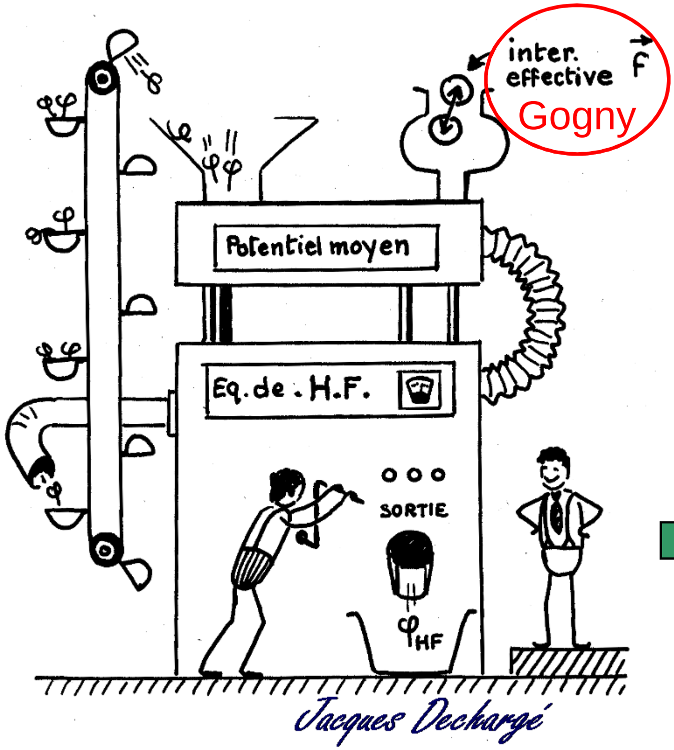
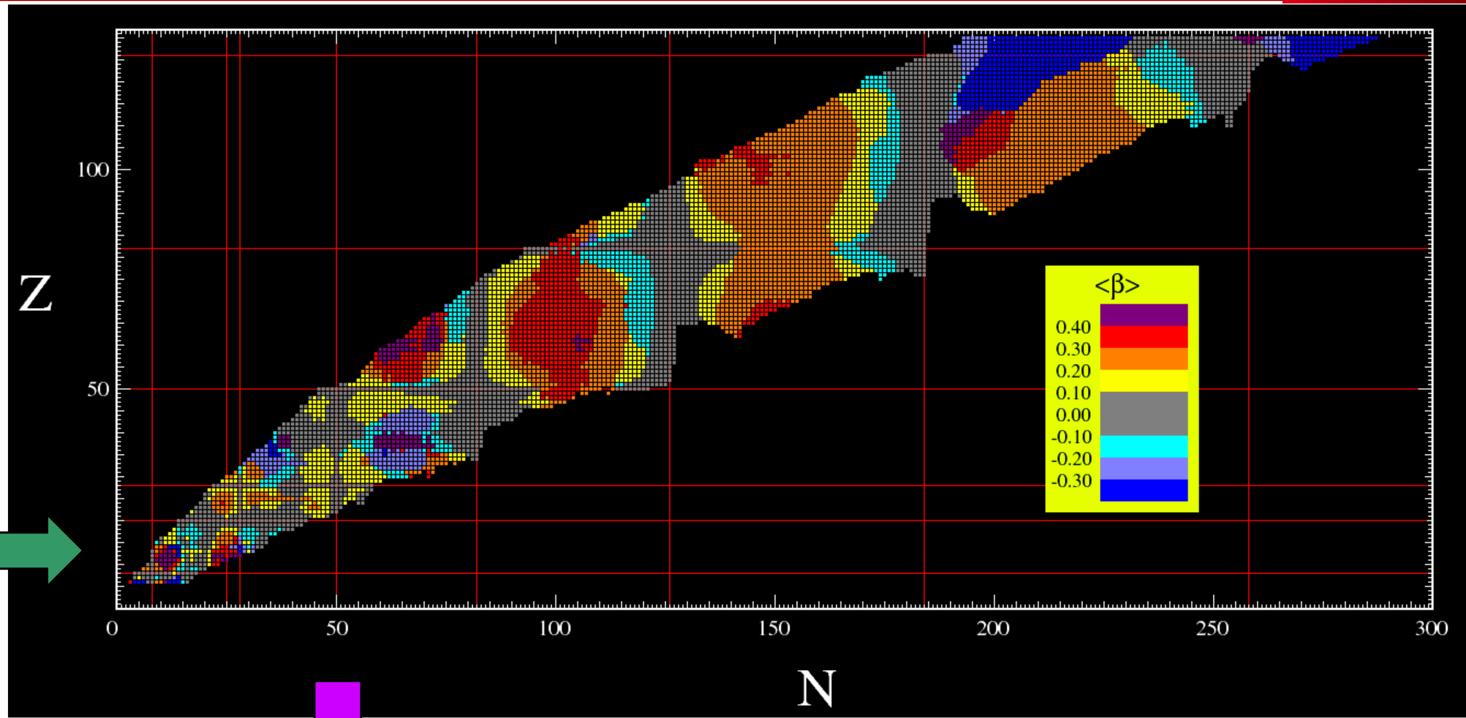
QRPA with the Gogny force: description of vibrational states up to octupole

