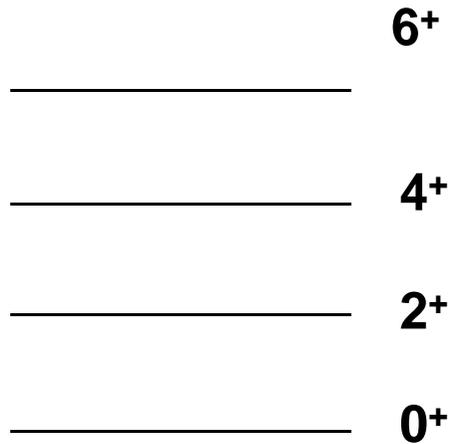


When odd nuclei break symmetries of the mean field

Sophie Péru

«vibrational» spectrum

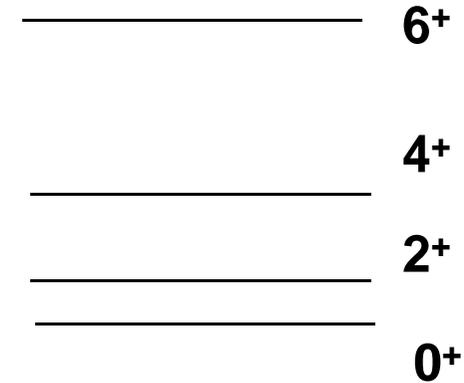
$$E^* \propto J$$



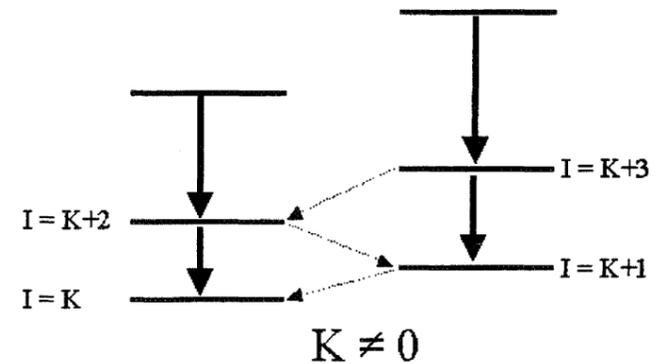
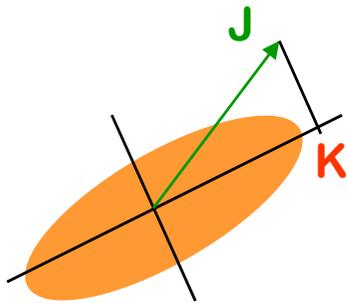
even-even nuclei
 $K = 0$

«rotational» spectrum

$$E^* \propto J(J+1)$$

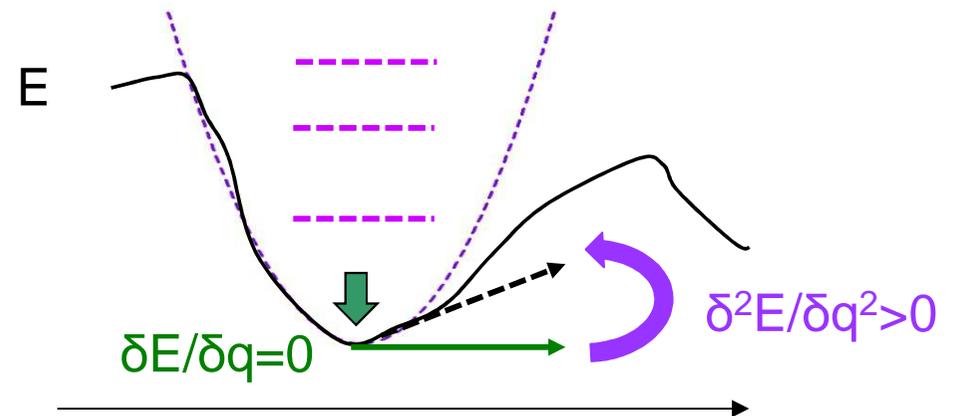


$K \neq 0$



RPA approaches describe
all multipolarities and **all** parities,
collective states and **individual** ones,
low energy and **high energy** states
 with the same accuracy.

Within the **small amplitude approximation**,
 i.e. « harmonic » nuclei

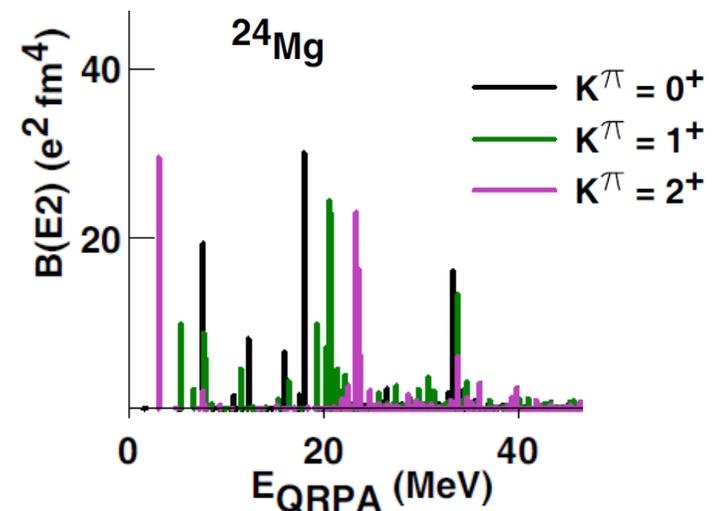


Spherical RPA with Gogny force

- J. Dechargé and L.Sips, Nucl. Phys. **A 407**,1 (1983)
- J.P. Blaizot et al, Nucl. Phys. **A 591**, 435 (1995)
- S. Péru, JF. Berger, PF. Bortignon, Eur. Phys. J. A **26**, 25-32, (2005)

Axially symmetric deformed QRPA with Gogny force

- S. Péru, H. Goutte, Phys. Rev. C **77**, 044313, (2008)
- M. Martini, S. Péru and M. Dupuis, Phys. Rev. C **83**, 034309 (2011)
- S. Péru et al, Phys. Rev. C **83**, 014314 (2011)
- F. Lechaftois, I. Deloncle, S. Peru, Phys. Rev. C **92**, 034315 (2015)
- M. Martini et al, Phys. Rev. C **94**, 014304 (2016)



! QRPA approach does not describe rotational motion !

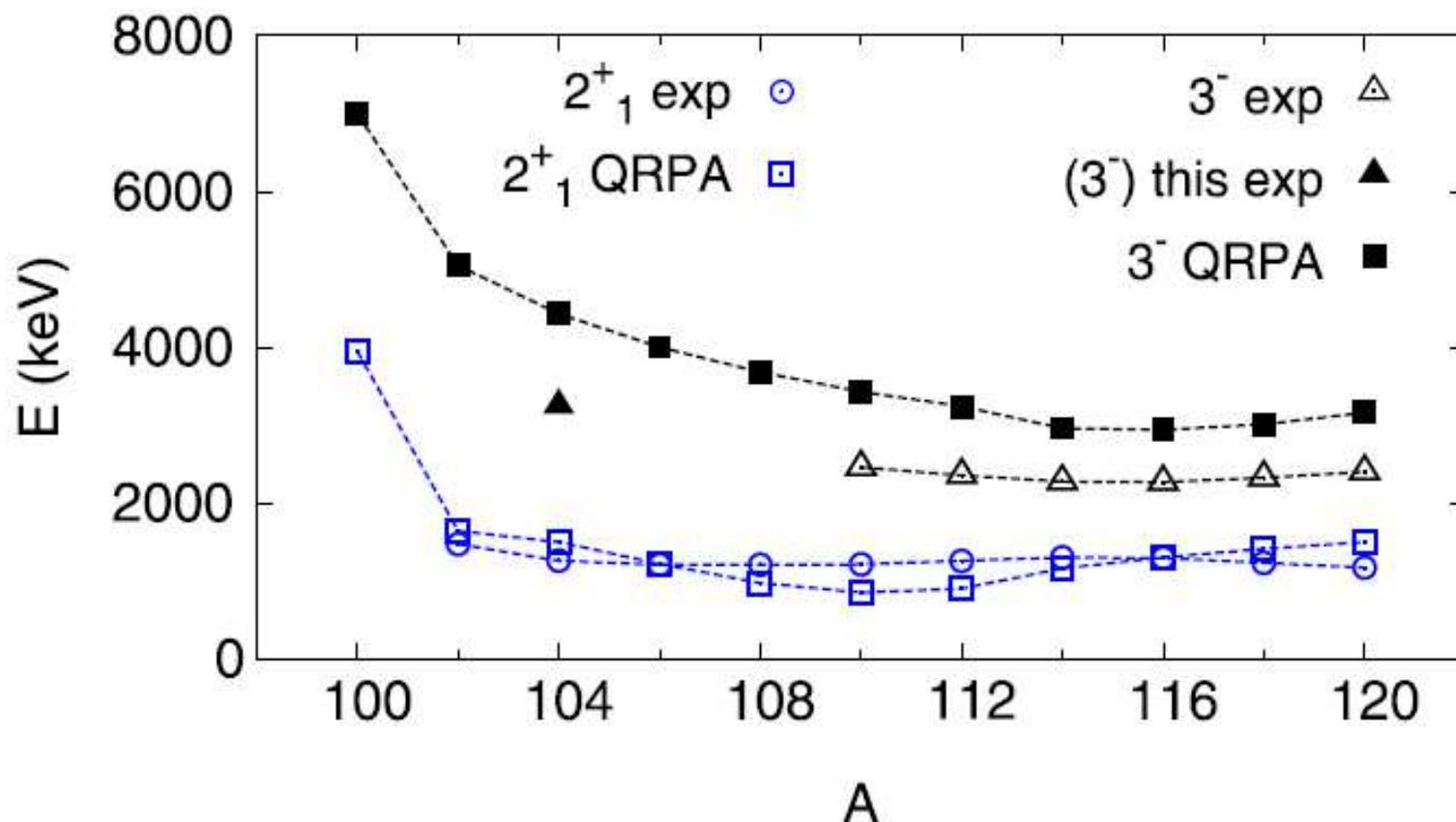


Fig. 3. (Color online.) Systematics of 2⁺ and 3⁻ excitation energies in tin isotopes from experiment and HFB + QRPA calculations using the Gogny D1M interaction.

