QRPA approach for nuclear structure, nuclear reactions and astrophysics

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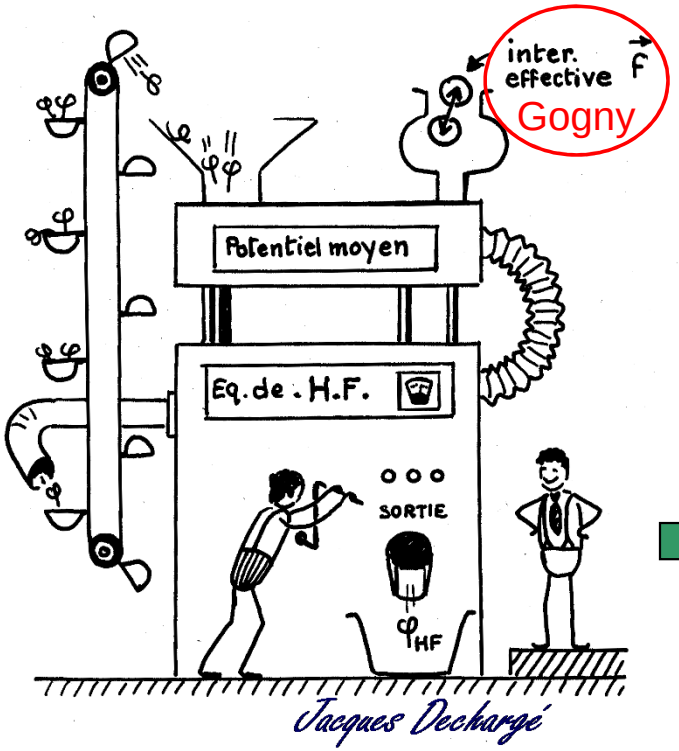
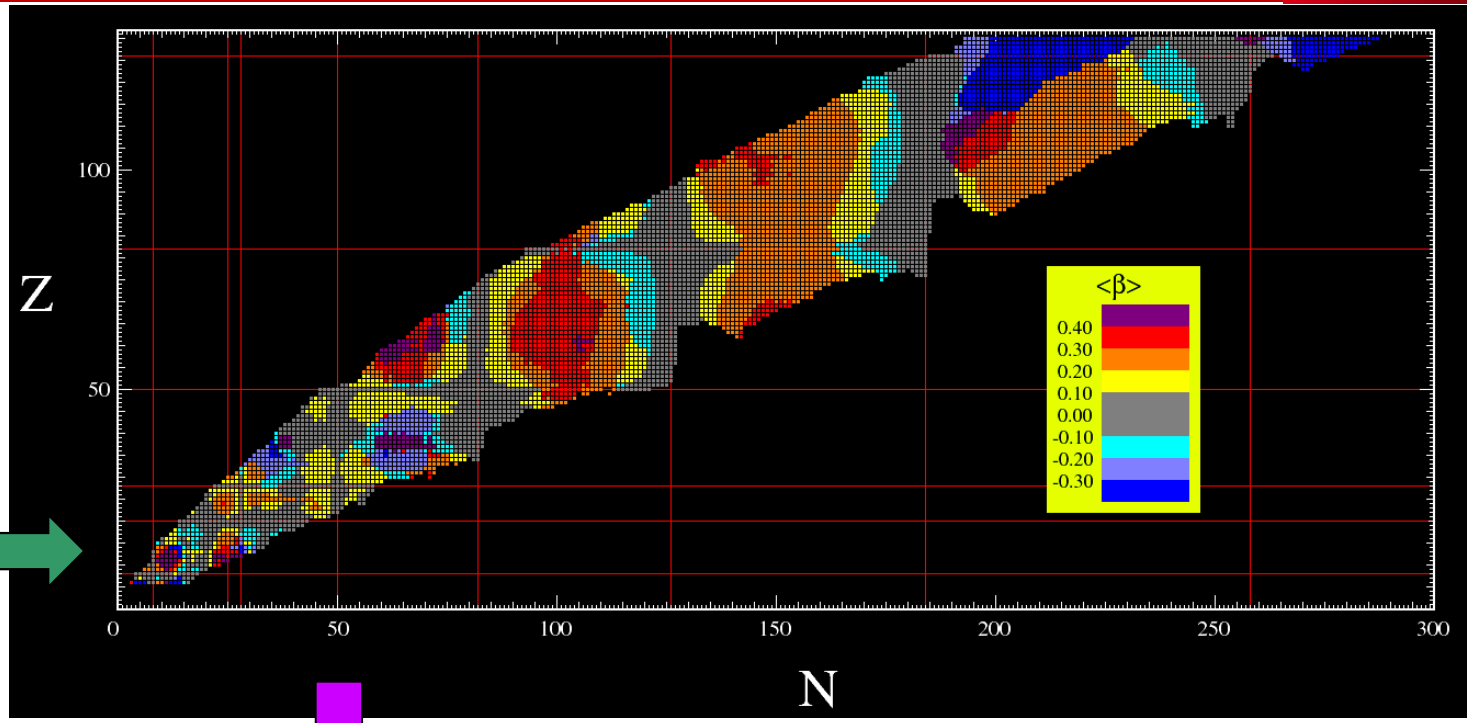
S. Hilaire (CEA,DAM,DIF)

Reminder





Static mean field (HFB)
for Ground State Properties :

- **Masses**
- **Deformation**
- **(Single particle levels)**

Amedee database :
http://www-phynu.cea.fr/HFB-Gogny_eng.htm
*S. Hilaire & M. Girod, EPJ **A33** (2007) 237*

Beyond static mean field approximation (for exple QRPA)
for description of Excited State Properties

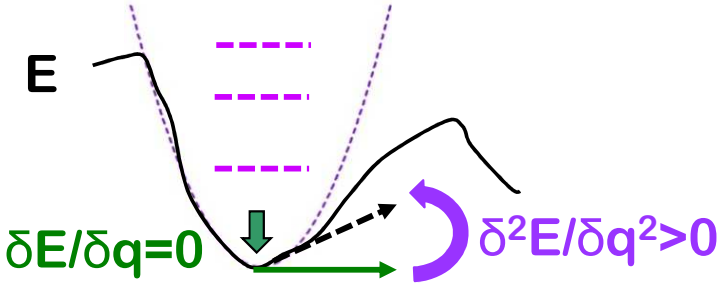
- **Low-energy collective levels**
- **Giant Resonances**
- **Beta decay**

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

BUT

with small amplitude approximation i.e. « harmonic » nuclei

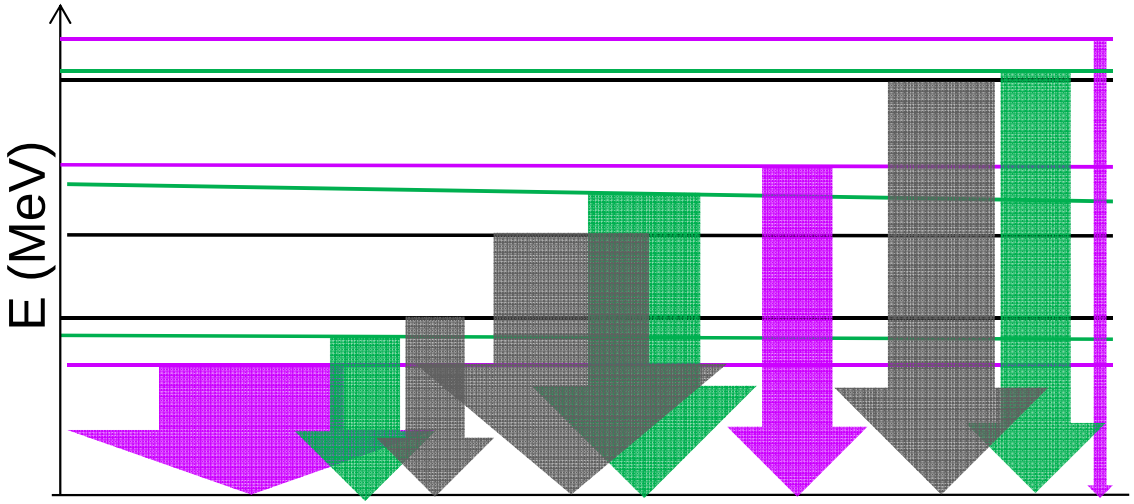
=> Octupole, as well quadripole and hexadecapole vibrations can be described within spherical QRPA.

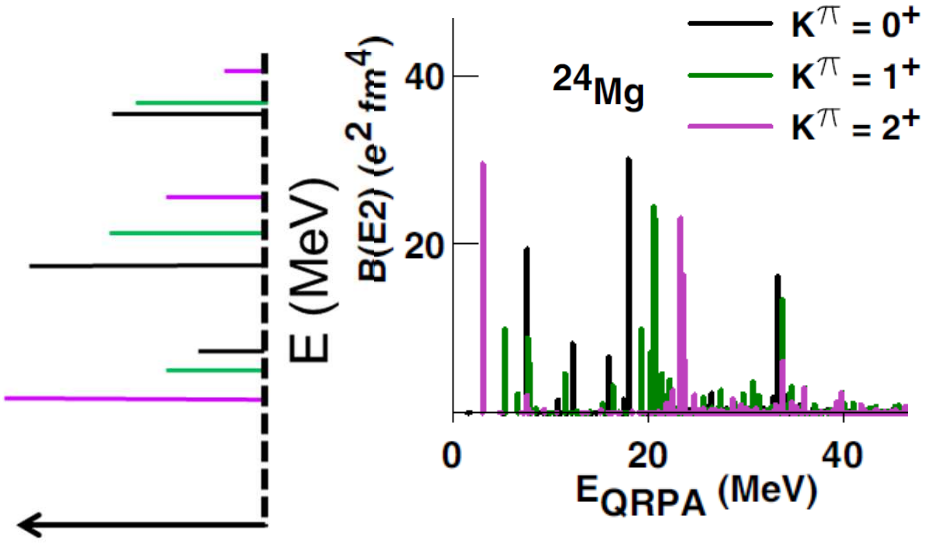


What can we do in CEA/DIF?

ISAAC describes excited states , transition probabilities for intrinsic deformed nuclei with axial symmetry.

Solutions are:





RPA approaches describe all multipolarities and all parities

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

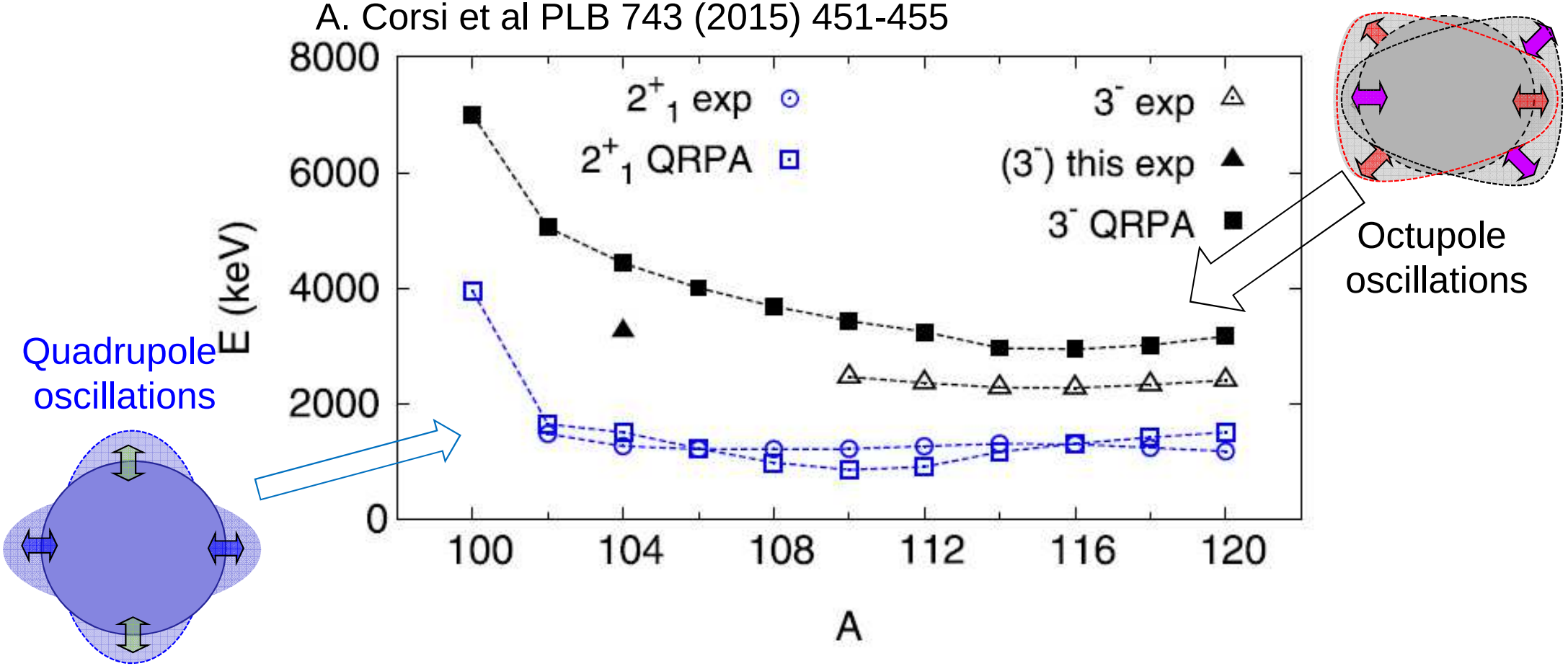


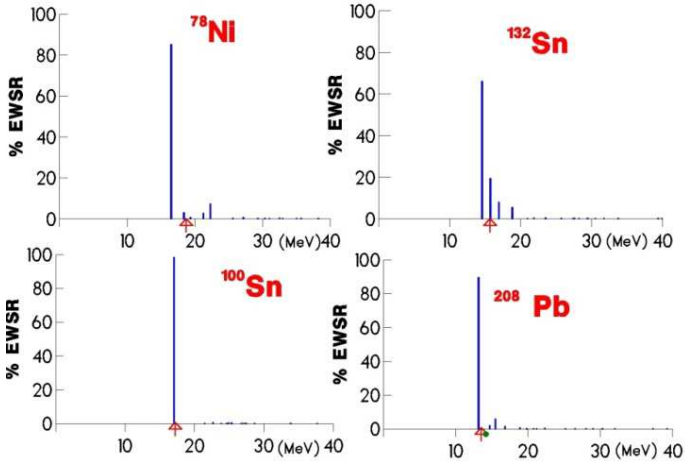
Fig. 3. (Color online.) Systematics of 2^+ and 3^- excitation energies in tin isotopes from experiment and HFB + QRPA calculations using the Gogny D1M interaction.