Sophie Péru
and
I. Deloncle (CSNSM)
M. Dupuis (CEA, DAM)
S. Goriely (ULB)
S. Hilaire (CEA, DAM)
F. Lechaftois (CEA, DAM)
M. Martini (CEA, ESNT)

Reminder





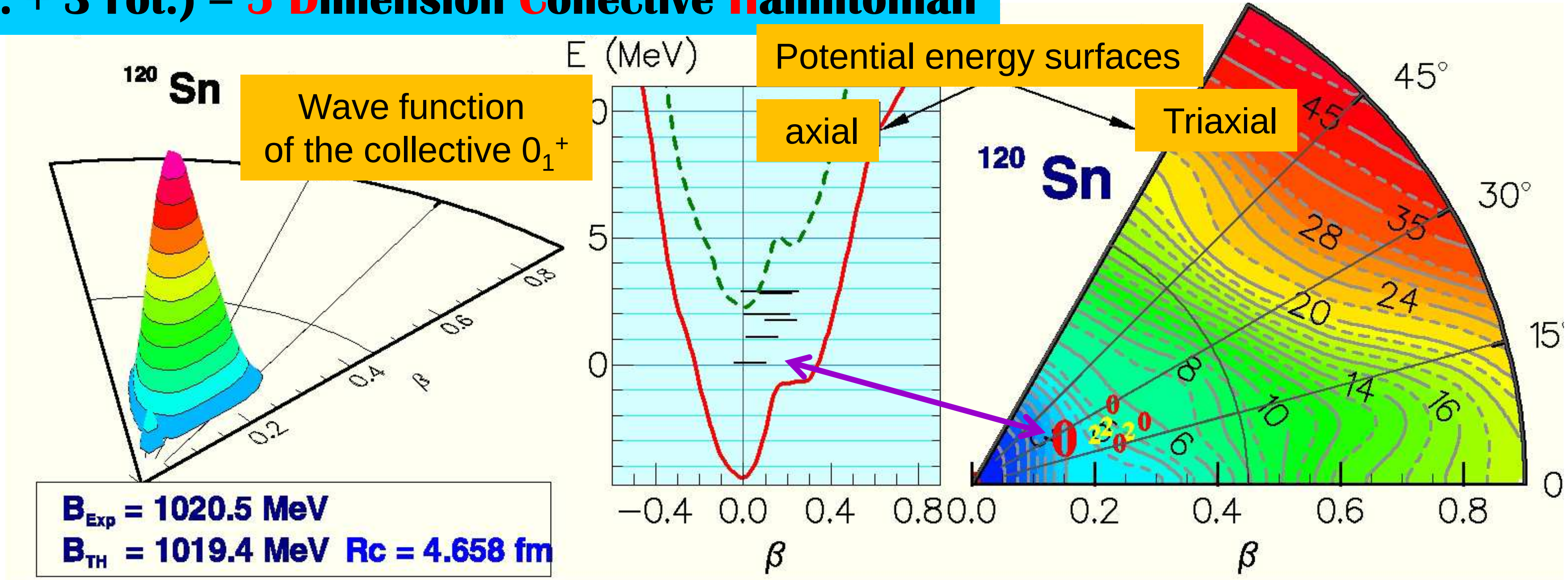
Static mean field (HFB)
for Ground State Properties :
- **Masses**
- **Deformation**
- **(Single particle levels)**

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

Beyond static mean field approximation (5DCH or QRPA)
for description of Excited State Properties
- **Low-energy collective levels**
- **Giant Resonances**

Beyond mean field … with 5DCH

(2 vibr. + 3 rot.) = 5 Dimension Collective Hamiltonian



B_{Exp} = 1020.5 MeV
B_{TH} = 1019.4 MeV Rc = 4.658 fm

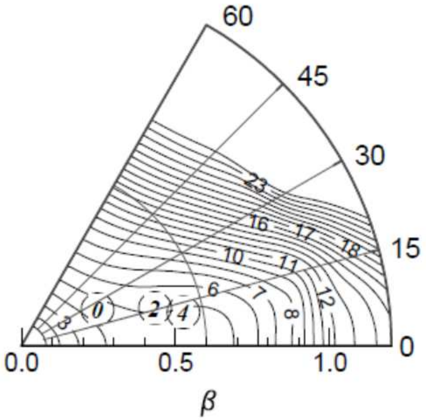
First collective states

E_x (MeV) $\langle\beta\rangle$

State	E_x (MeV)	$\langle\beta\rangle$
0^+	3.52	0.3
0^+	2.88	0.26
0^+	1.68	0.25
0^+	0.00	0.17
2^+	2.76	0.27
2^+	1.93	0.24
2^+	1.04	0.22
3^+	2.88	0.26
4^+	2.84	0.26
4^+	1.92	0.25
6^+	2.82	0.27