A. Corsi et al PLB 743 (2015) 451-455

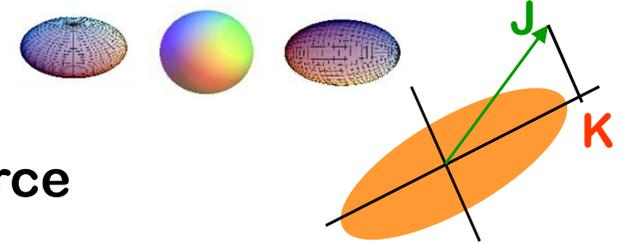
Axially-symmetric deformed QRPA

$$|\alpha, K\rangle = \theta_{\alpha, K}^+ |0\rangle \quad \theta_{n, K}^+ = \sum_{i < j} X_{n, K}^{ij} \eta_{i, k_i}^+ \eta_{j, k_j}^+ - (-)^K Y_{n, K}^{ij} \eta_{j, -k_j} \eta_{i, -k_i}$$

$$\begin{pmatrix} A & B \\ B & A \end{pmatrix} \begin{pmatrix} X_{\alpha, K} \\ Y_{\alpha, K} \end{pmatrix} = \omega_{\alpha, K} \begin{pmatrix} X_{\alpha, K} \\ -Y_{\alpha, K} \end{pmatrix}$$

Main features:

- Possibility to treat axially-symmetric deformed nuclei
- Pairing correlations consistently included
- Use of an unique nuclear force: finite range Gogny force
 - same interaction for all the nuclei
 - same interaction for ground state and excited states (self-consistency)



essential features to treat consistently isotopic chains from drip line to drip line

Gogny force (D1M, D1S)

$$V(1, 2) = \sum_{j=1,2} e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_j^2}} (W_j + B_j P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau) \quad \text{central} \quad \text{finite range}$$

$$+ t_0 (1 + x_0 P_\sigma) \delta(\vec{r}_1 - \vec{r}_2) \left[\rho \left(\frac{\vec{r}_1 + \vec{r}_2}{2} \right) \right]^\alpha \quad \text{density dependent}$$

$$+ i W_{ls} \overleftarrow{\nabla}_{12} \delta(\vec{r}_1 - \vec{r}_2) \times \overrightarrow{\nabla}_{12} \cdot (\vec{\sigma}_1 + \vec{\sigma}_2) \quad \text{spin-orbit}$$

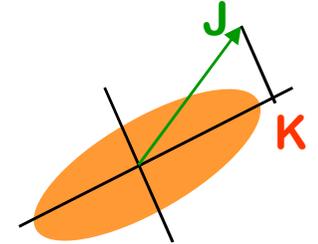
Axially-symmetric deformed QRPA

$$|\alpha, K\rangle = \theta_{\alpha, K}^+ |0\rangle$$

$$\theta_{n, K}^+ = \sum_{i < j} X_{n, K}^{ij} \eta_{i, k_i}^+ \eta_{j, k_j}^+ - (-)^K Y_{n, K}^{ij} \eta_{j, -k_j} \eta_{i, -k_i}$$

Restoration of rotational symmetry for deformed states

$$|JM(K)\rangle = \frac{\sqrt{2J+1}}{4\pi} \int d\Omega D_{MK}^J(\Omega) R(\Omega) |\theta_K\rangle + (-)^{J-K} D_{M-K}^J(\Omega) R(\Omega) |\bar{\theta}_K\rangle$$



to calculate: $\langle \tilde{0} | \hat{Q}_{\lambda\mu} | JM(K) \rangle$ for all QRPA states ($K \leq J$)

$$\hat{Q}_{\lambda\mu} \propto \sum r^\lambda (Y_{\lambda\mu})$$

$$r^2 Y_{\lambda\mu} = \sum_{\nu} D_{\mu\nu}^{\lambda} r^2 Y_{\lambda\nu}$$

In intrinsic frame

We use rotational approximation and relations for 3j symbols

For example: $J^\pi = 2^+$

$$\langle \tilde{0} | \hat{Q}_{20} | JM(K) \rangle = \frac{1}{\sqrt{5}} \langle 0 | \hat{Q}_{20} | \theta_K \rangle \delta_{K,0} + \frac{\sqrt{3}}{\sqrt{5}} \langle 0 | \hat{Q}_{2-1} | \theta_K \rangle \delta_{K,\pm 1} + \frac{\sqrt{3}}{\sqrt{5}} \langle 0 | \hat{Q}_{22} | \theta_K \rangle \delta_{K,\pm 2}$$

Using time reversal symmetry, three independent calculations ($K^\pi = 0^+, 1^+, 2^+$) are needed.

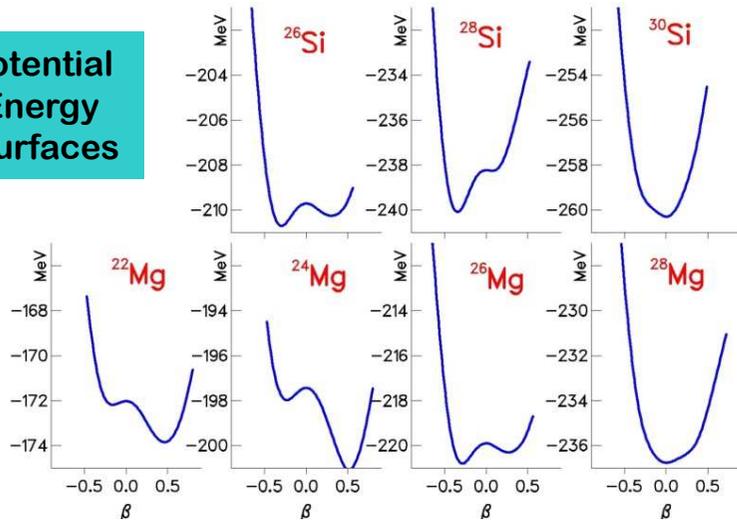
Main features:

- Possibility to treat axially-symmetric deformed nuclei
- Pairing correlations consistently included
- Use of an unique nuclear force: finite range Gogny force
- same interaction for all the nuclei
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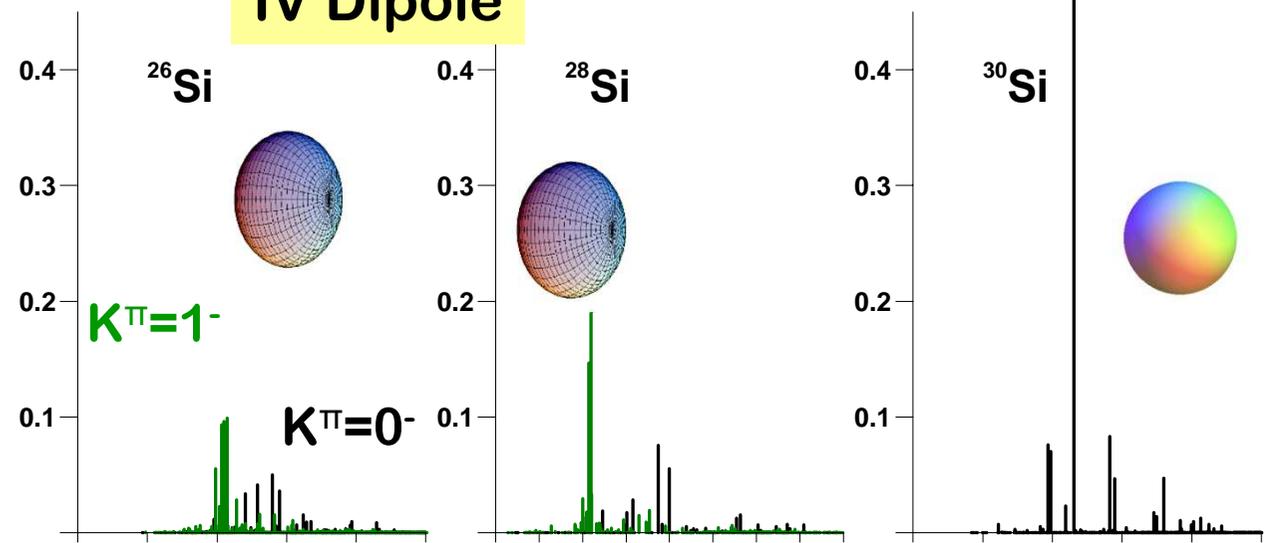
essential features to treat consistently isotopic chains from drip line to drip line