RPA approaches describe low energy and high energy states

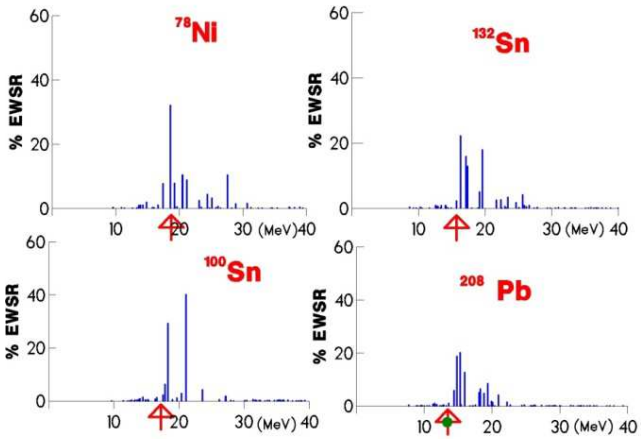
Giant resonances in exotic nuclei: RPA in spherical symmetry

^{100}Sn, ^{132}Sn, ^{78}Ni; S. Péru, J.F. Berger, and P.F. Bortignon, Eur. Phys. Jour. A 26, 25-32 (2005)

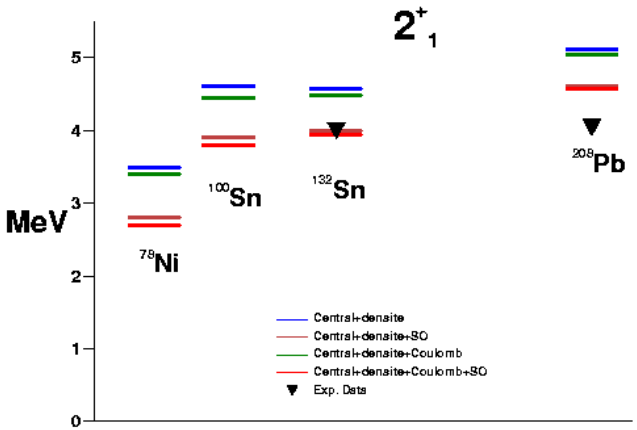
Monopole

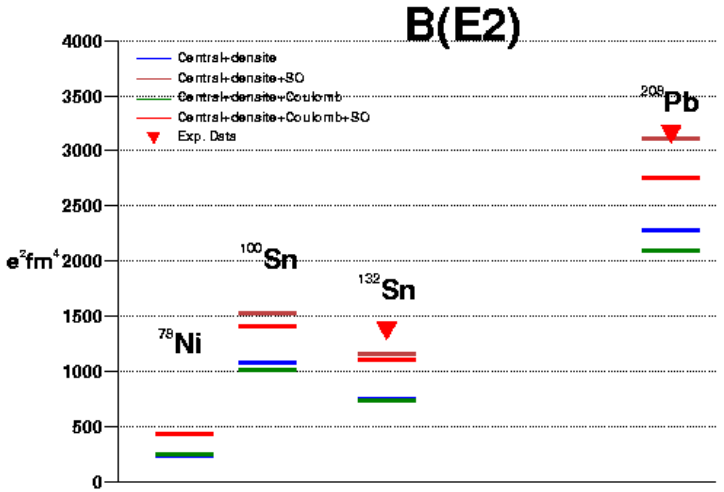


Dipole



Quadrupole



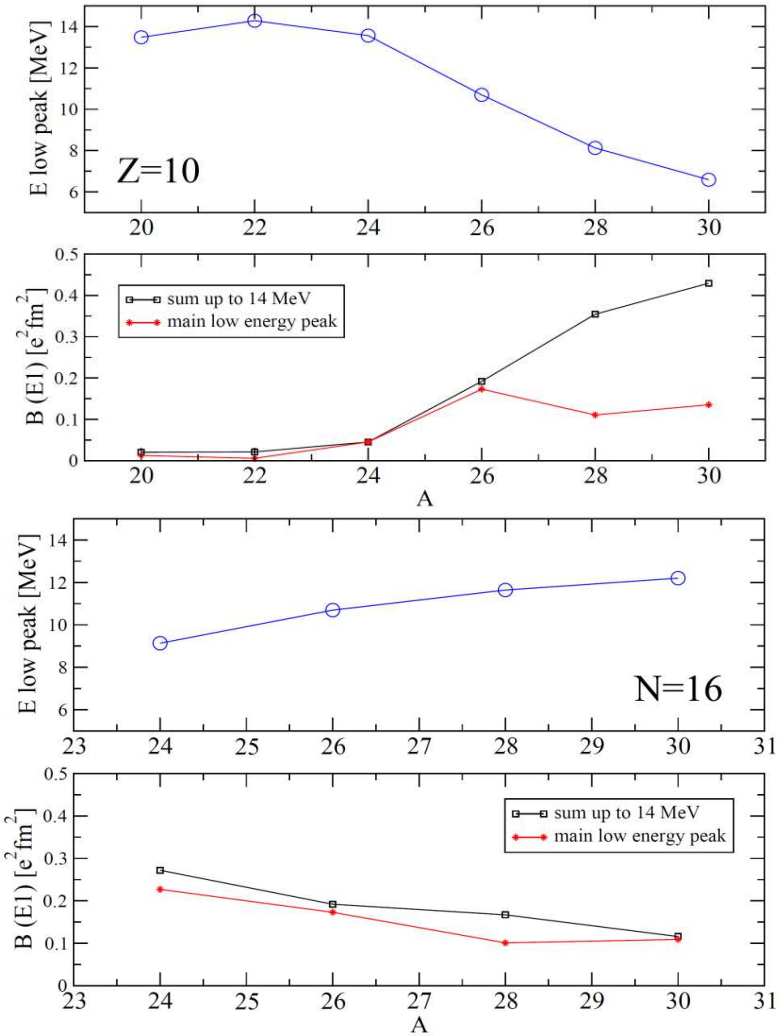


→ Such study have shown the role of the consistence between mean field and RPA matrix.

Approach limited to Spherical nuclei with no pairing

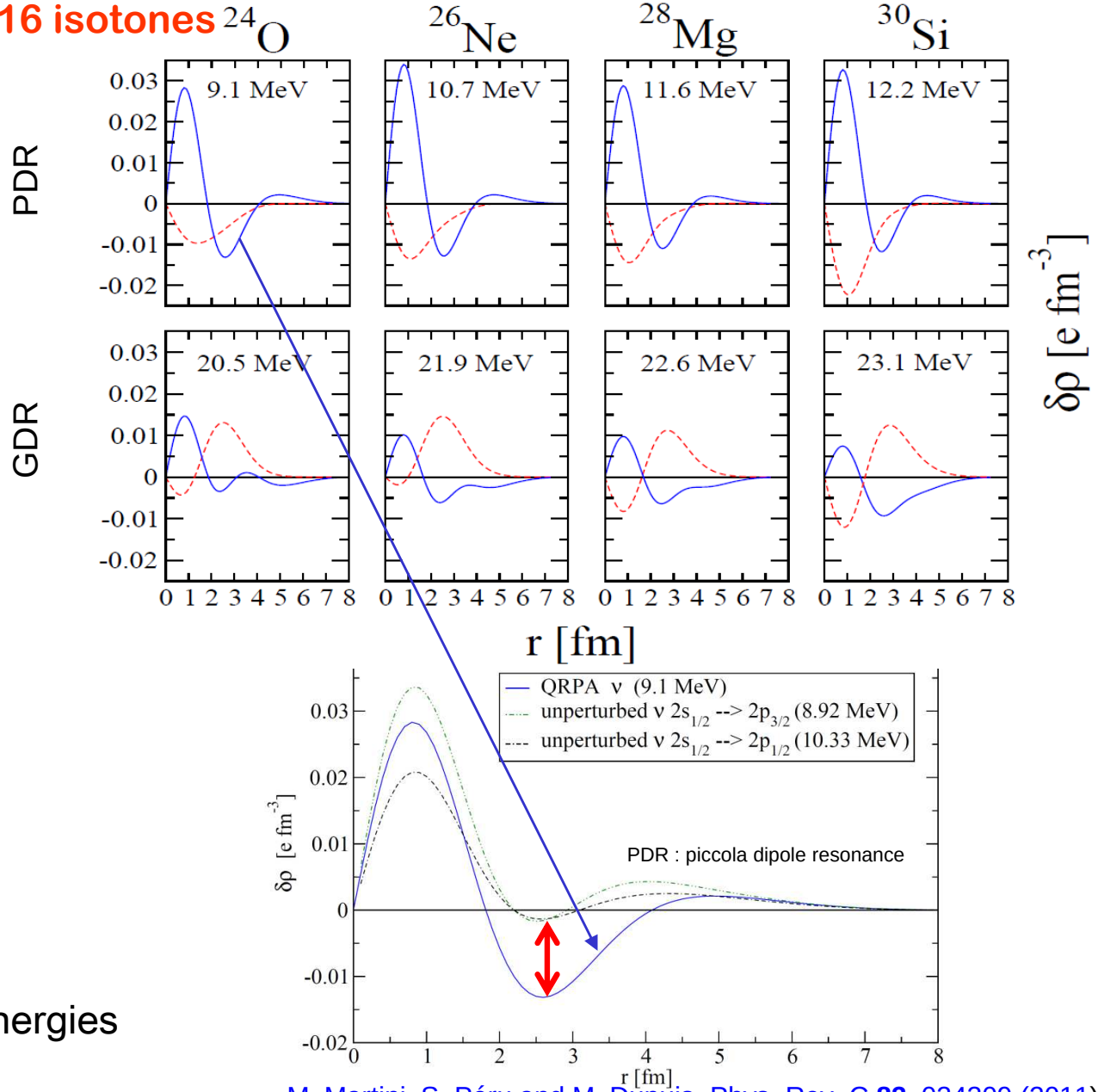
RPA approaches describe collective and individual states

Dipole response for Neon isotopes and N=16 isotones



Increasing |N-Z| number :

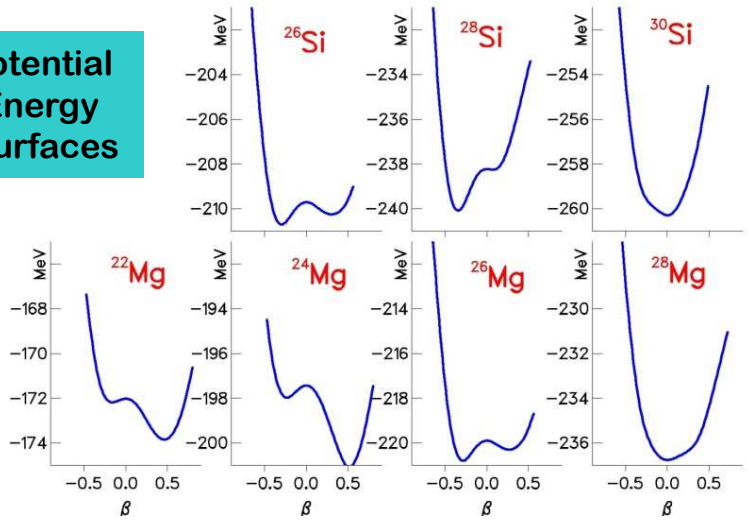
- Low energy dipole resonances shift to low energies
- Increasing of fragmentation and collectivity



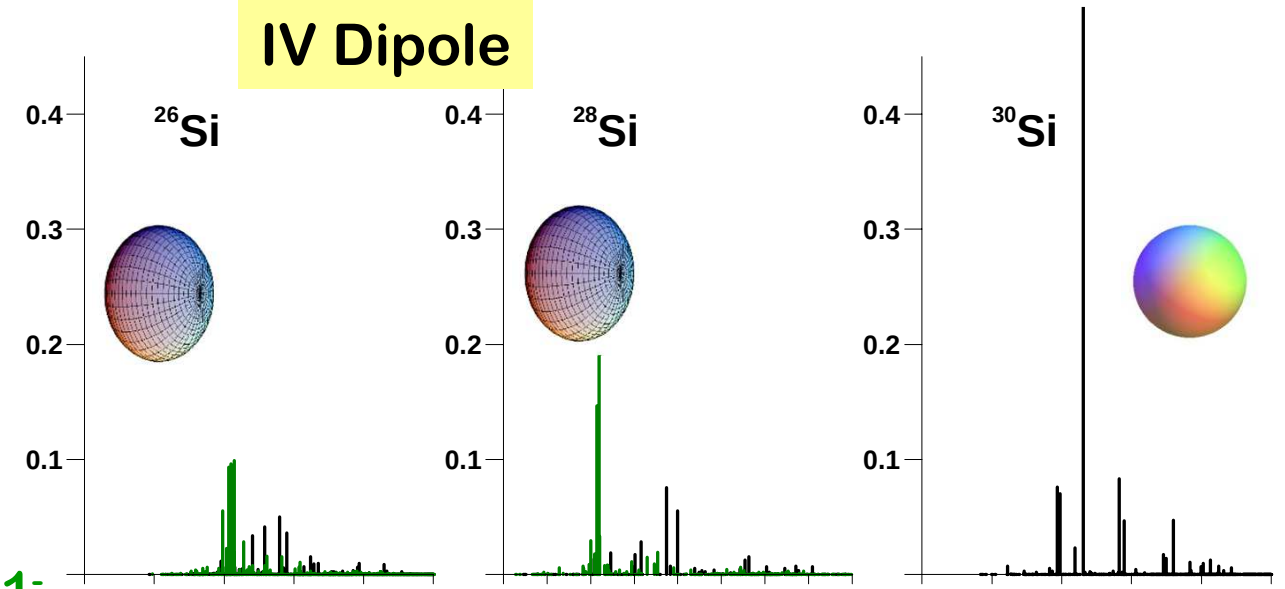
M. Martini, S. Péru and M. Dupuis, Phys. Rev. C **83**, 034309 (2011)