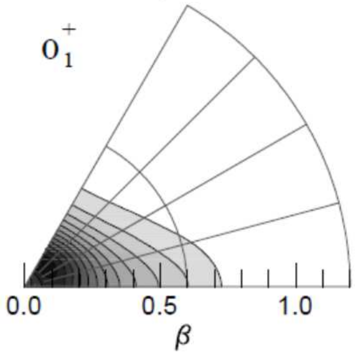
$$\hat{H}_{coll} = \frac{\hbar^2}{2}\sum_{k=1}^{3}\frac{\hat{I}_k^2}{J_k} - \frac{\hbar^2}{2}\sum_{m,n=0 \text{ and } 2} D^{-1/2}\frac{\partial}{\partial a_m} D^{1/2}\left(B_{mn}\right)^{-1}\frac{\partial}{\partial a_n} + V\left(a_0,a_2\right) - \Delta V\left(a_0,a_2\right)$$

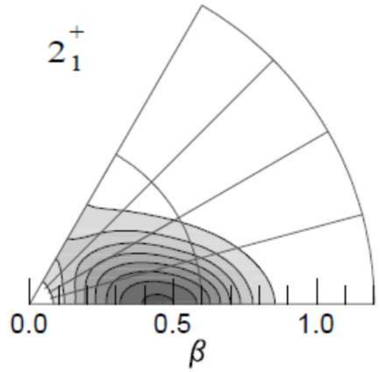
Shell closure studies with 5DCH



E $(2^+_1)_{\text{Theo.}}$ = 1.32 MeV