Role of deformation

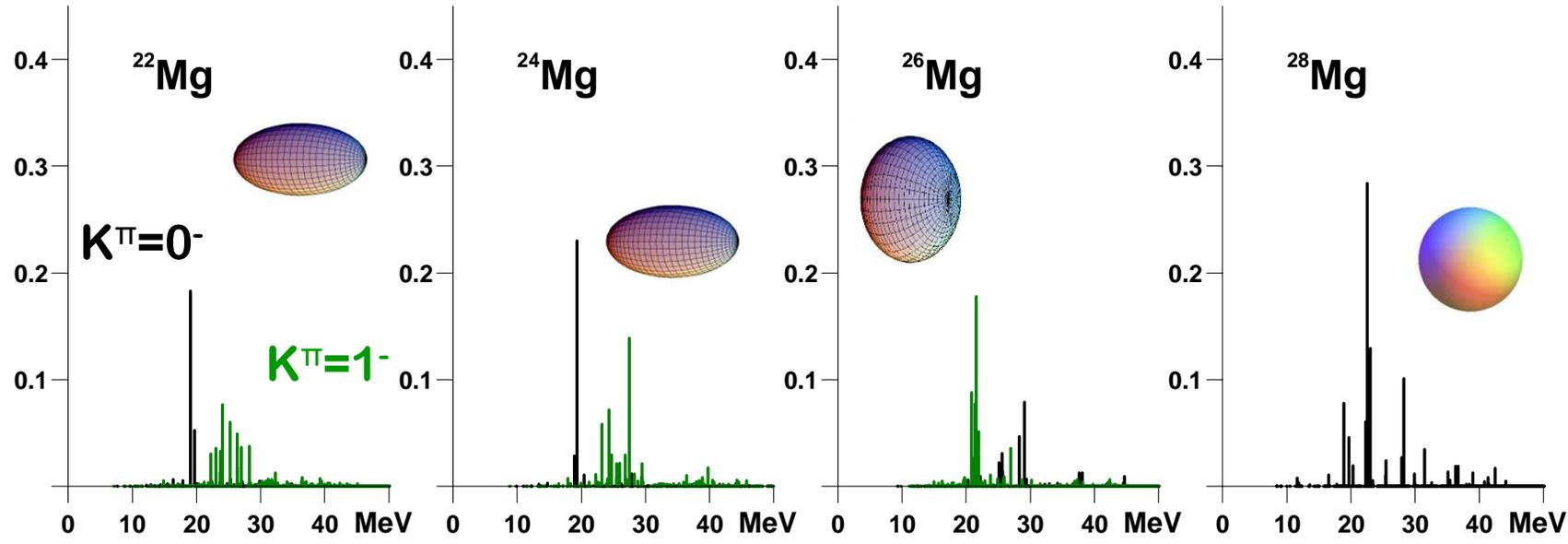
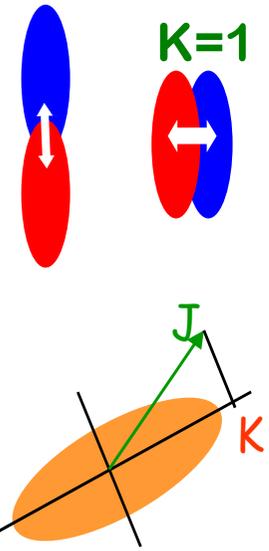
Potential Energy Surfaces