whatever the intrinsic deformation of the ground state

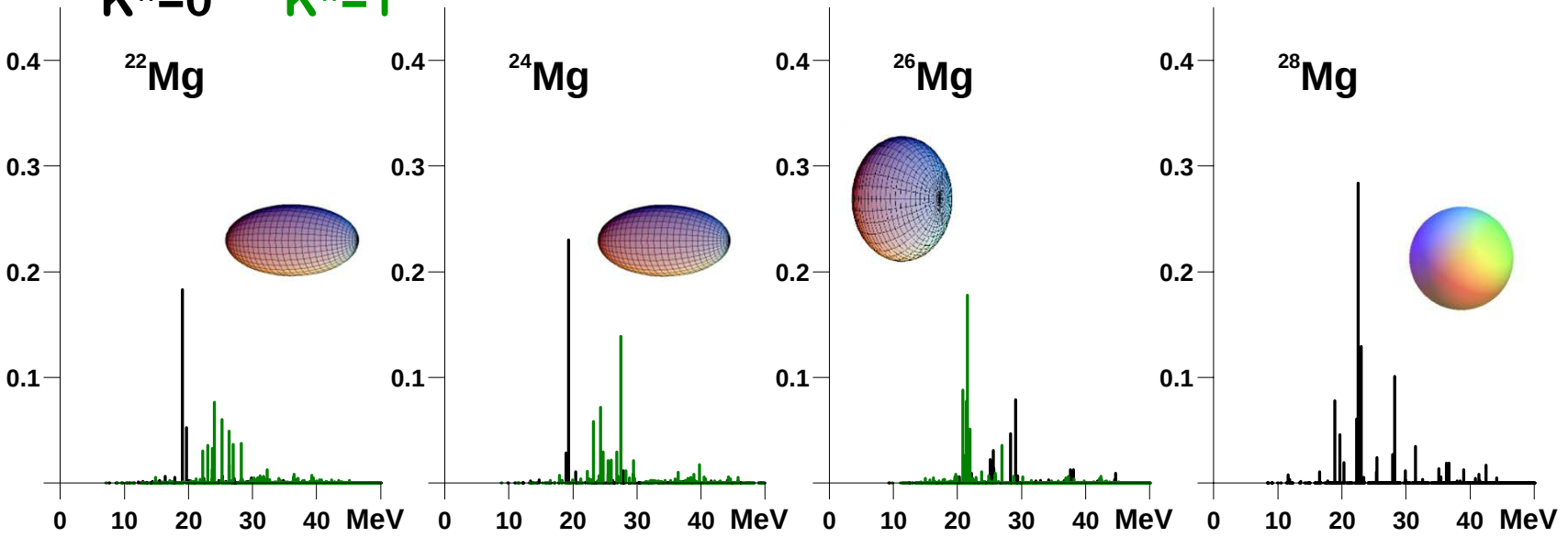
Potential Energy Surfaces

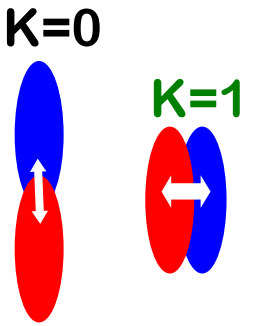


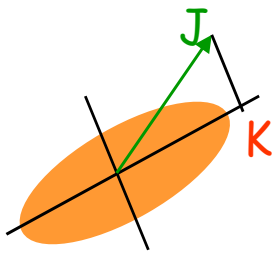
IV Dipole



$K^{\pi}=0^-$ $K^{\pi}=1^-$



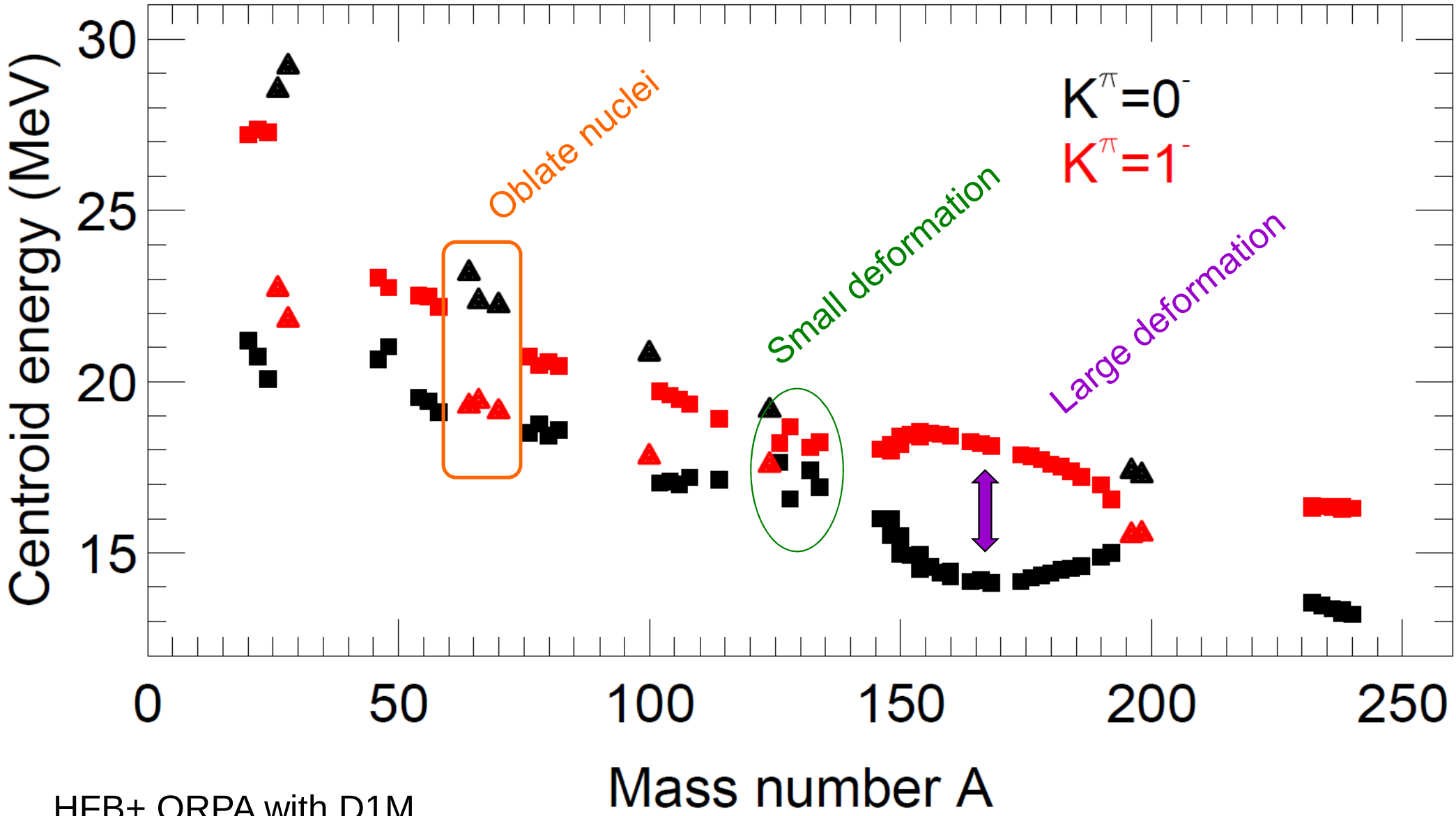




"First study" with QRPA in axial symmetry

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

Impact of the deformation

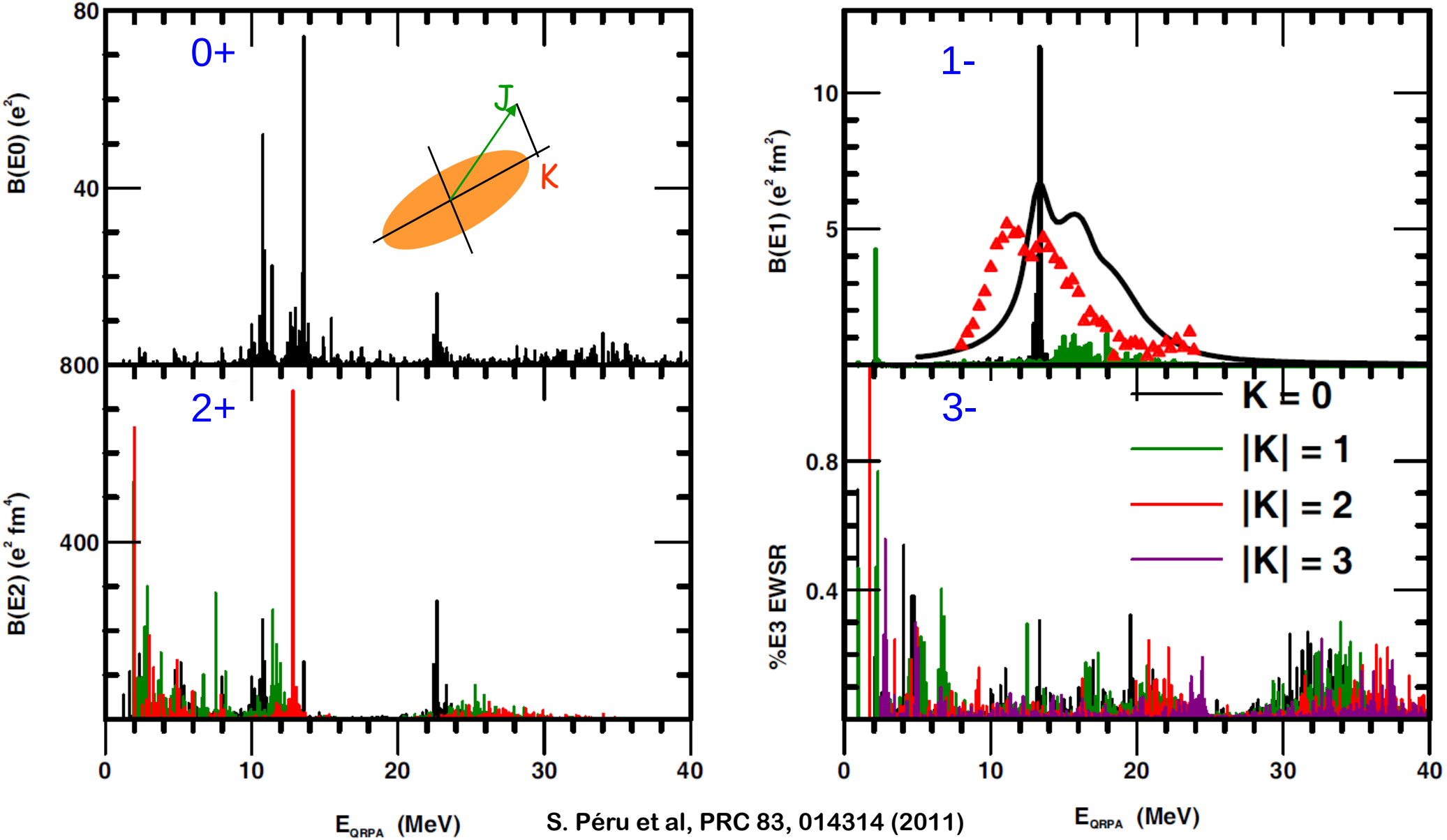


HFB+ QRPA with D1M

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

Multipolar responses for ^{238}U

"First study" Heavy deformed nucleus ⟶ massively parallel computation

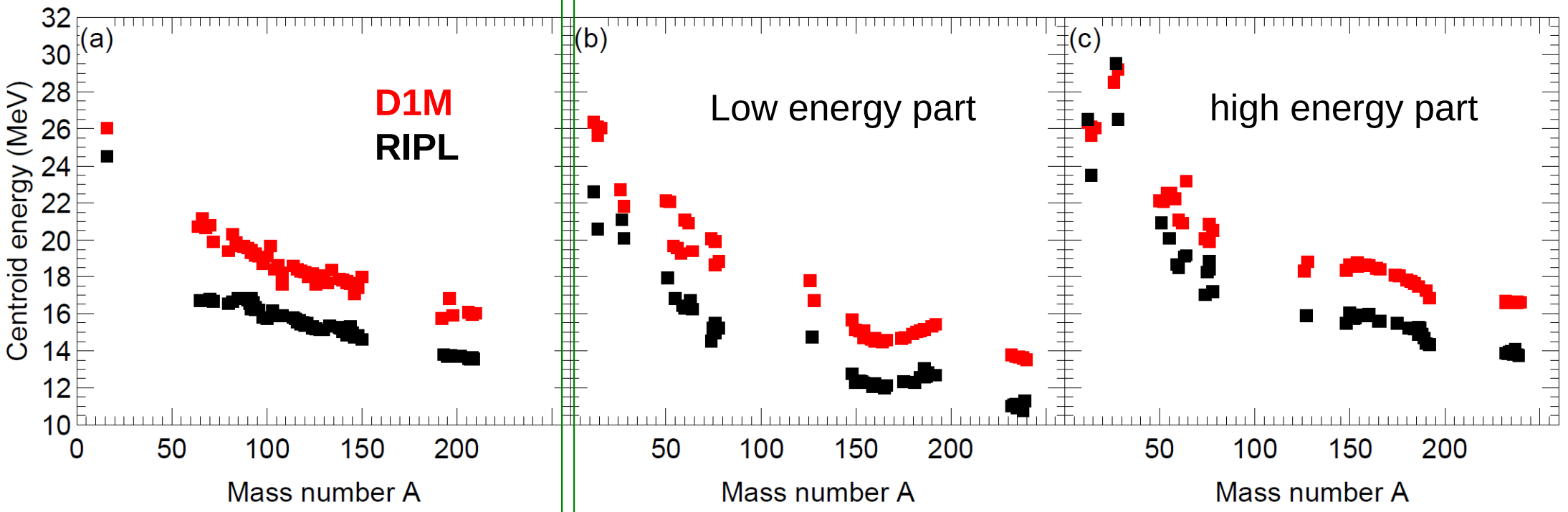


S. Péru et al, PRC 83, 014314 (2011)

Comparison with experimental data

One Lorentzian in RIPL

Two Lorentzians in RIPL



Systematic overestimation of the centroid energies :~ 2MeV

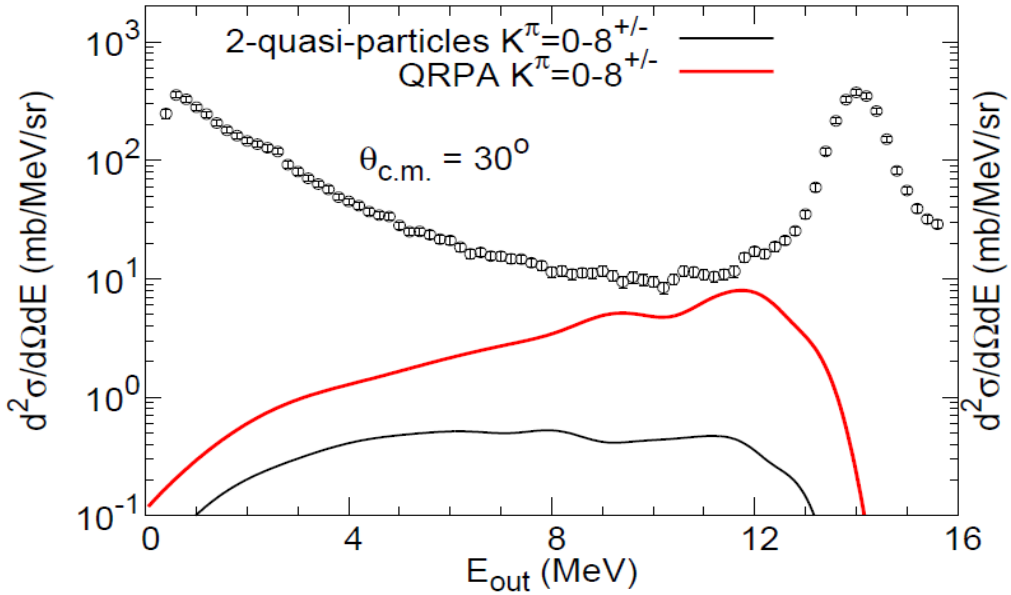
M. Martini et al, PRC 94, 014304 (2016)