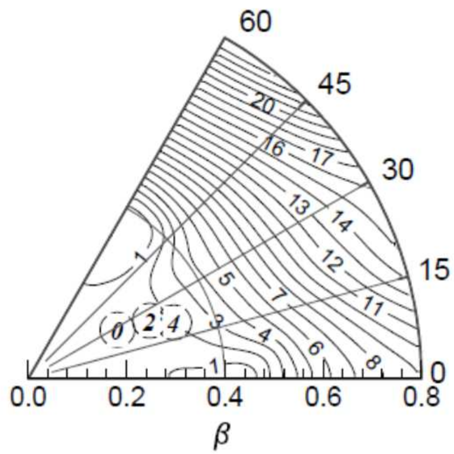
E $(2^+_1)_{\text{Exp.}}$ = 885 keV

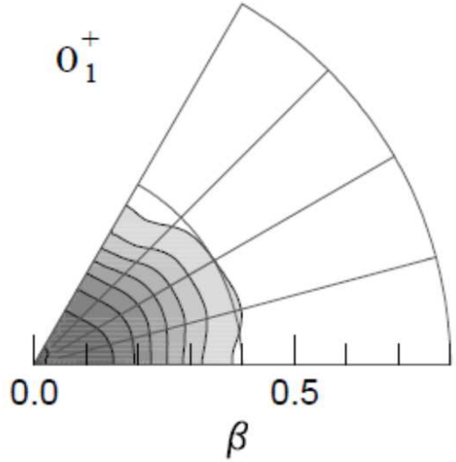




N=20, ^{32}Mg

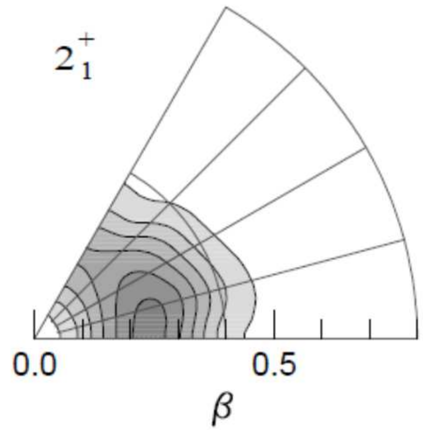
N=28, ^{44}S





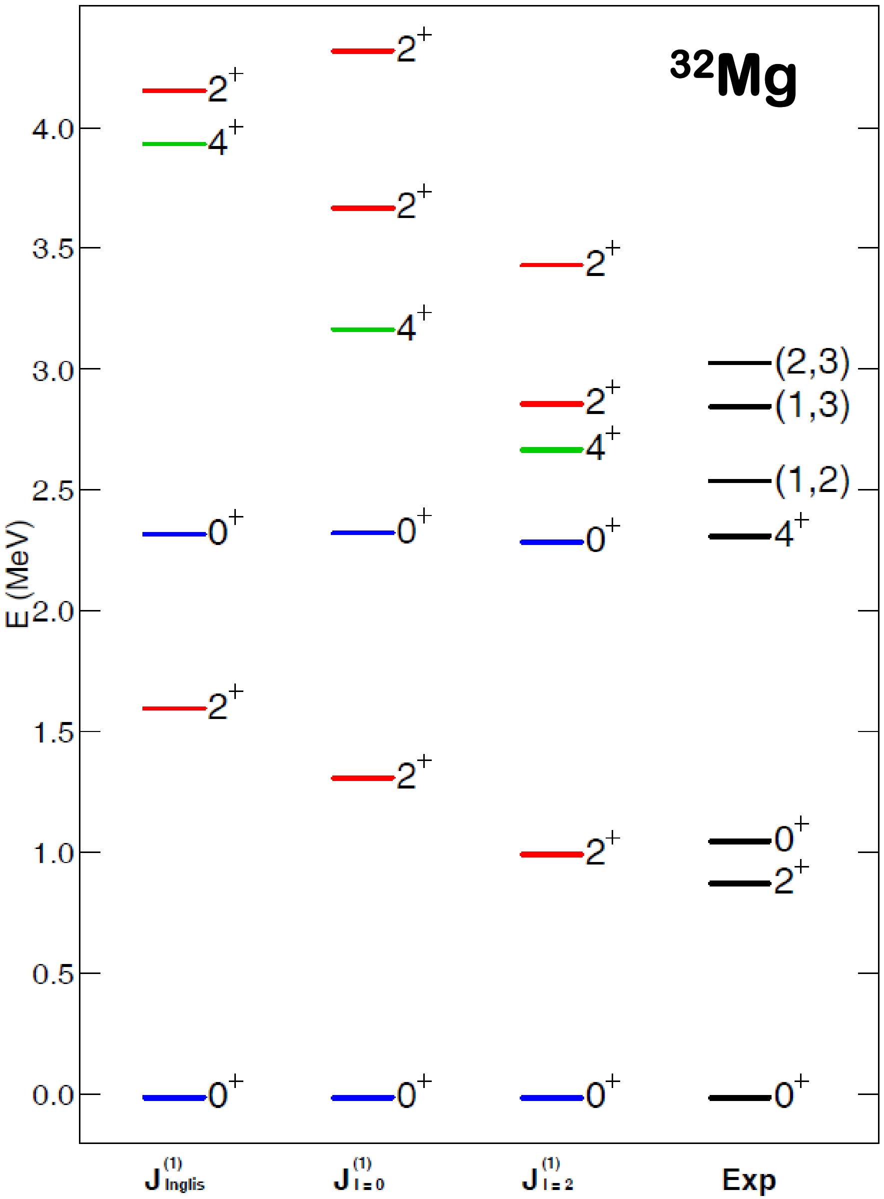
$E(2^+_1)_{\text{Theo.}}$ = 1.46 MeV,
$E(2^+_1)_{\text{Exp.}}$ = 1.297 (0.018)MeV,

$B(E2,0^+_{gs}\rightarrow 2^+_1)$ = 420 e^2fm^4
$B(E2,0^+_{gs}\rightarrow 2^+_1)$ = 314 (88) e^2fm^4