IV Dipole

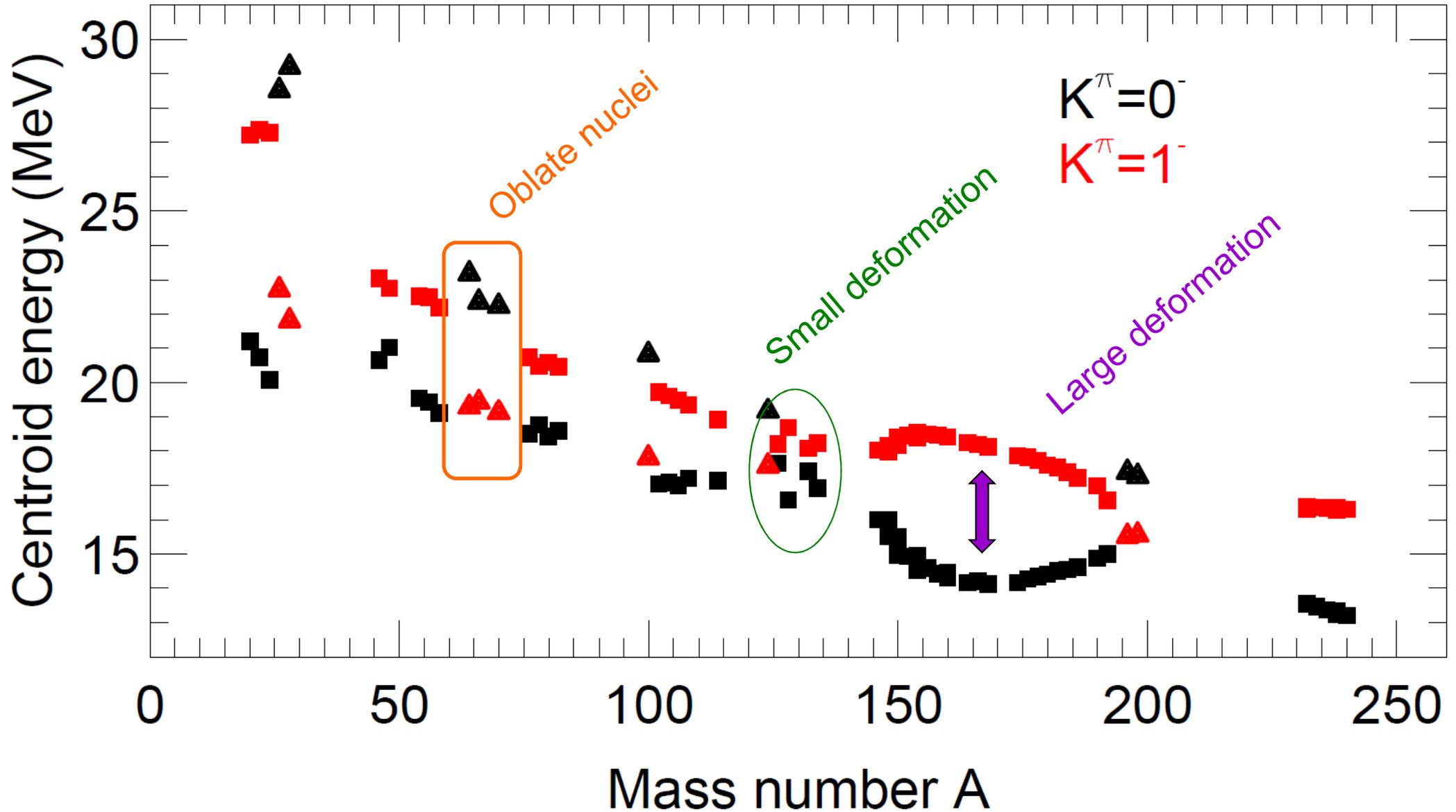


$K=0$



S. Péru and H. Goutte, Phys. Rev. C 77, 044313 (2008).

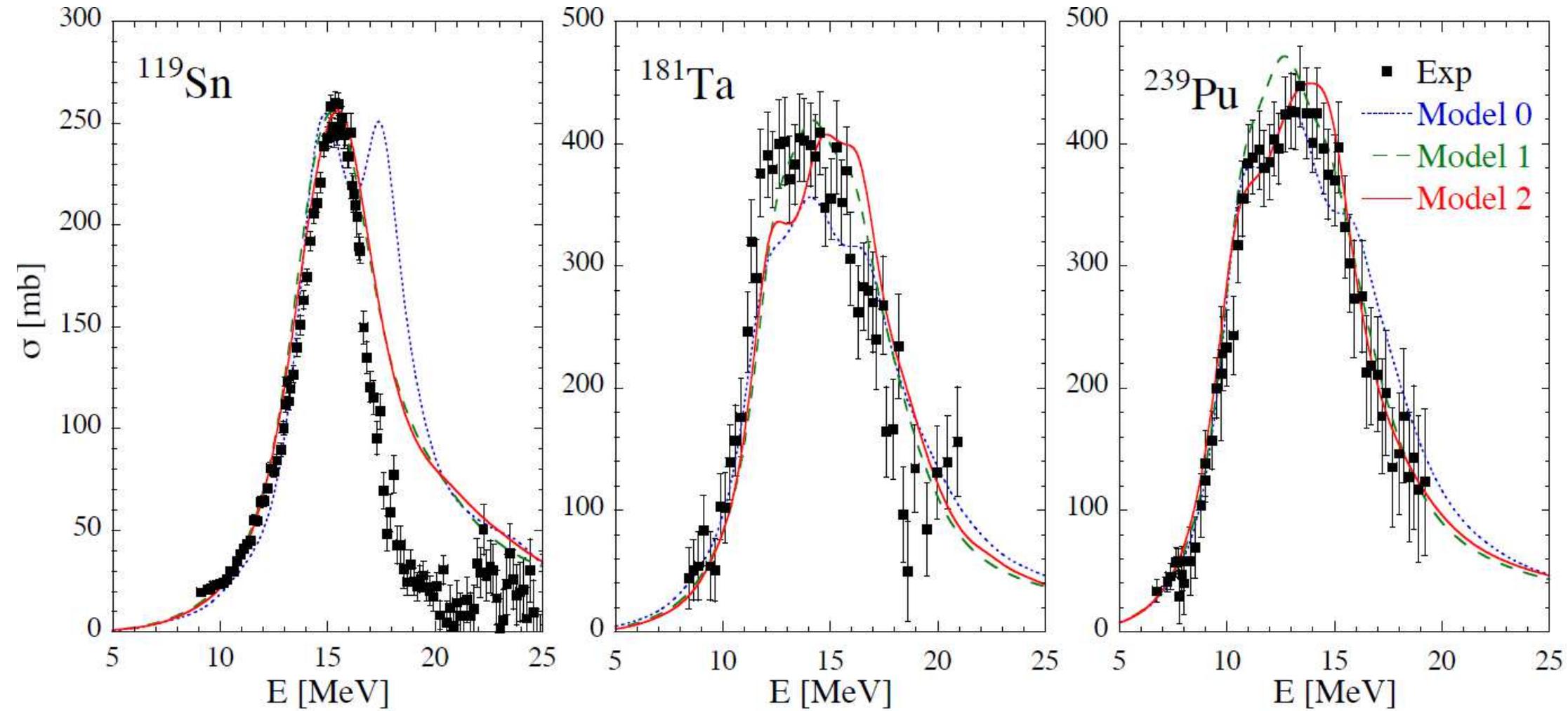
Impact of the deformation on dipole resonances



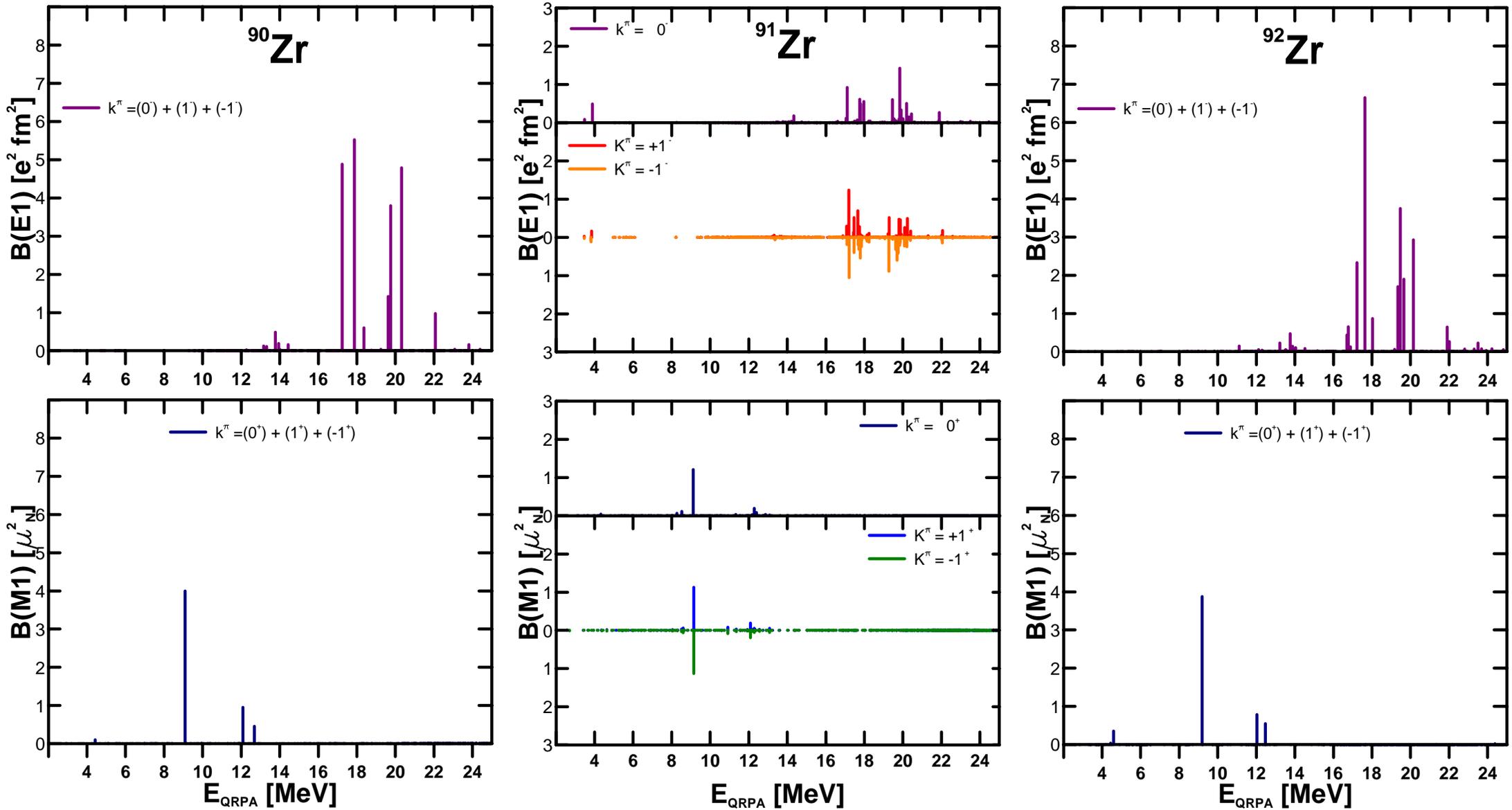
M. Martini et al, PRC 94, 014304 (2016)