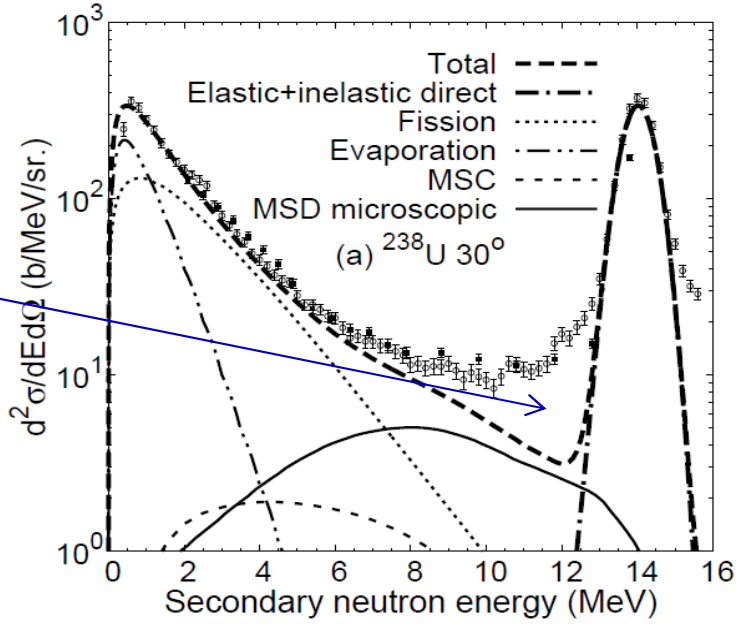
Beyond the nuclear structure

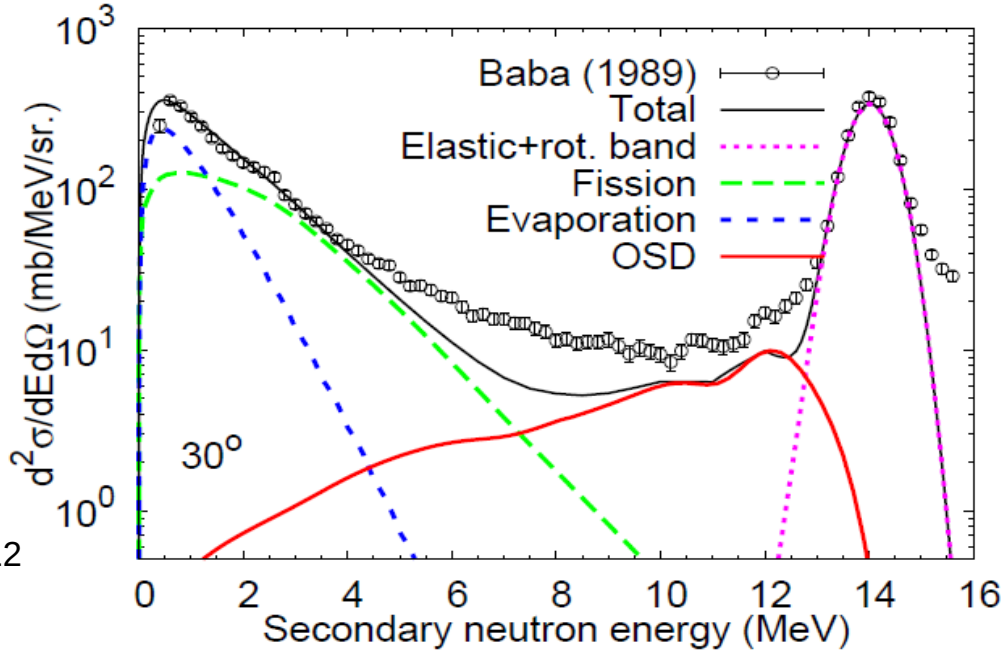
(n, *x* n) cross section on ^{238}U

Problem of underestimation of
n emission cross section at high energy

QRPA provides
enough collective contribution



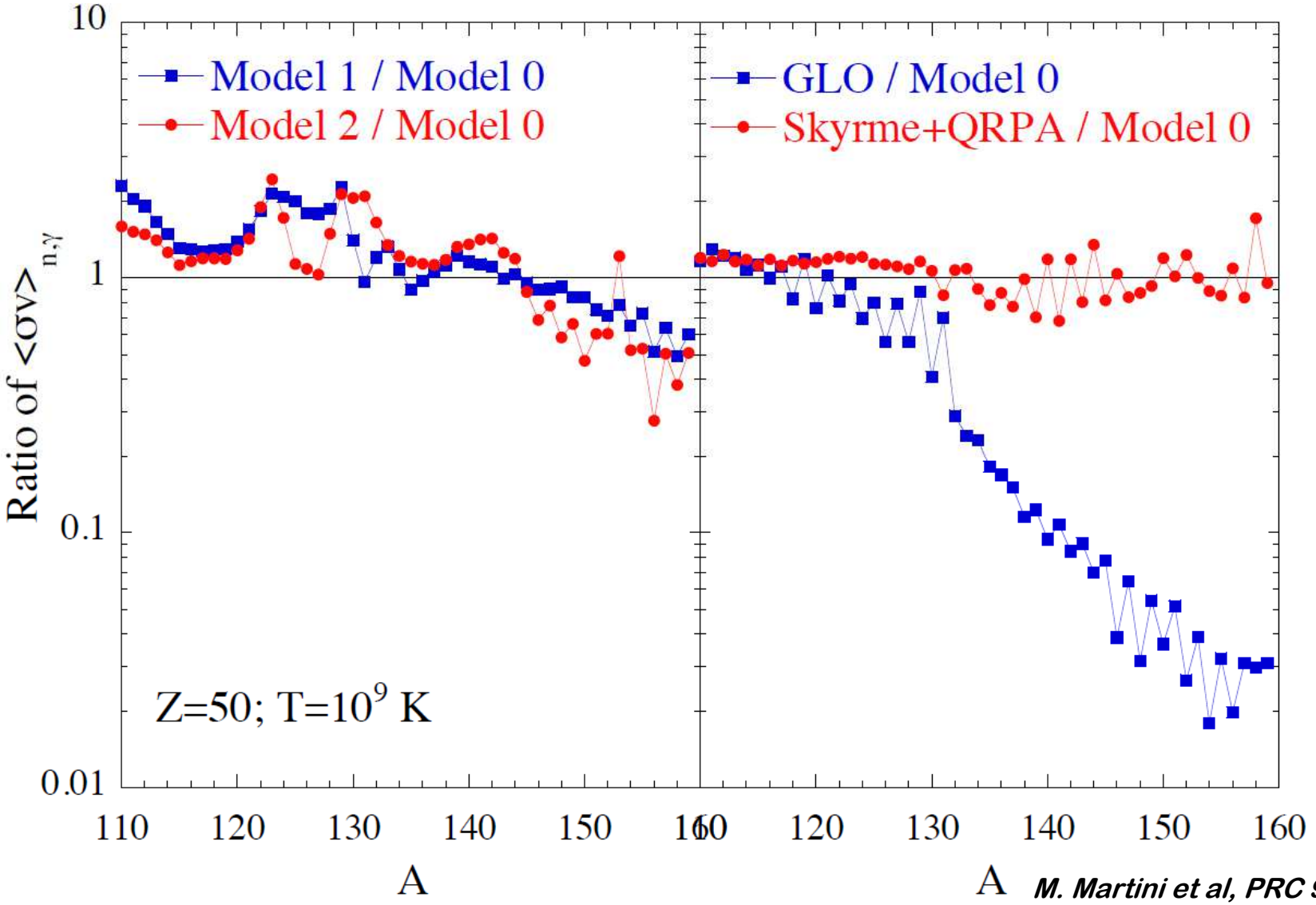




M. Dupuis, S.Péru, E. Bauge and T. Kawano,
13th International Conference on Nuclear Reaction Mechanisms, Varenna 2012
CERN-Proceedings-2012-002, p 95

predicted neutron-capture cross section

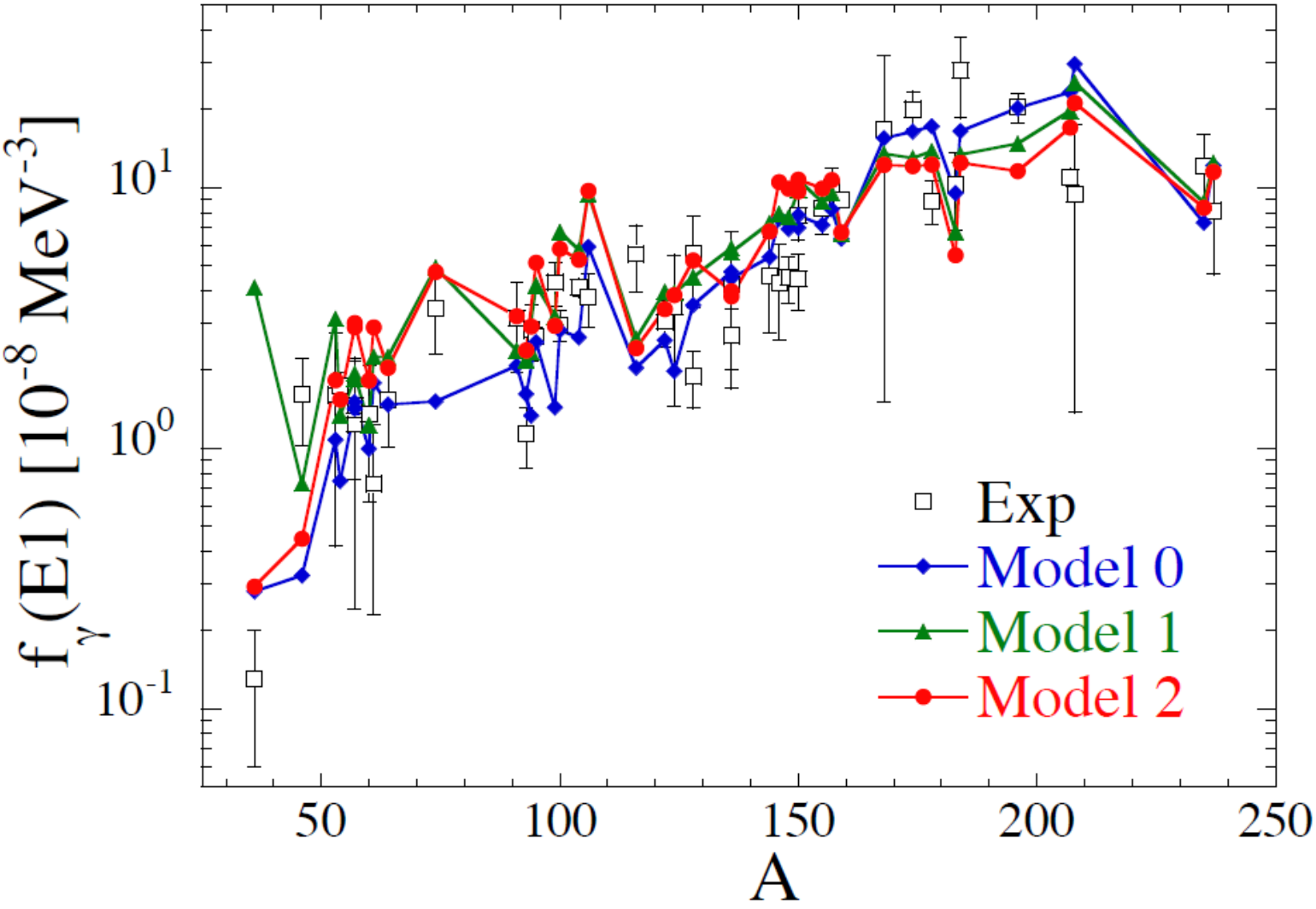
Impact on the predicted neutron-capture cross section of astrophysical interest



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

Low energy dipole excitations

Comparison of the QRPA low-energy E1 strength functions with experimental compilation for nuclei from ^{33}S up to ^{239}U at energies ranging from 4 to 8 MeV.