S. Péru, M. Girod, JF. Berger, Eur. Phys. J. A 9,35-47, (2000)

Further analysis : moments of inertia



S. Péru & M. Martini, EPJA (2014) **50** : 88

Sulfur isotopes

D. SOHLER *et al.* PHYSICAL REVIEW C **66**, 054302 (2002)

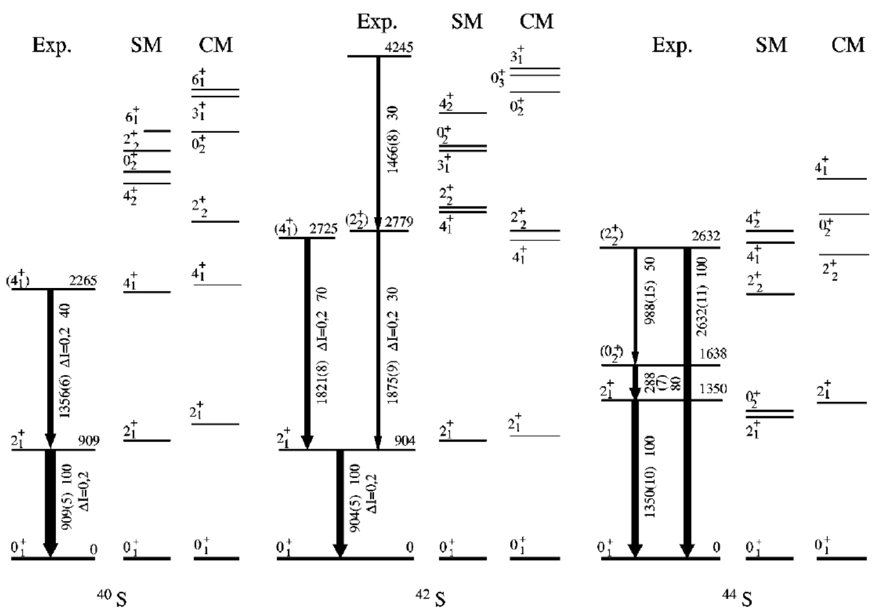
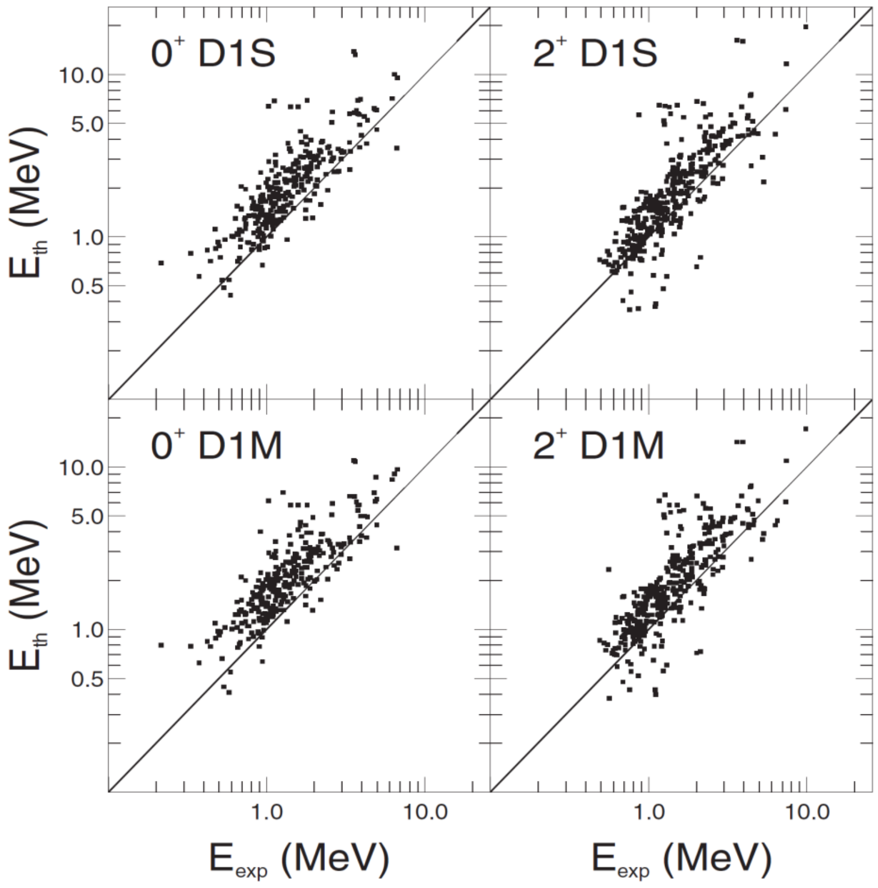