Interpolation for odd nuclei

Dipole excitations and photoabsorption results

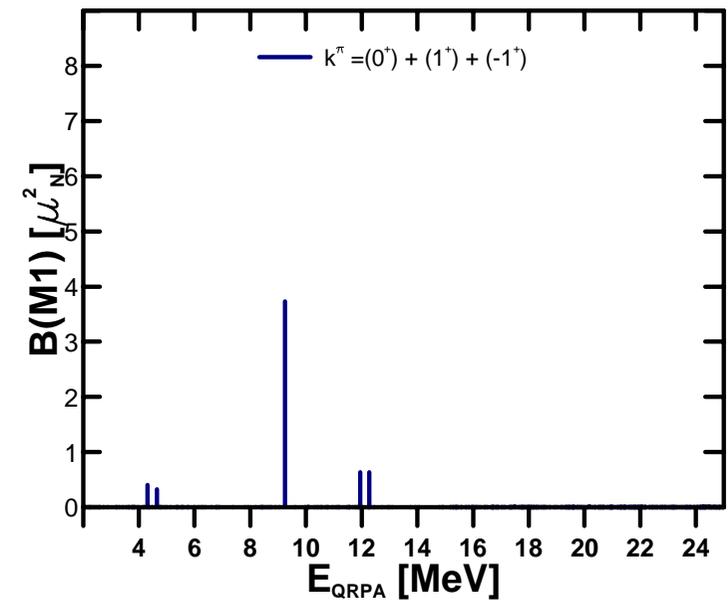
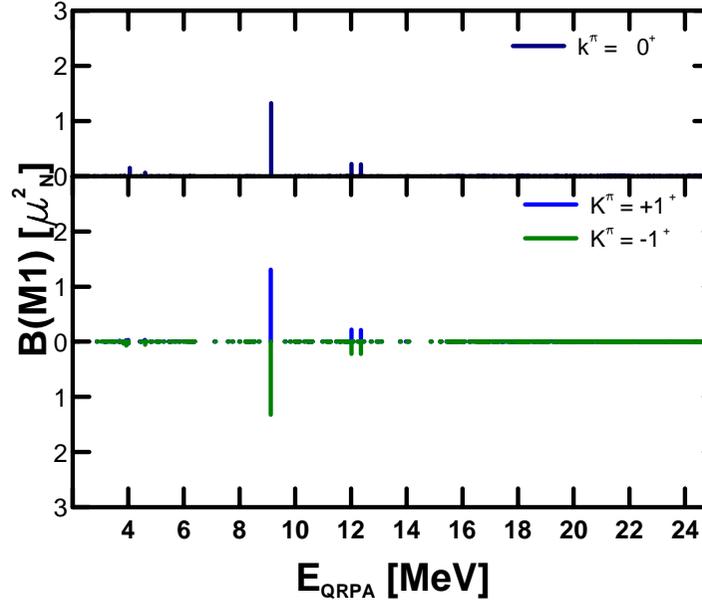
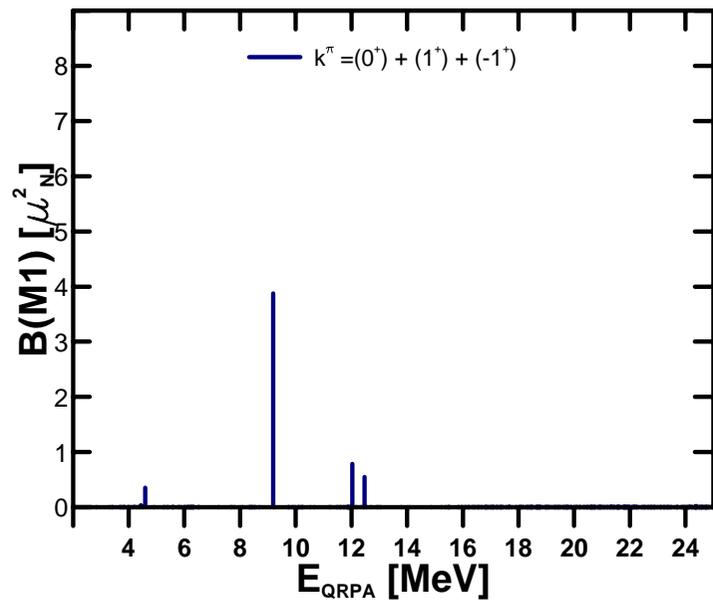
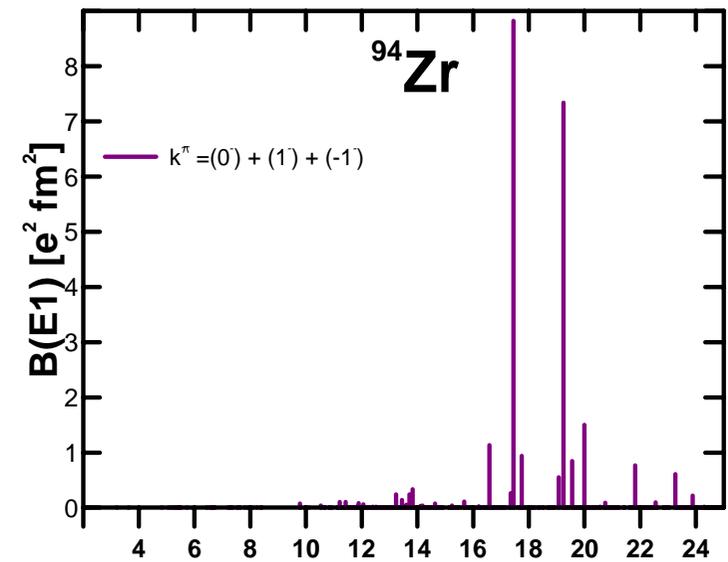
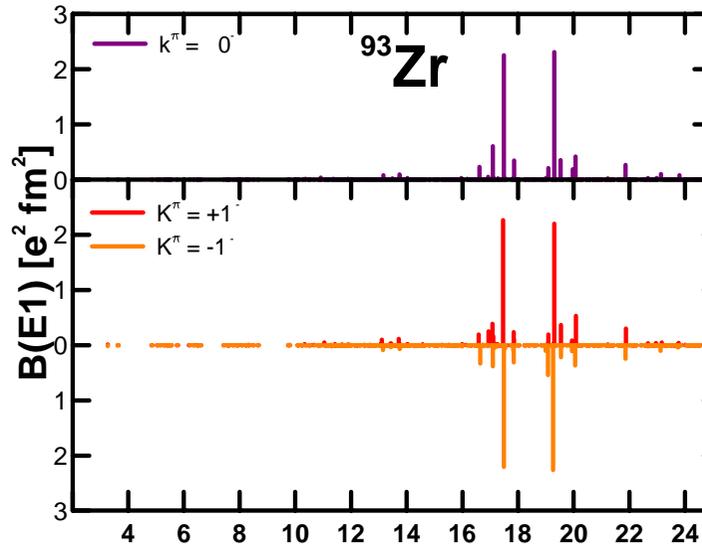
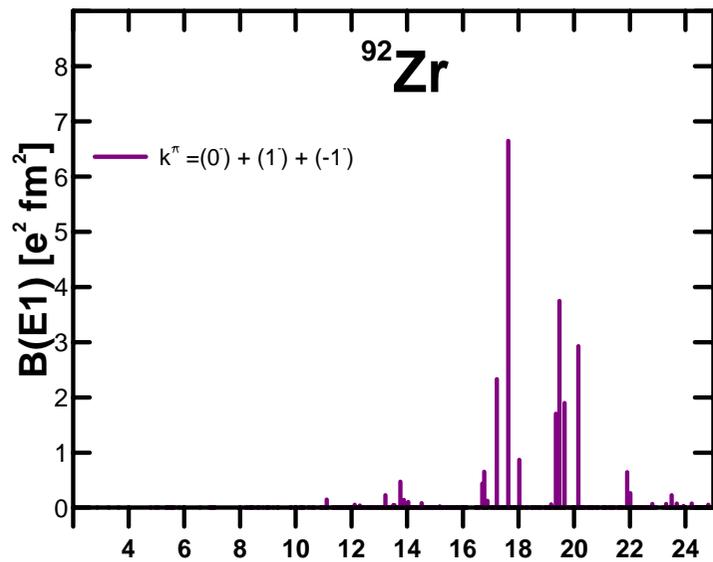


Dipole states in odd and even Zr isotopes



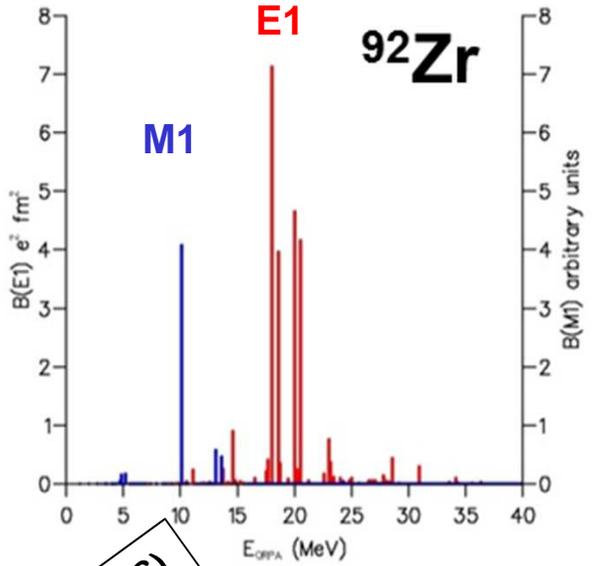
I. Deloncle, S. Péru, M. Martini, EPJA under revision

Dipole states in odd and even Zr isotopes

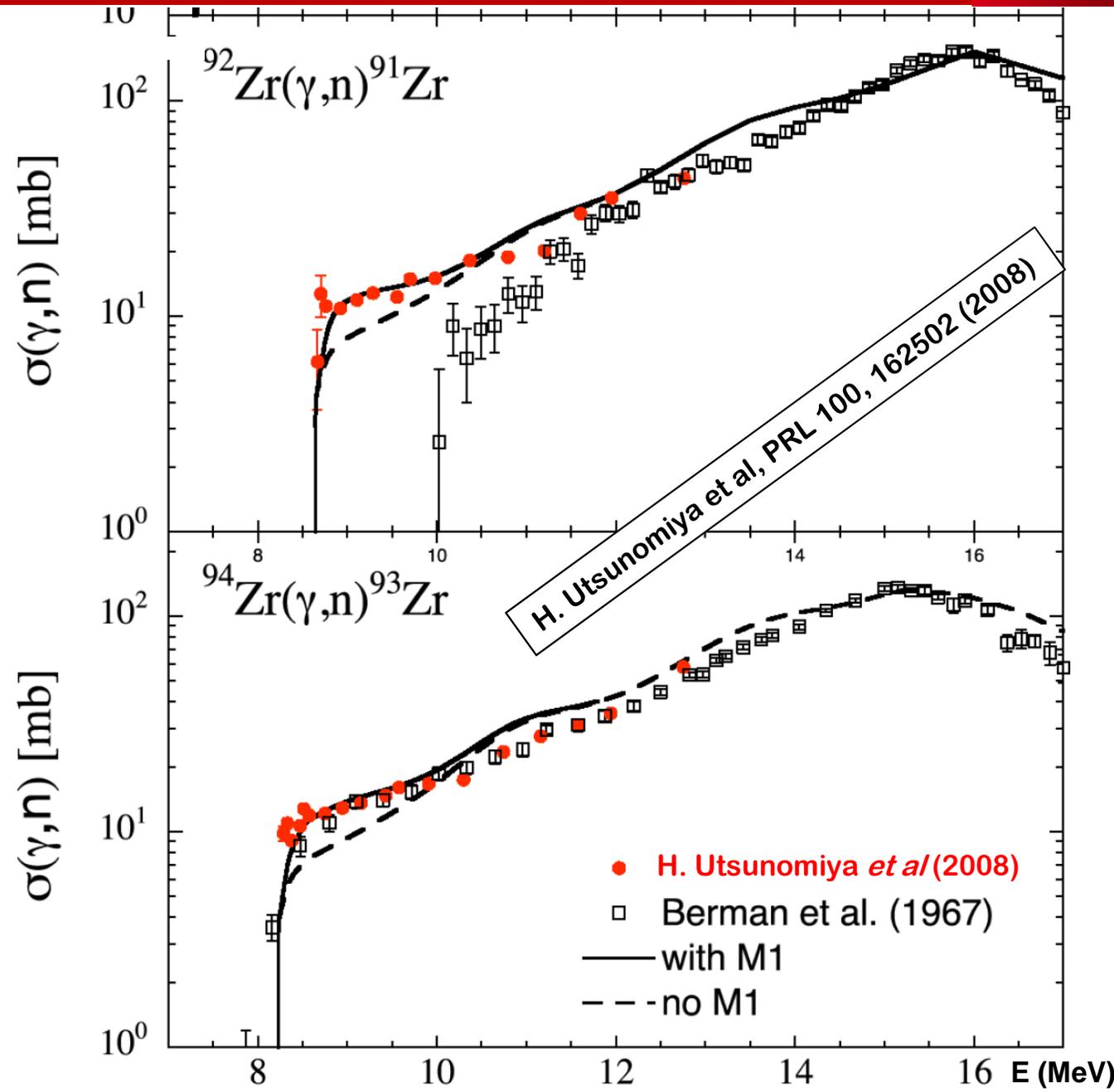
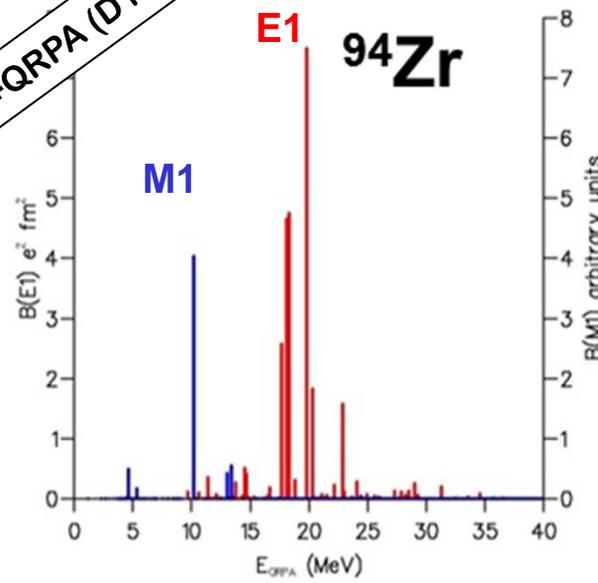


