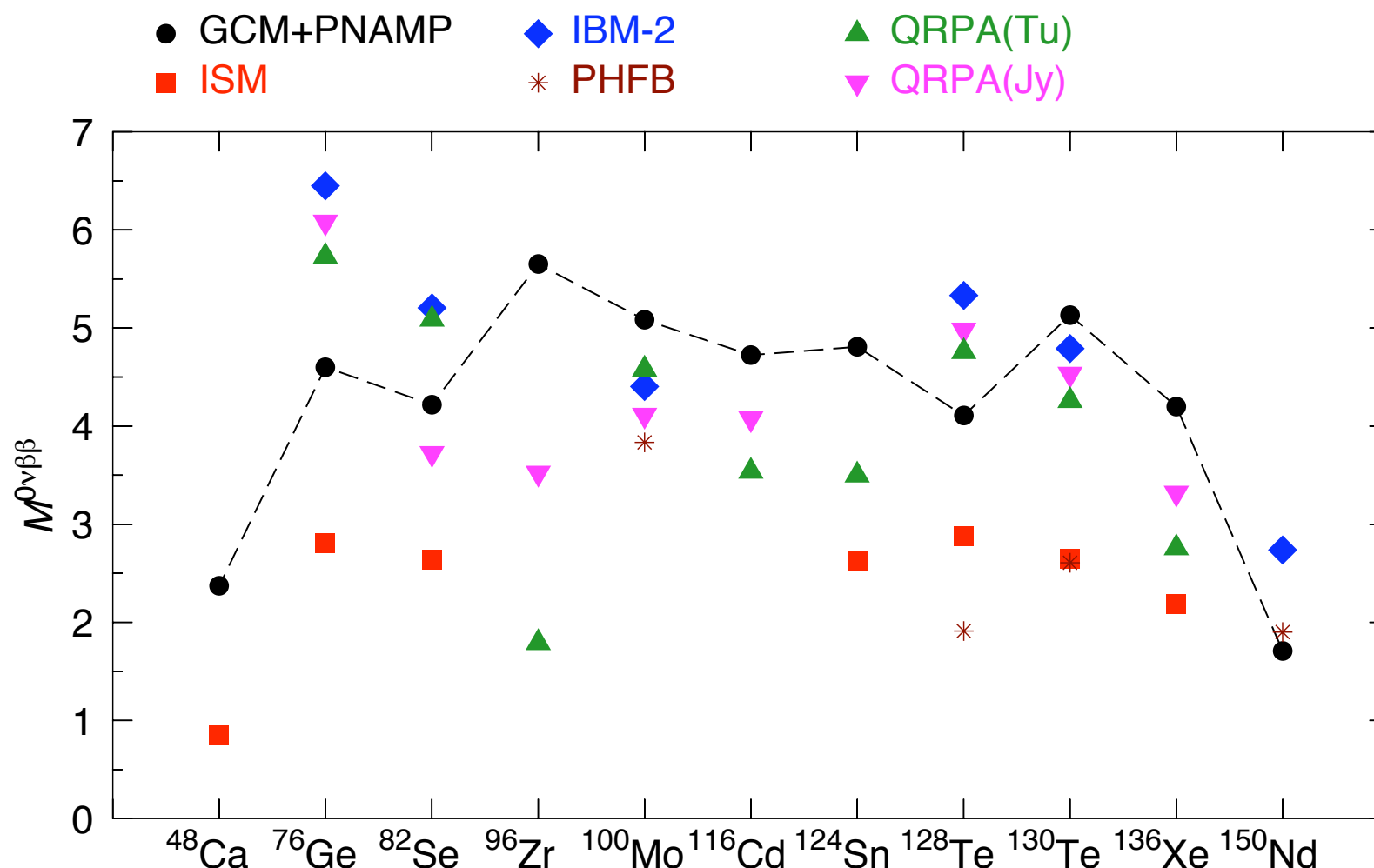
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QRPA (Jy): M. Kortelainen, J. Suhonen, PRC 75, 051303(R) (2007) and PRC 76, 024315 (2007)

QRPA(Tu): F. Simkovic et al., PRC 77, 045503 (2008)

ISM: J. Menendez et al., PRL 100, 52503 (2008)

IBM-2: J. Barea, F. Iachello, PRC 77, 045503 (2008)

PHFB: K. Chaturvedi et al. PRC 78, 054302 (2008)

- Higher values than the ones predicted by ISM calculations (larger valence space, lower seniority components).
- For $A=76, 82, 128, 150$ we predict smaller values than the ones given by QRPA and/or IBM while for $A=96, 100, 116, 124, 130, 136$ larger values are obtained.
- Consistent results with the rest of the models. Notice that we are using the same interaction for all the nuclei.
- Further studies are needed to understand what is missing in the different models.

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Summary and Conclusions (I)

- First calculations of neutrinoless double beta decay using GCM+PNAMP with the Gogny DIS interaction.
- First calculations with Particle Number Projection for different number of particles in bra and ket states.
- Formalism equivalent to a pairing term in the multi-reference EDF formalism.
- Explicit inclusion of deformation and shape mixing.
- Axial calculations with parity and time reversal conservation.

CONTENTS

1. Introduction

2. Method: GCM
+PNAMP

3. Results: GCM
+PNAMP

**4. Summary
and
Conclusions**

Summary and Conclusions (II)

- Transition operators favor similar deformation for mother and granddaughter nuclei.
- Fermi contributions are smaller than Gamow-Teller.
- The structure can be understood studying the p-p channel of the nuclei involved in the transition.
- For $A = 76, 82, 96, 100, 116, 124, 128, 130, 136$ values between 4.1-5.6 are obtained
- For $A = 150$ the difference between deformation of the initial and final states lowers the value of the NME.
- For $A = 48$ the small pairing correlations in Ca and Ti produces a small NME.
- Results of the same order of magnitude than ISM, QRPA and IBM are obtained.
- Similarities and differences between different models will be investigated

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