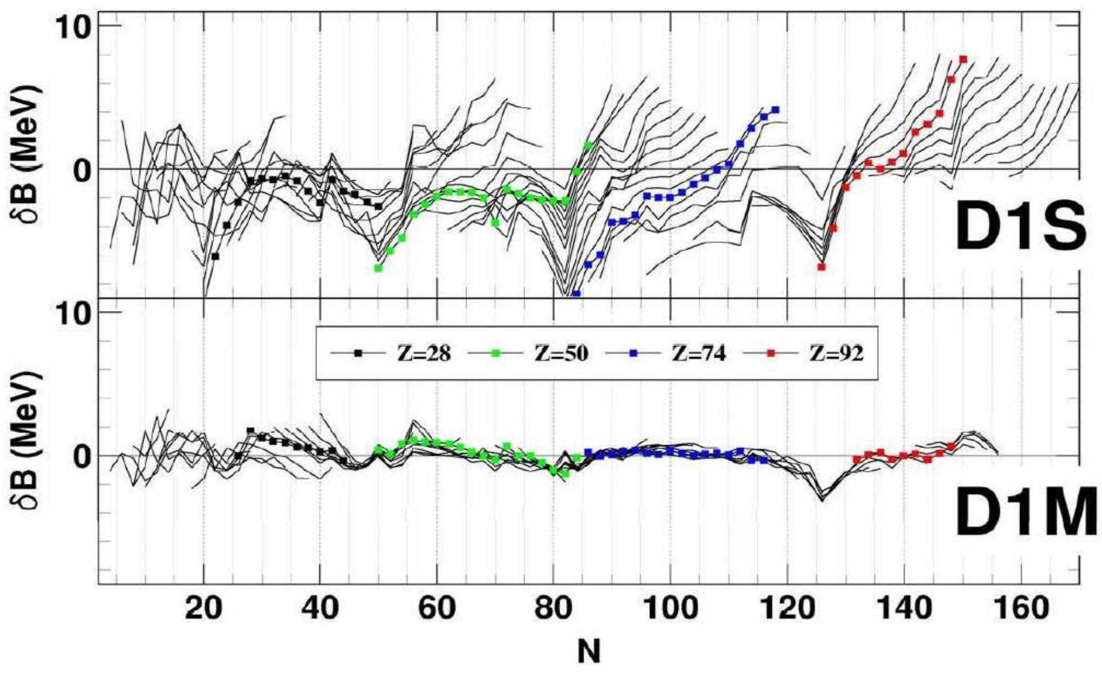
FIG. 3. Proposed level schemes of ^{40,42,44}S from the present experiment in comparison with the results of shell-model (SM) and microscopic collective-model (CM) calculations. γ-ray energies (with uncertainties), multipolarities, and relative intensities are given.

Some exploitation of 5DCH with Gogny forces

Systematics studies

D1S: J. P. Delaroche et al. PRC 81, 014303 (2010)
D1M: S. Hilaire et al. PRC 86, 064317 (2012)

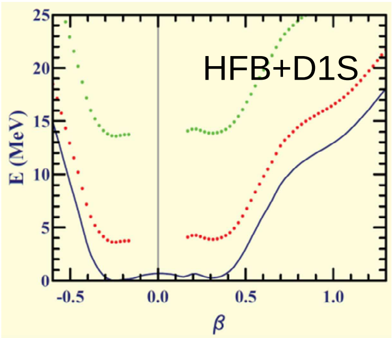


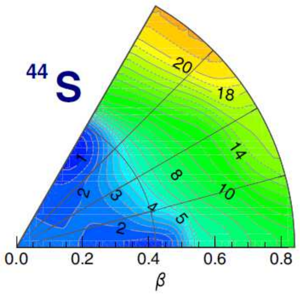


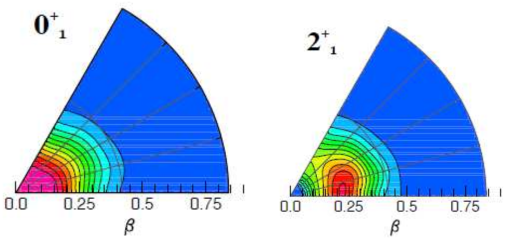
S. Goriely, S. Hilaire, M. Girod, S. Péru , PRL 102, 242501 (2009)

Beyond static mean field … with 5DCH or QRPA

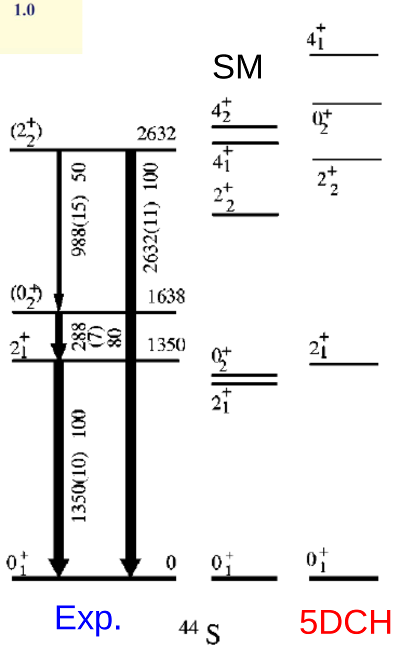
5 Dimension Collective Hamiltonian
describes ground state and excited states within configuration mixing : quadrupole vibration and rotational degrees of freedom.







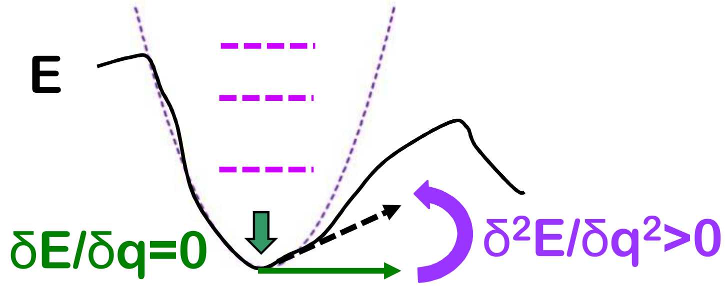
S.Péru and M. Martini, EPJA (2014) 50: 88.