I. Deloncle, S. Péru, M. Martini, EPJA under revision

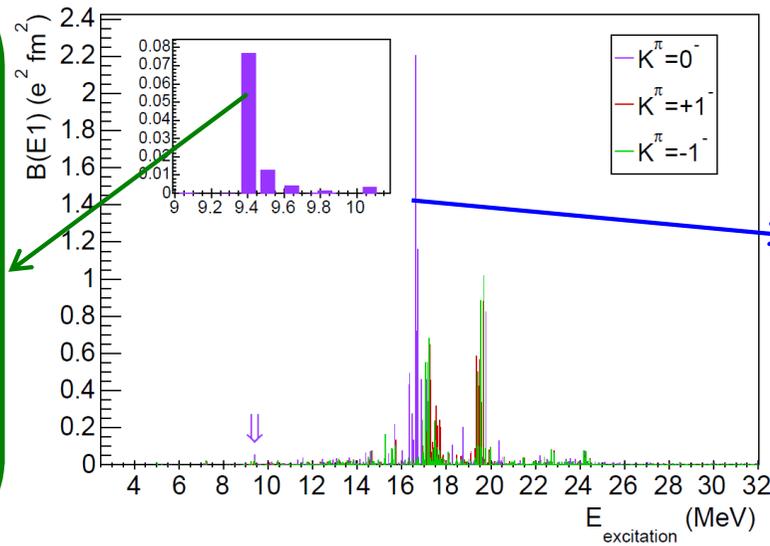
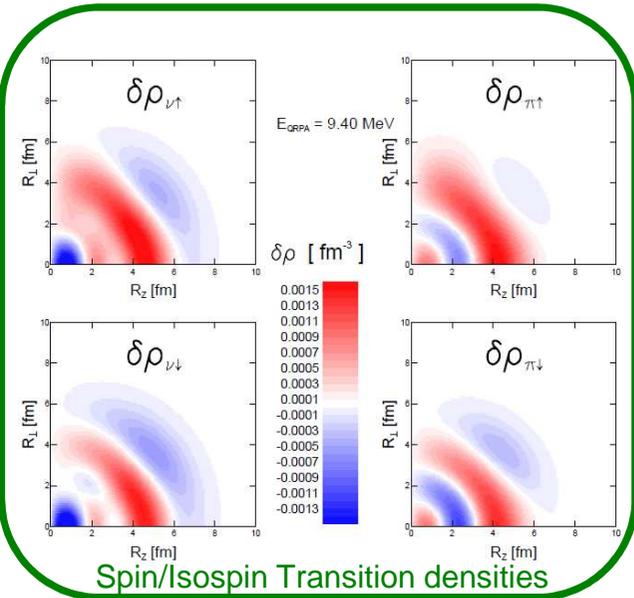
Dipole electric and magnetic excitations for Zr isotopes



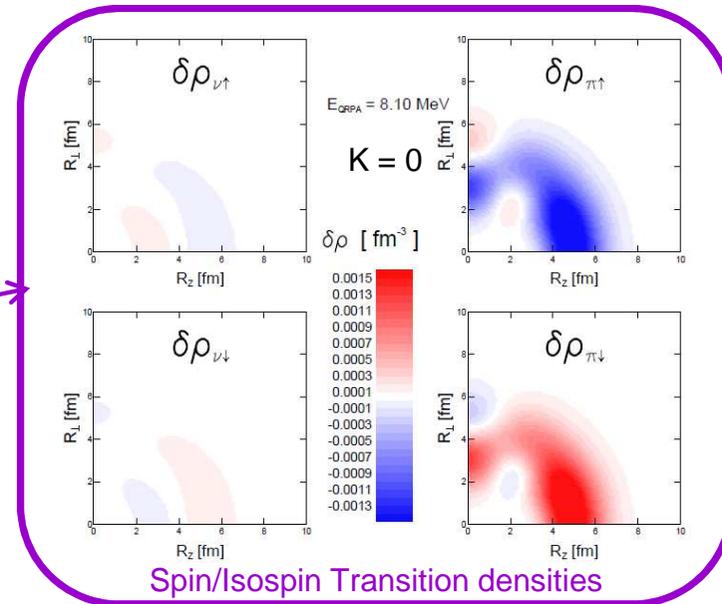
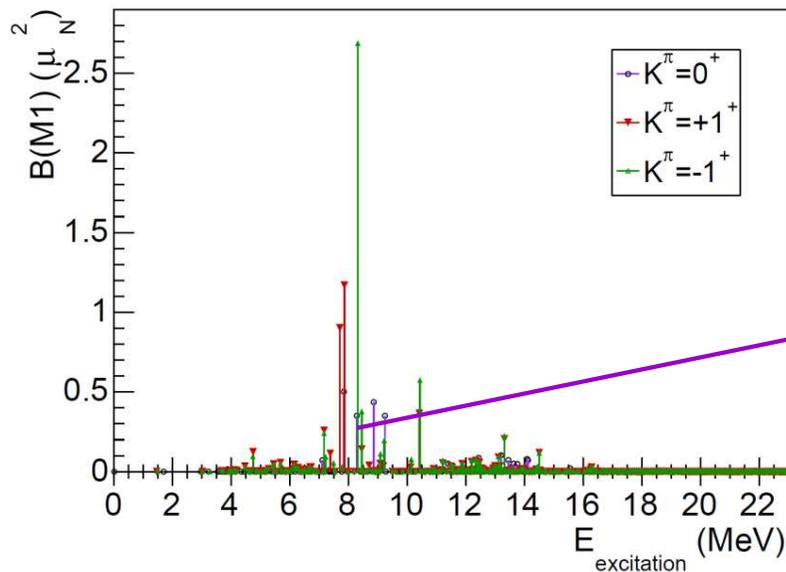
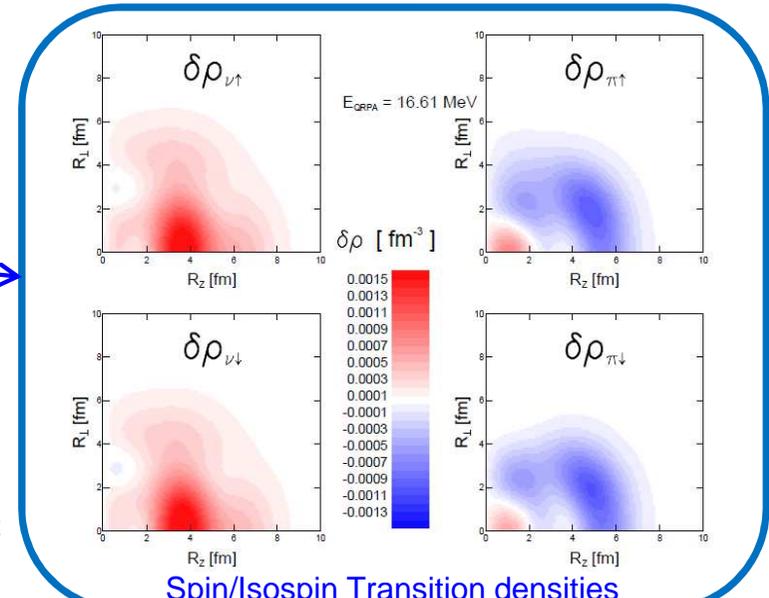
HFB+QRPA (D1S)