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

Photoneutron cross sections for Mo isotopes

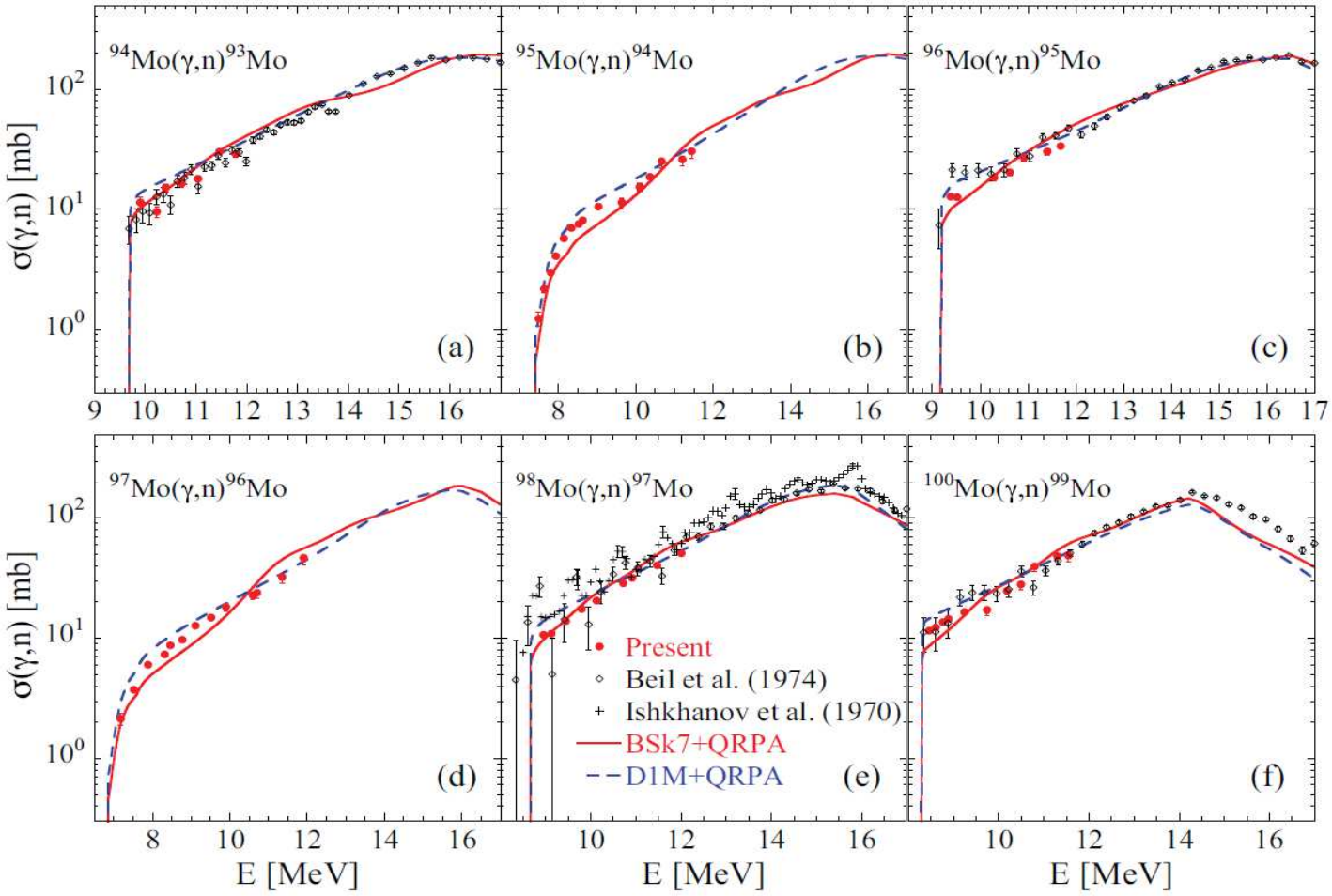
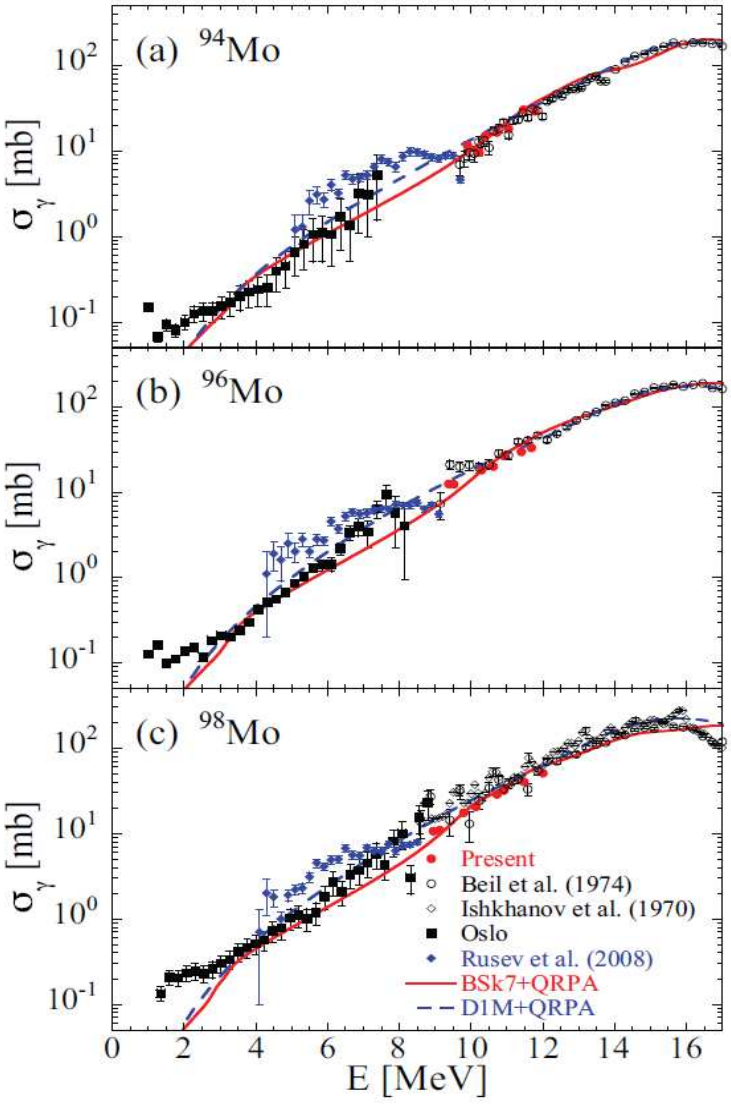
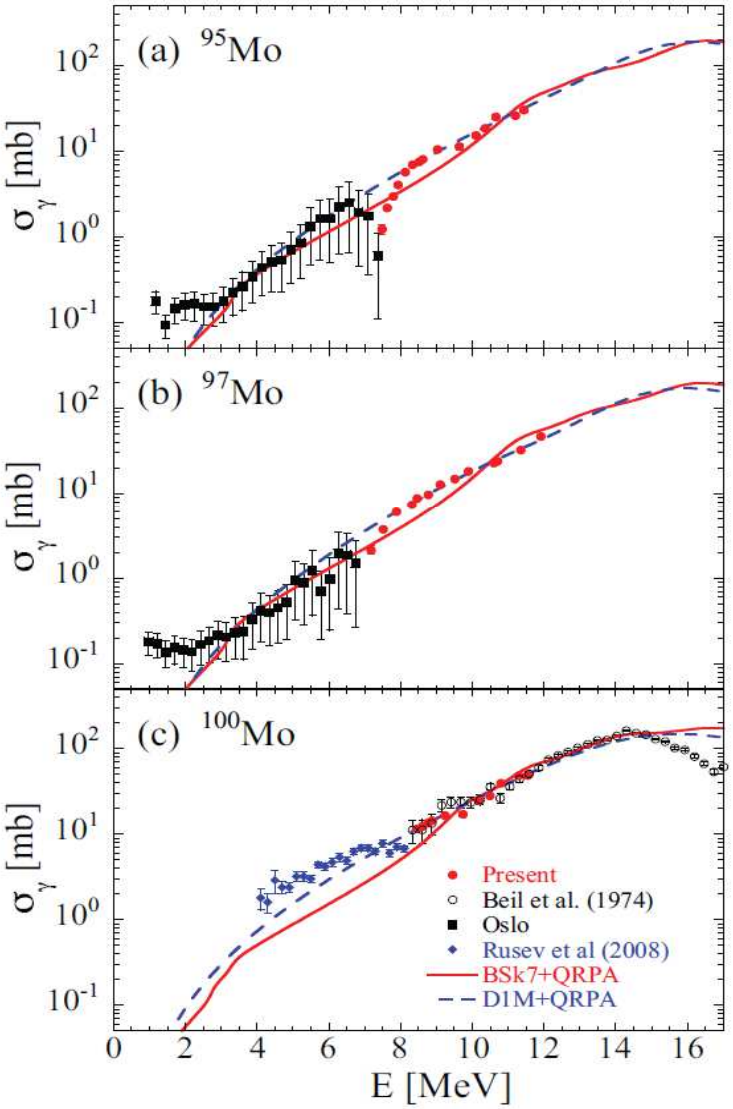


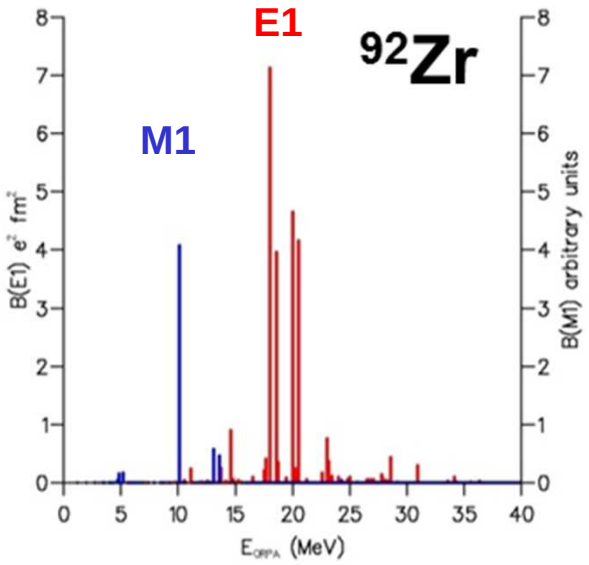
FIG. 3. (Color online) Comparison between the present photoneutron emission cross sections and previously measured ones [17,18] for six Mo isotopes, ^{94}Mo (a), ^{95}Mo (b), ^{96}Mo (c), ^{97}Mo (d), ^{98}Mo (e), and ^{100}Mo (f). Also included are the predictions from Skyrme HFB + QRPA (based on the BSk7 interaction) [20] and axially deformed Gogny HFB + QRPA models (based on the D1M interaction) [23].

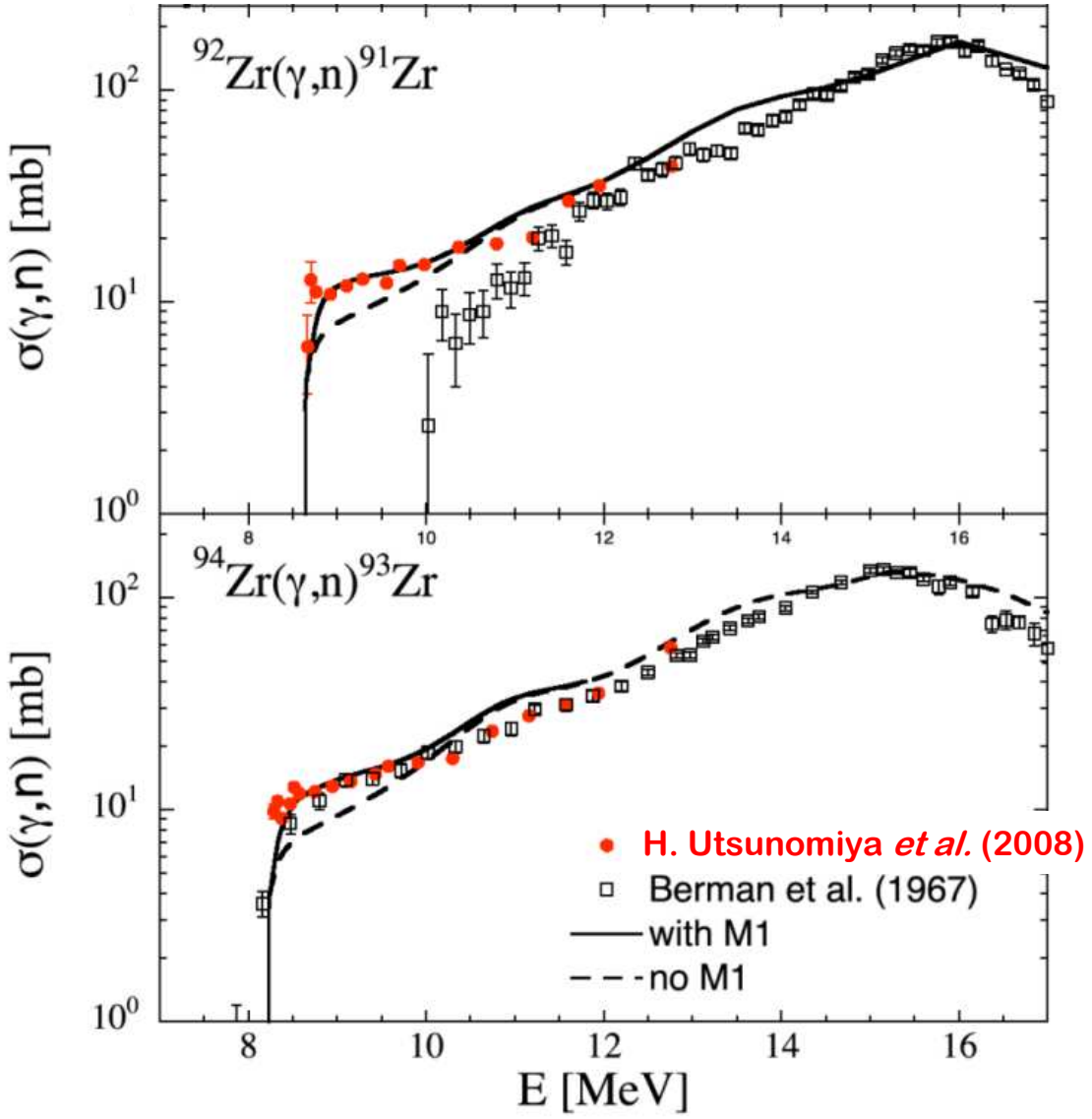
Photo-absorption cross sections for Mo isotopes





Dipole electric and magnetic excitations for Zr isotopes

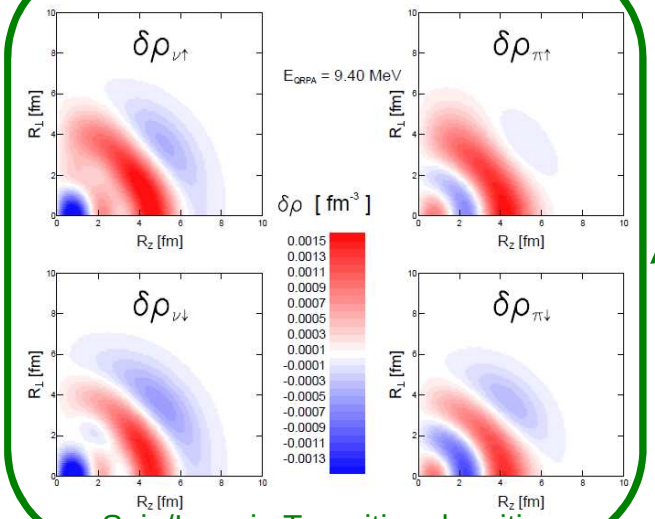




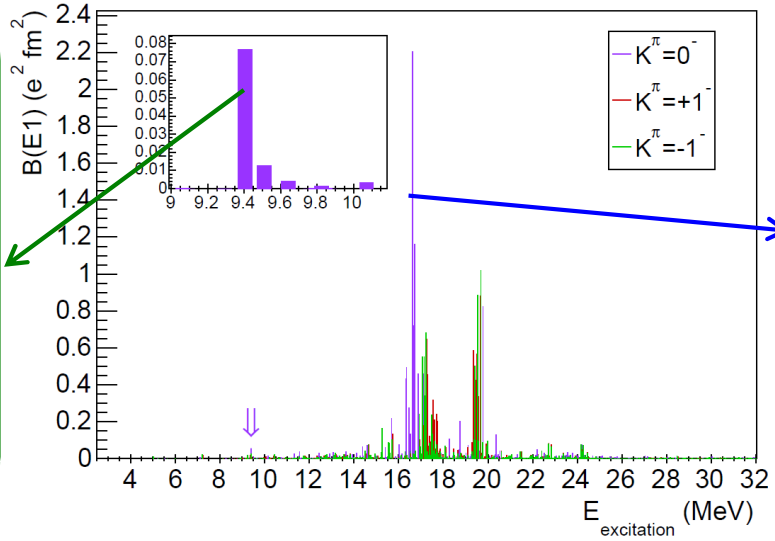
H. Utsunomiya et al, PRL 100, 162502 (2008)