D. Sohler et al, PRC 66, 054302 (2002)

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

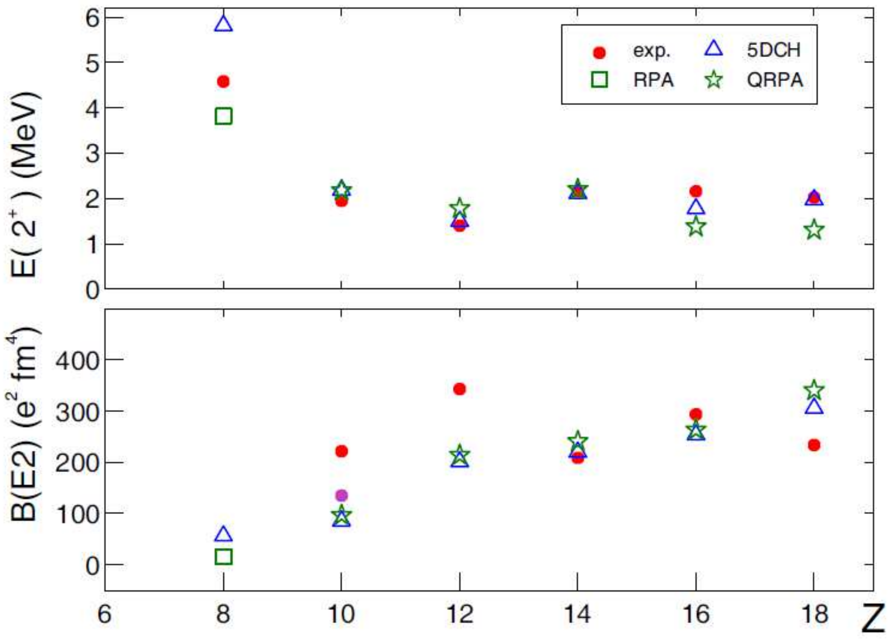
But small amplitude approximation
i.e. « harmonic » nuclei



! QRPA approaches
don't describe rotational motion !