PDR Iso Scalar dipole



Iso Vector dipole

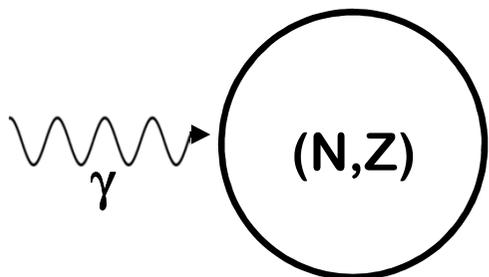


Spin flip

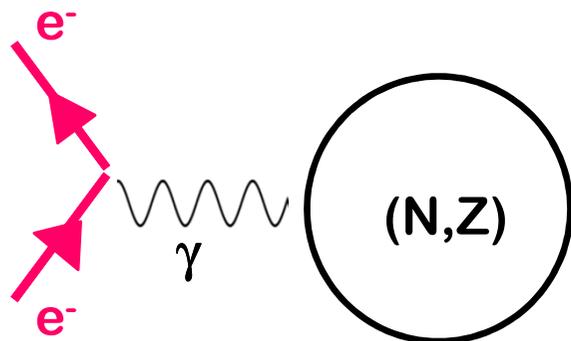
M. Versteegen et al, PRC 94, 044325 (2016)

Nuclear Excitations

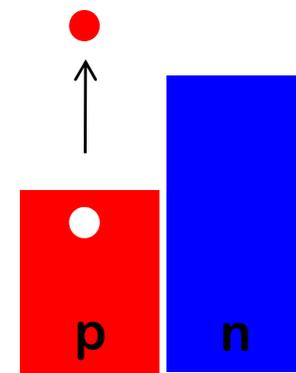
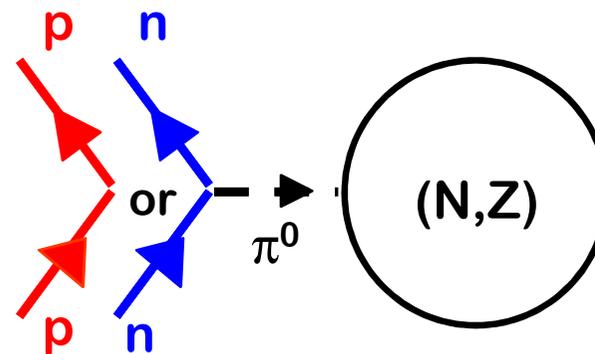
Photo-absorption



Electron scattering

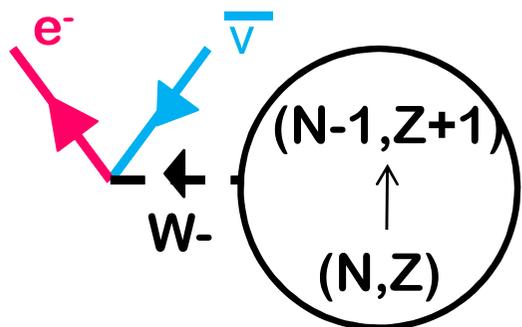


(p,p) or (n,n)

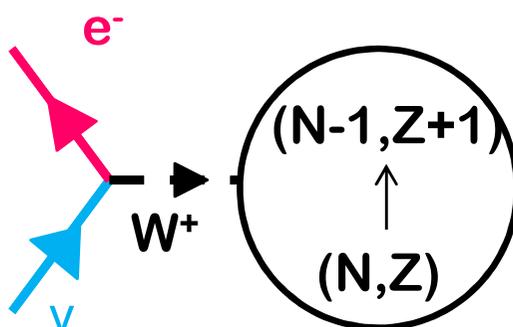


Charge exchange:

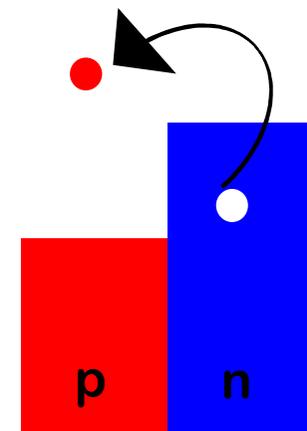
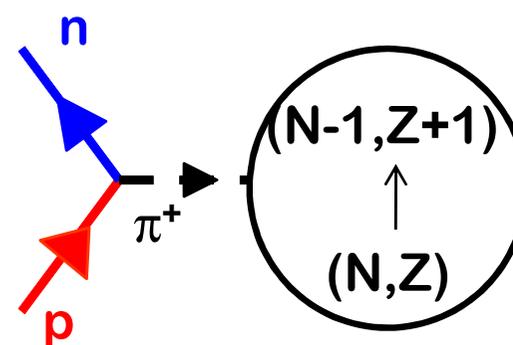
β decay



Neutrino scattering



(p,n) or (^3He , t)

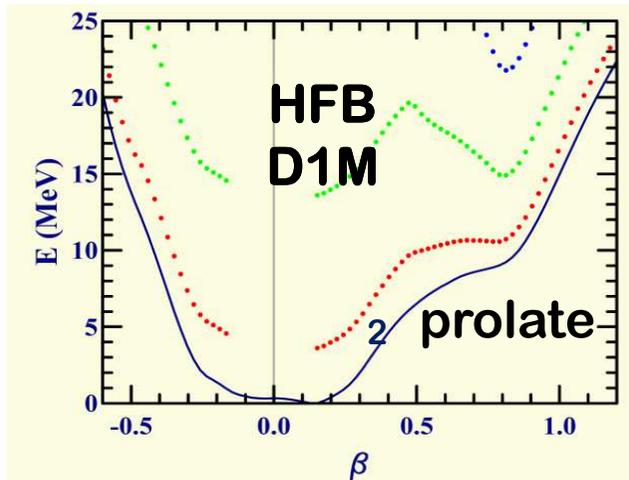


Charge exchange QRPA : GT resonances for β decay

M. Martini, S. Péru and S. Goriely, Phys. Rev. C **89**, 044306 (2014)

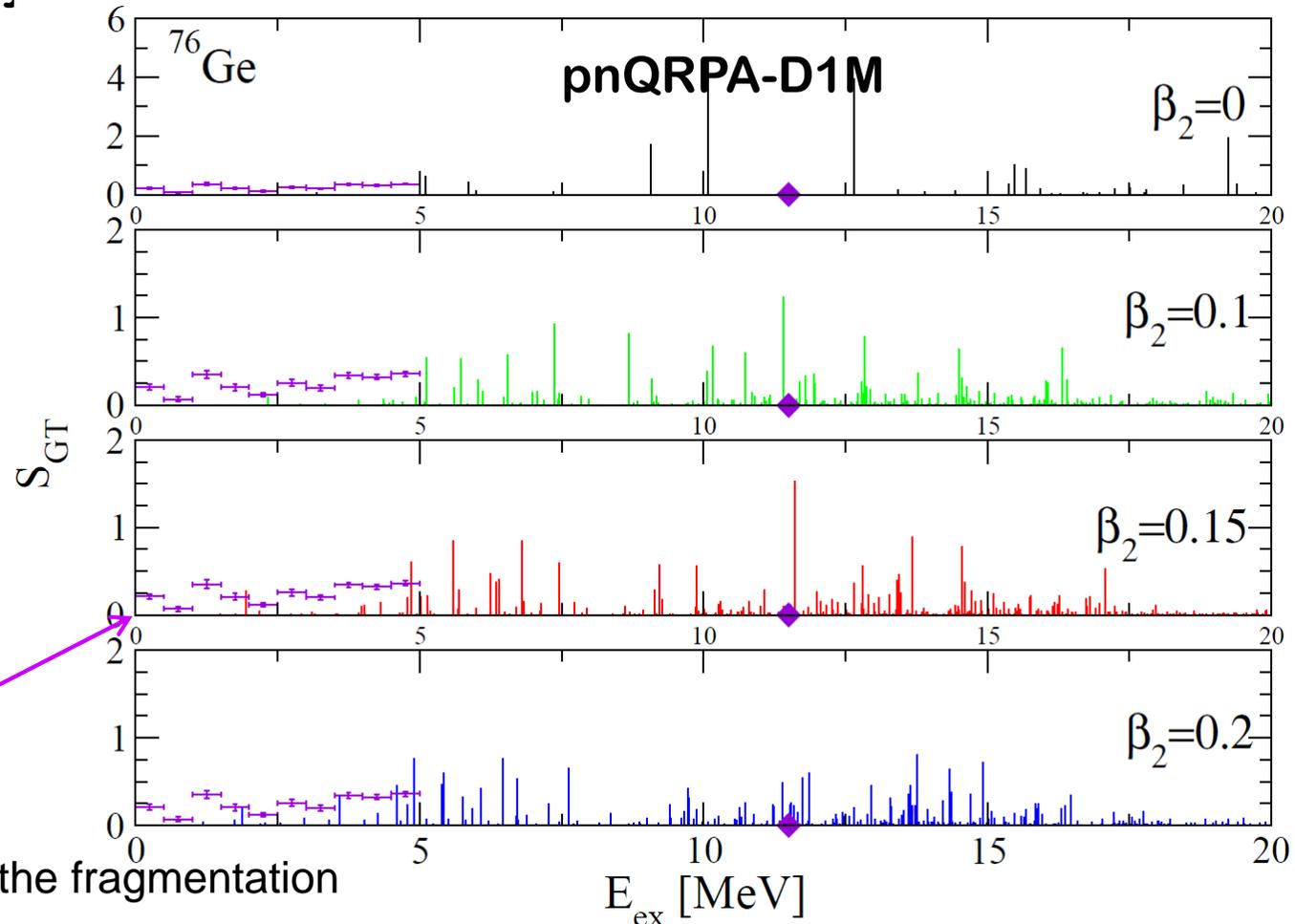
An example of deformed nucleus : ^{76}Ge