Low Energy Enhancement in the γ Strength of the Odd-Even Nucleus ^{115}In

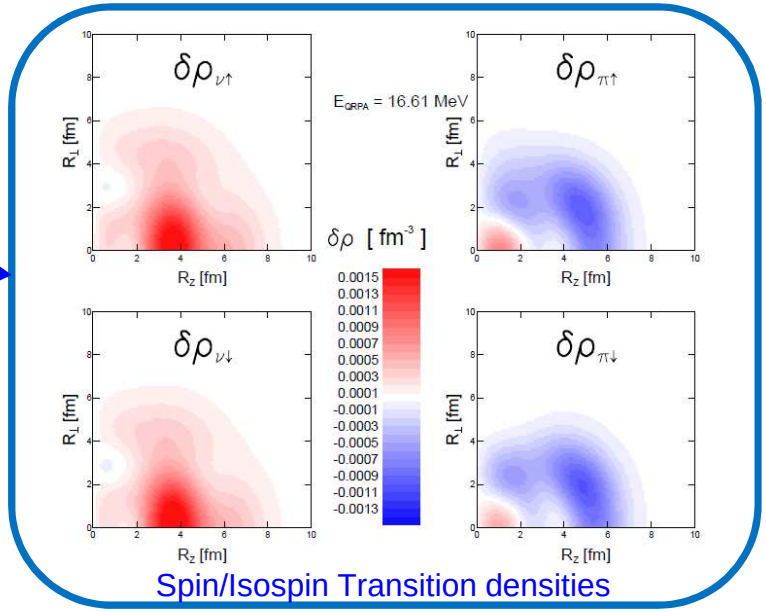
PDR Iso Scalar dipole



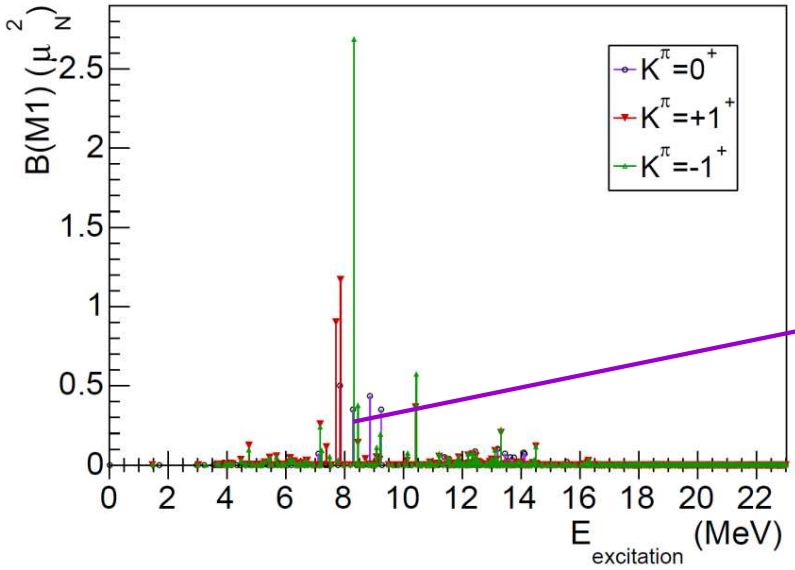
Spin/Isospin Transition densities

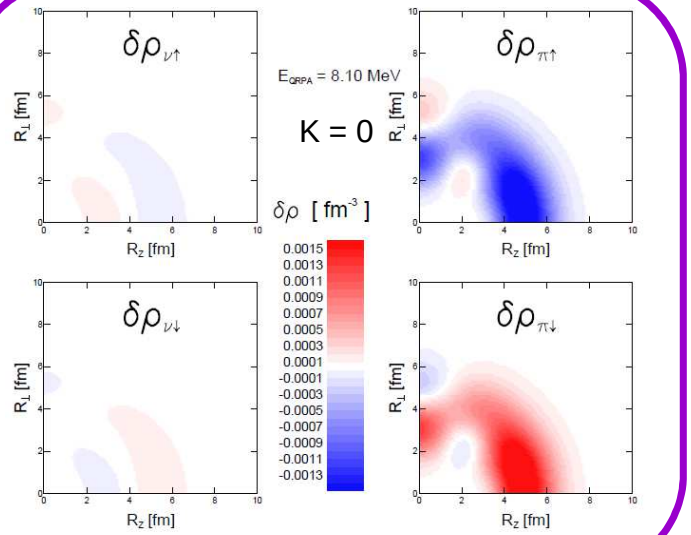


Iso Vector dipole



Spin/Isospin Transition densities



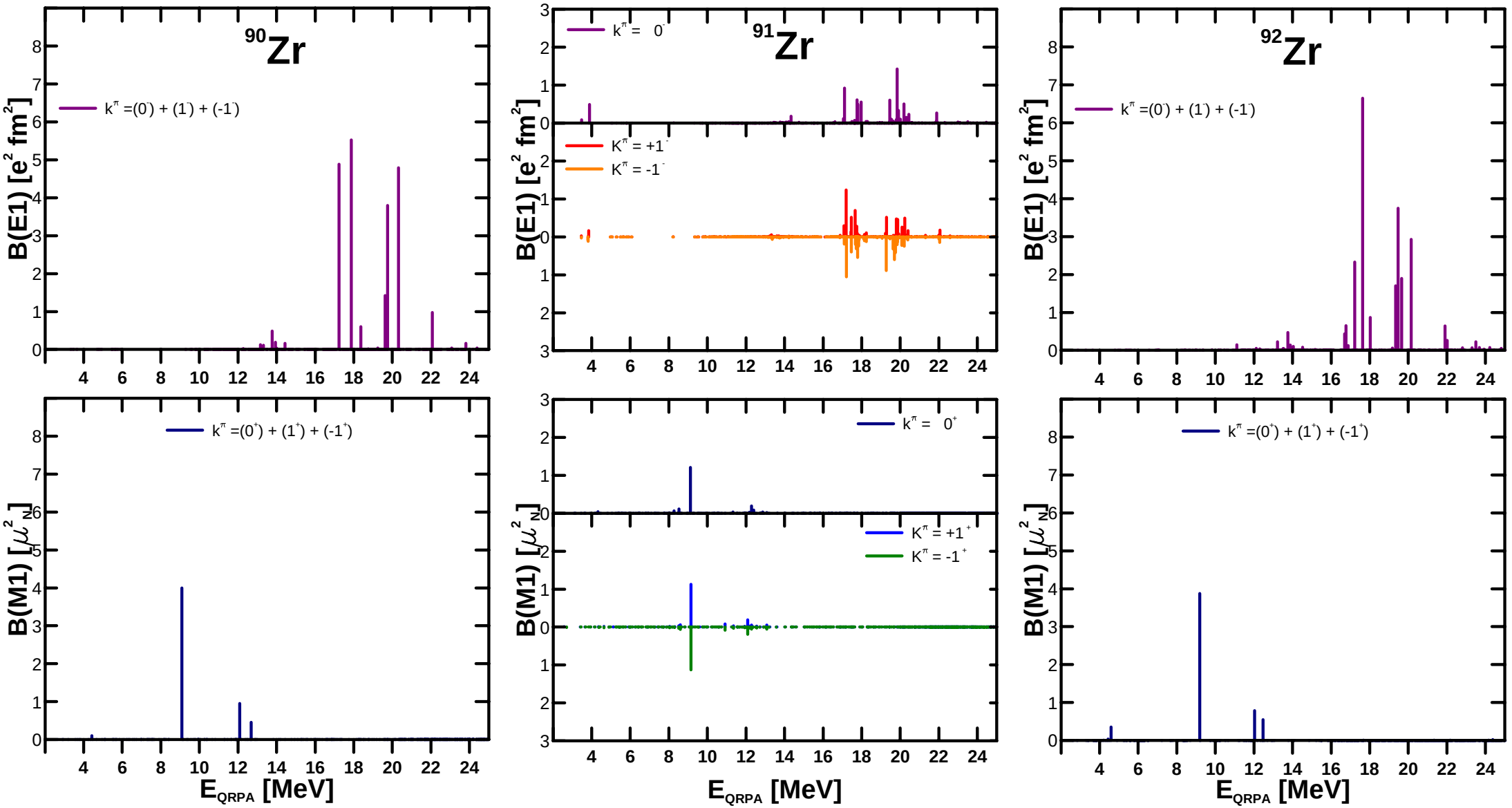


Spin/Isospin Transition densities

Spin flip

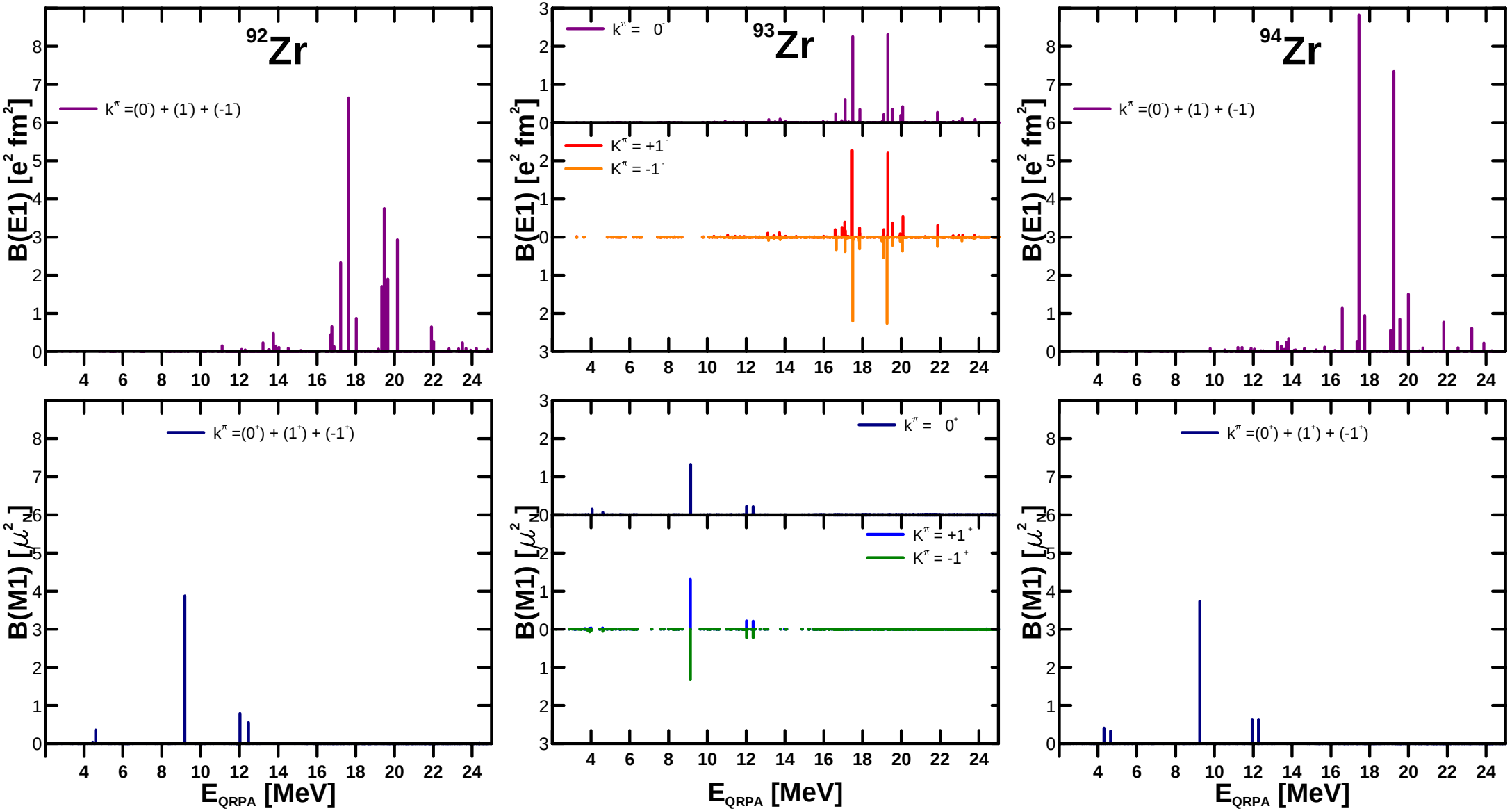
M. Versteegen et al, PRC 94, 044325 (2016)

Dipole states in odd and even Zr isotopes



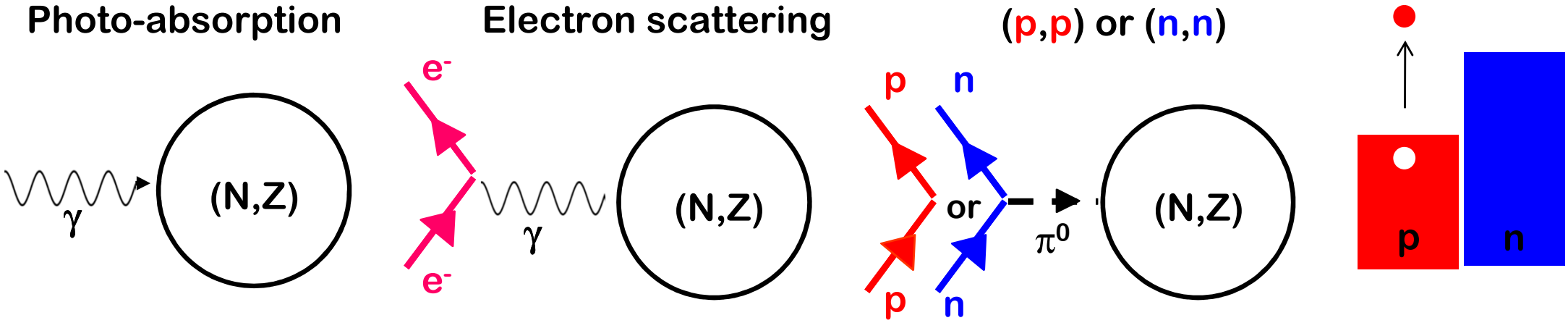
I. Deloncle, S. Péru, M. Martini, Eur. Phys. J. A (2017) **53**: 170