GT $J^\pi=1^+$ distributions obtained by adding twice the $K^\pi=1^+$ result to the $K^\pi=0^+$ one



$\beta_2(\text{min. HFB}) = 0.15$ $\gamma(\text{min.HFB}) = 0^\circ$
 $\beta_2(0^+_{1};5\text{DCH}) = 0.26$ $\gamma(0^+_{1};5\text{DCH}) = 26^\circ$

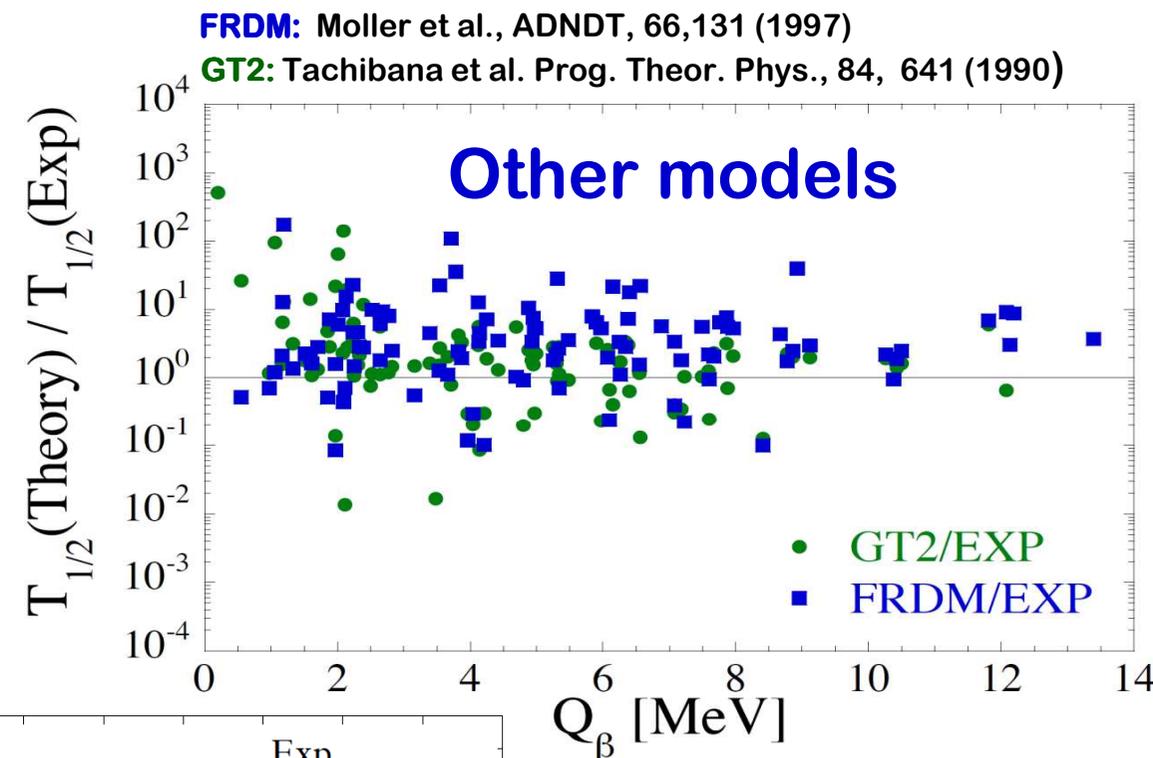
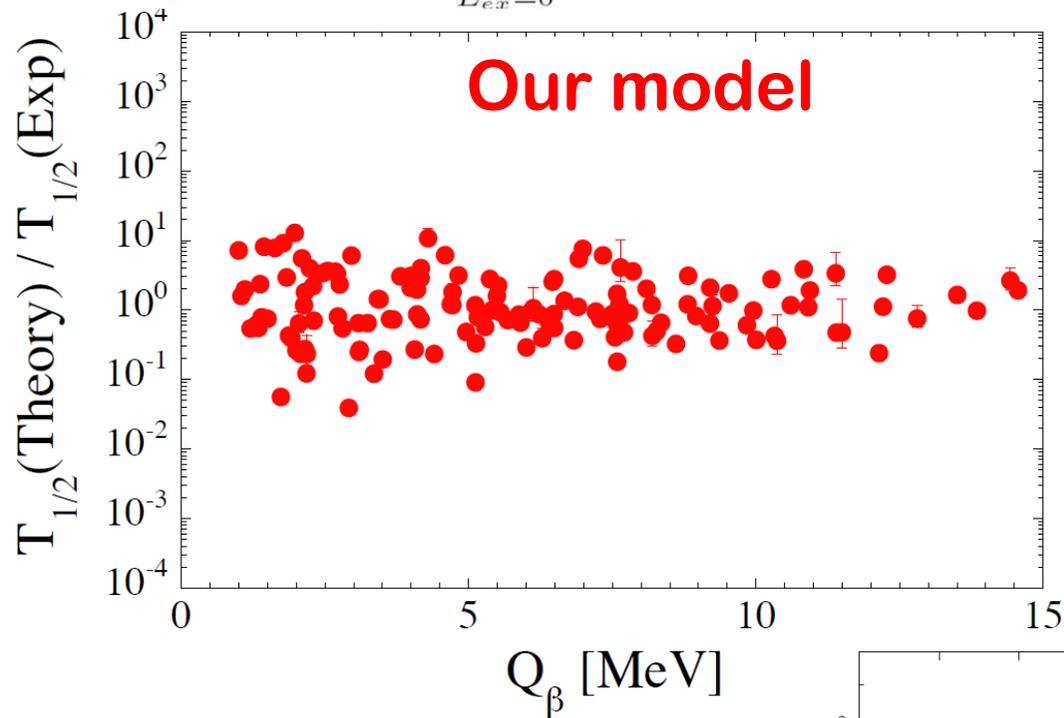
Experiment
 Thies et al., Phys. Rev. C 86, 014304 (2012)



- The deformation tends to increase the fragmentation
- Displacements of the peaks
- Deformation influences the low energy strength hence β decay half-lives are expected to be affected

β^- decay half-life $T_{1/2}$: Comparison with other models

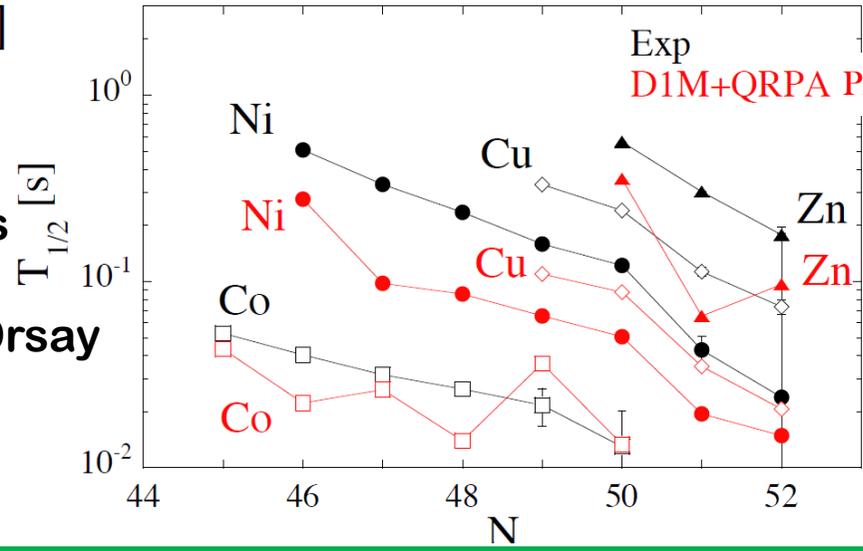
$$\frac{\ln 2}{T_{1/2}} = \frac{(g_A/g_V)_{\text{eff}}^2}{D} \sum_{E_{ex}=0}^{Q_\beta} f_0(Z, A, Q_\beta - E_{ex}) S_{GT}(E_{ex})$$



FRDM: Moller et al., ADNDT, 66,131 (1997)

GT2: Tachibana et al. Prog. Theor. Phys., 84, 641 (1990)

Extension to **odd** systems
in collaboration with
Isabelle Deloncle (CSNSM) Orsay



Recent experimental results

Z.Y. Xu et al, PRL 113, 032505 (2014)

β^- -decay Half lives of $^{76,77}\text{Co}$, $^{79,80}\text{Ni}$
and ^{81}Cu : Experimental indication
of a Doubly Magic ^{78}Ni

Thanks for your attention