Dipole states in odd and even Zr isotopes

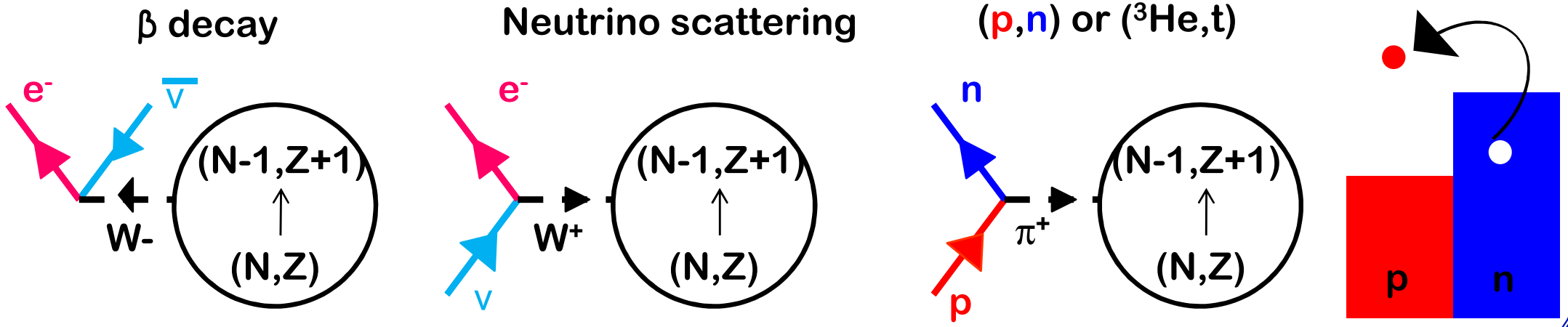


I. Deloncle, S. Péru, M. Martini, Eur. Phys. J. A (2017) **53**: 170

Nuclear Excitations

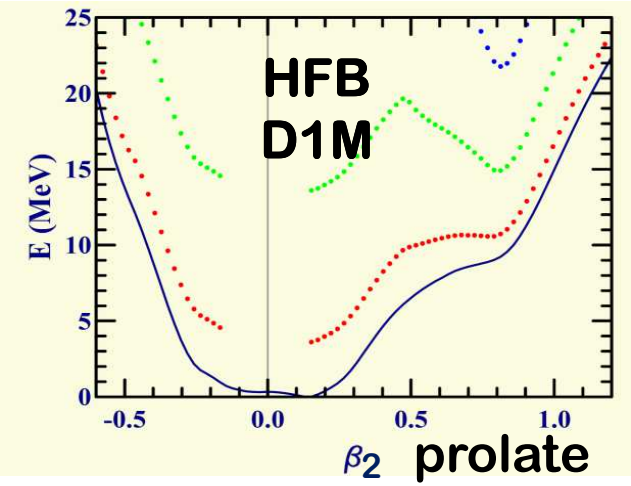


Charge exchange:



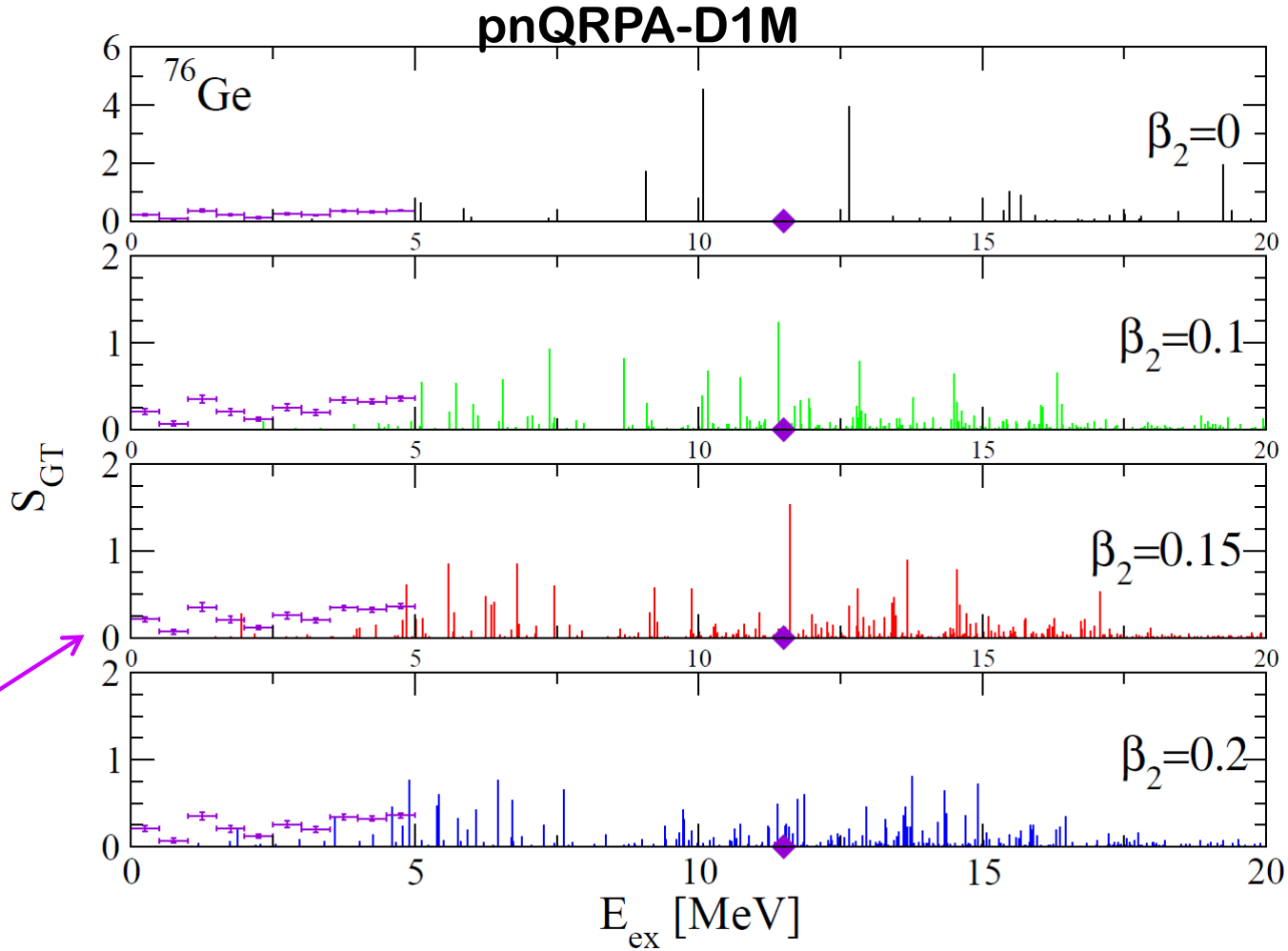
QRPA for charge exchange : ^{76}Ge a deformed nucleus

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



β_2(min. HFB) = 0.15 γ(min.HFB) = 0°

β_2 (0^+_1:5DCH) = 0.26 γ(0^+_1:5DCH) = 26°

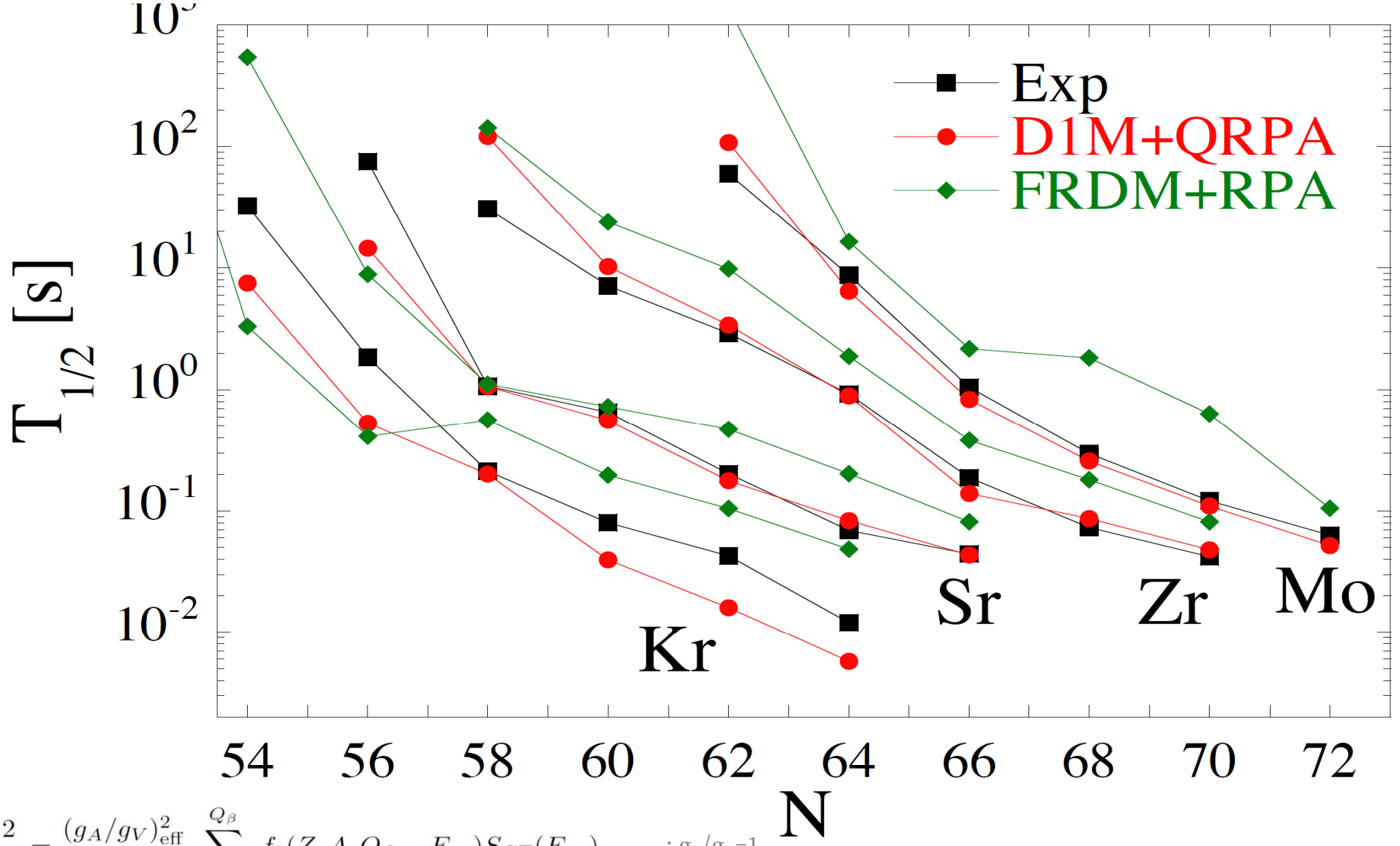


Experiment
Thies et al., Phys. Rev. C 86, 014304 (2012)

- 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

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

β^- decay half-lives of deformed isotopic chains

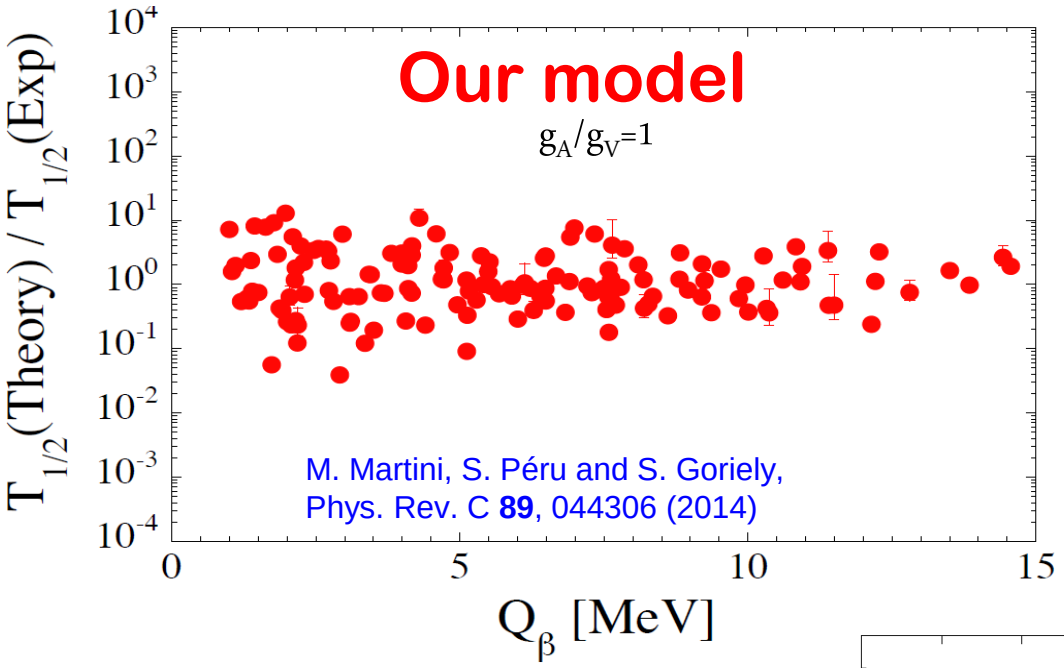


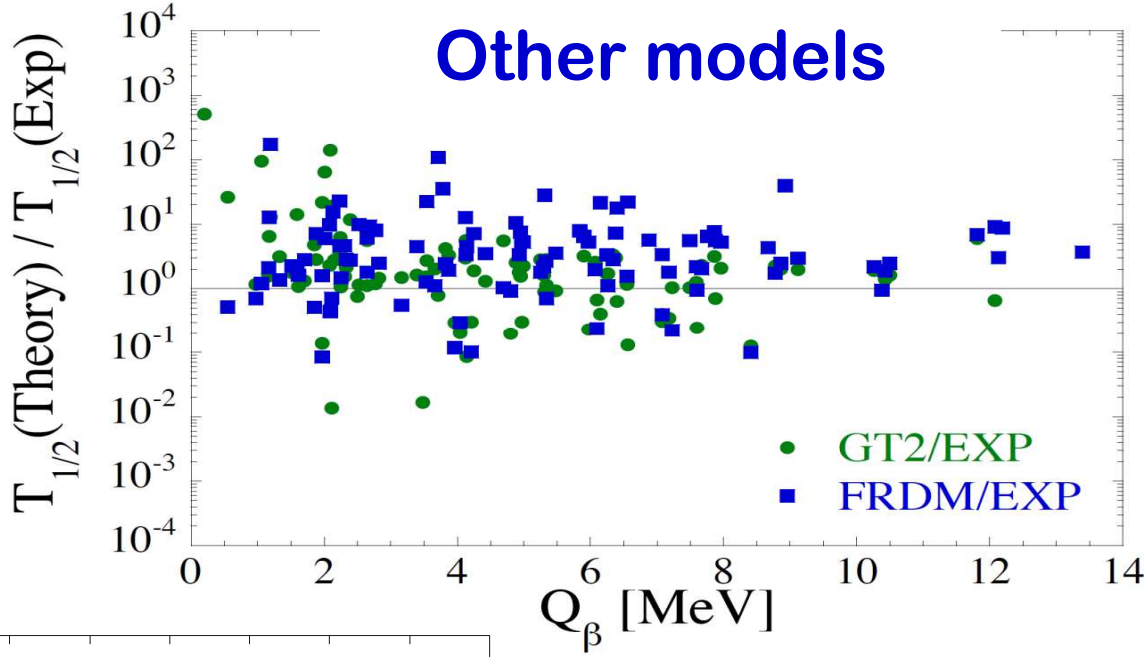
$$\frac{\ln 2}{T_{1/2}} = \frac{(g_A/g_V)^2_{\text{eff}}}{D} \sum_{E_{ex}=0}^{Q_\beta} f_0(Z, A, Q_\beta - E_{ex}) S_{GT}(E_{ex}) \qquad ; g_A/g_V=1$$

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

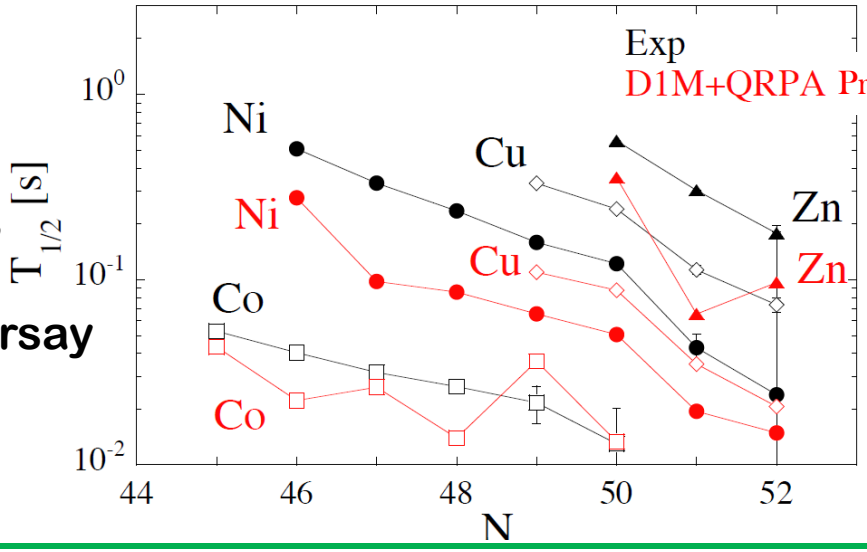
$$\frac{\ln 2}{T_{1/2}} = \frac{(g_A/g_V)^2_{\text{eff}}}{D} \sum_{E_{ex}=0}^{Q_\beta} f_0(Z, A, Q_\beta - E_{ex}) S_{GT}(E_{ex})$$

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



Experimental results

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

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

Gamow-Teller responses of odd and even Zr isotopes

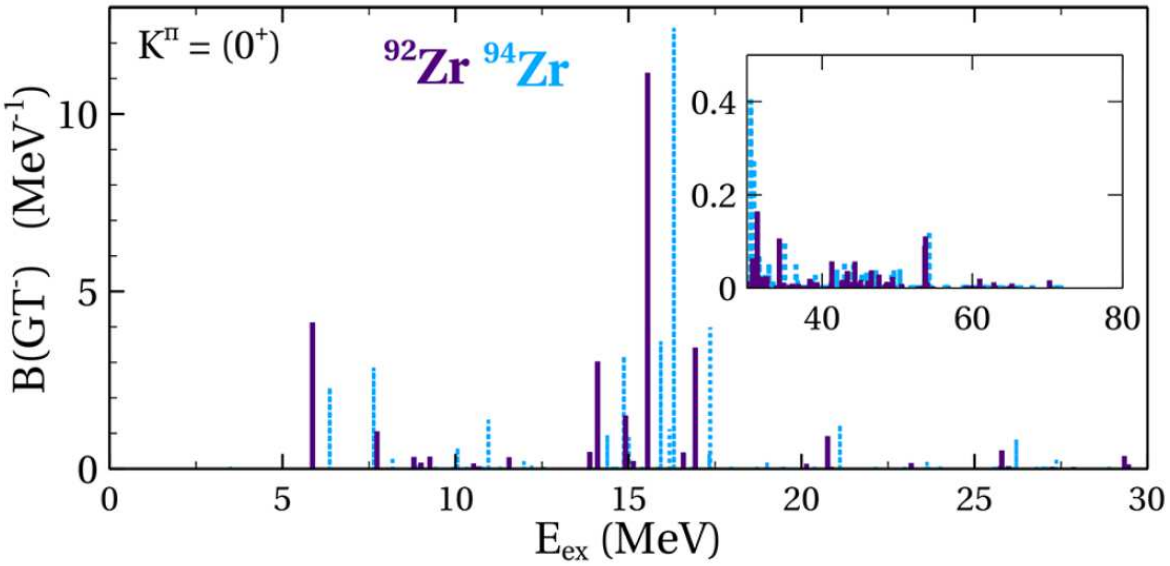
Eur. Phys. J. A (2017) 53: 170
DOI 10.1140/epja/i2017-12354-x

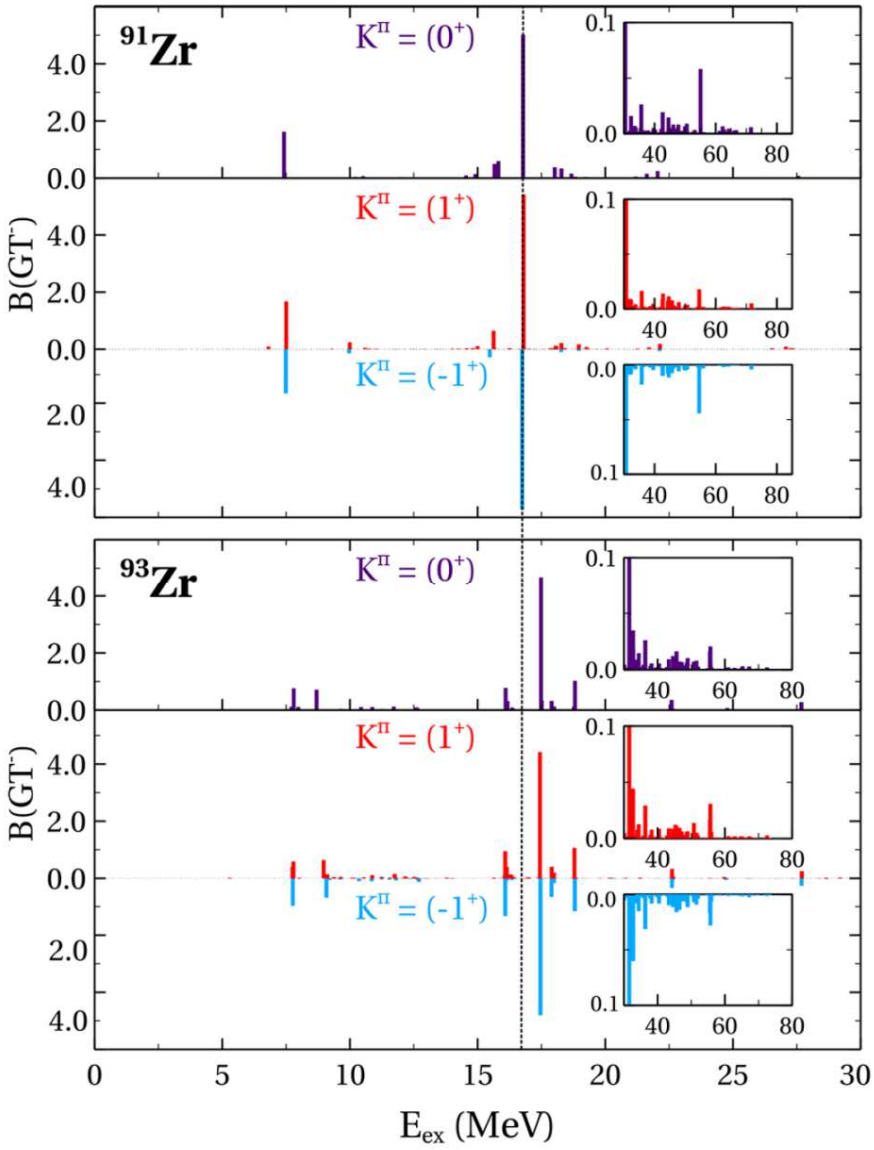
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Electromagnetic dipole and Gamow-Teller responses of even and odd $^{90-94}_{40}$Zr isotopes in QRPA calculations with the D1M Gogny force*

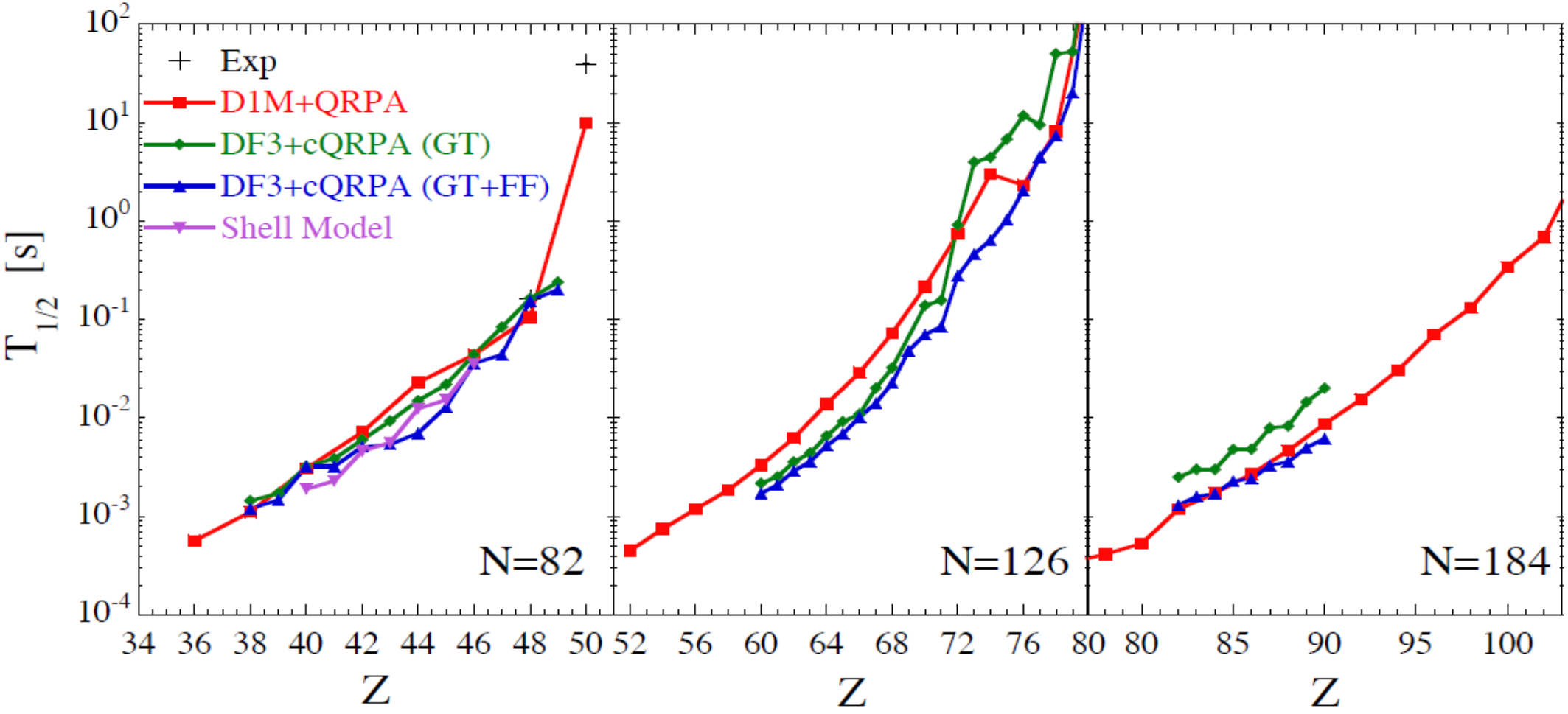
I. Deloncle[1,2,a], S. Péru[2,b], and M. Martini[3]





β^- decay half-lives of the N=82, 126, 184 isotones

Relevance for the r-process nucleosynthesis



DF3+cQRPA: Borzov et al., PRC 62, 035501 (2000)

Shell Model: Martinez-Pinedo et al., PRL 83, 4502 (1999)

Possible origins of differences: GT Strengths, estimation of Q_β values, …

To summarize

Beyond static mean field with the Gogny finite range force:

- Self-consistent QRPA approach can be applied to the deformed nuclei up to heavy ones.
- All multipolarities can be reached including electric octupole and magnetic dipole.
- The GDR energy position with QRPA is systematically predicted ~2MeV above the experimental values.
- Systematic studies have been undertaken for dipole response over the whole nuclear chart.

Extension of QRPA to charge exchange :

- The role of the intrinsic deformation has been shown for prolate ^{76}Ge.
- Predictions of the β decay half-lives are compatible with experimental data.

- Promising preliminary results for odd nuclei.

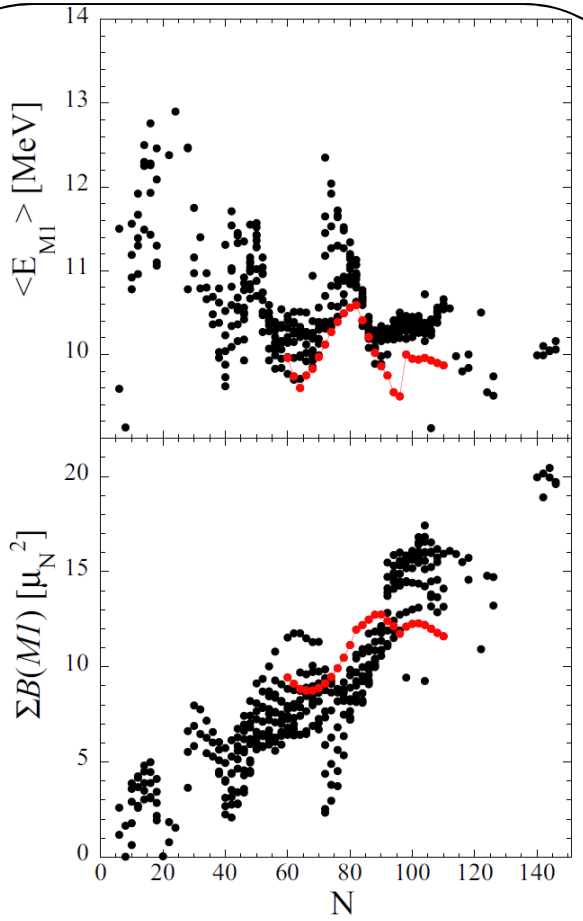


FIG. 2. Centroid $M1$ energy and total $B(M1)$ strength estimated for the 412 even-even nuclei around the valley of stability for which QRPA calculations have been performed. The Sn isotopic chain is shown by the red circles.

S. Goriely et al, PRC 94, 044306 (2016)