HFB+QRPA versus HFB+5DCH with the same interaction

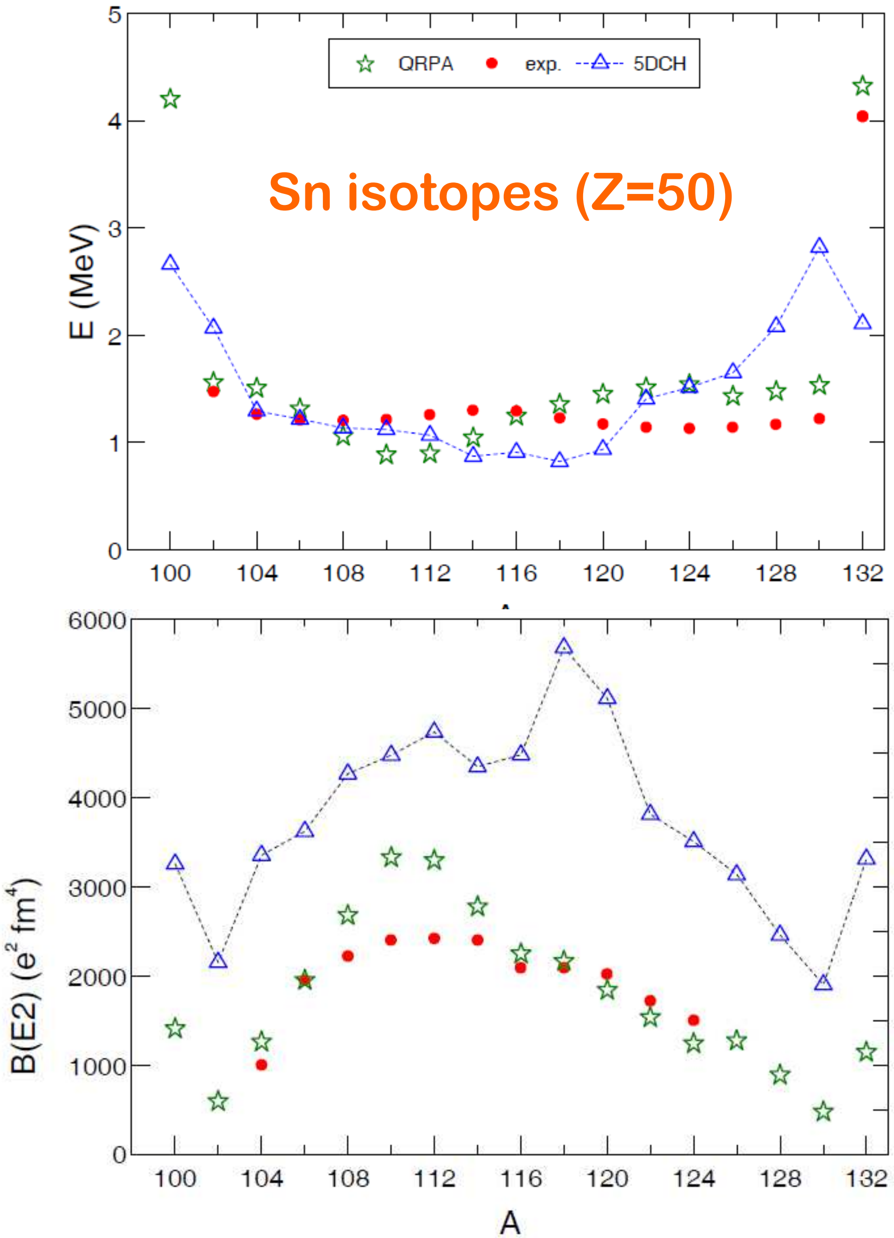
N=16 isotones



5DCH : A. Obertelli, et al, Phys. Rev. C **71**, 024304 (2005)

S. Péru and M. Martini, EPJA (2014) 50: 88.

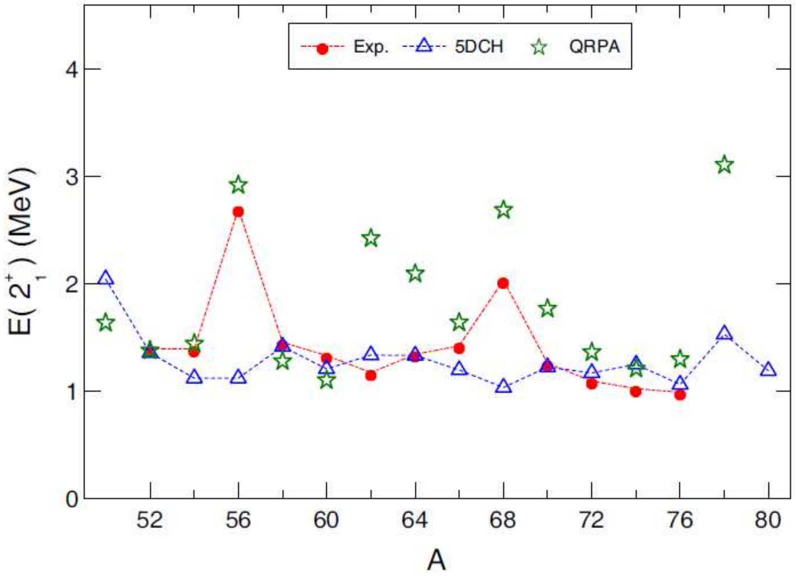
Sn isotopes (Z=50)

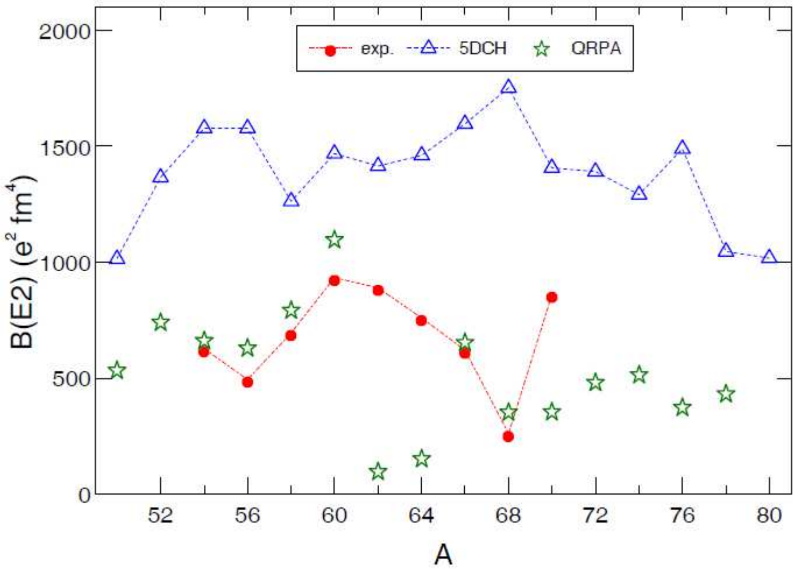


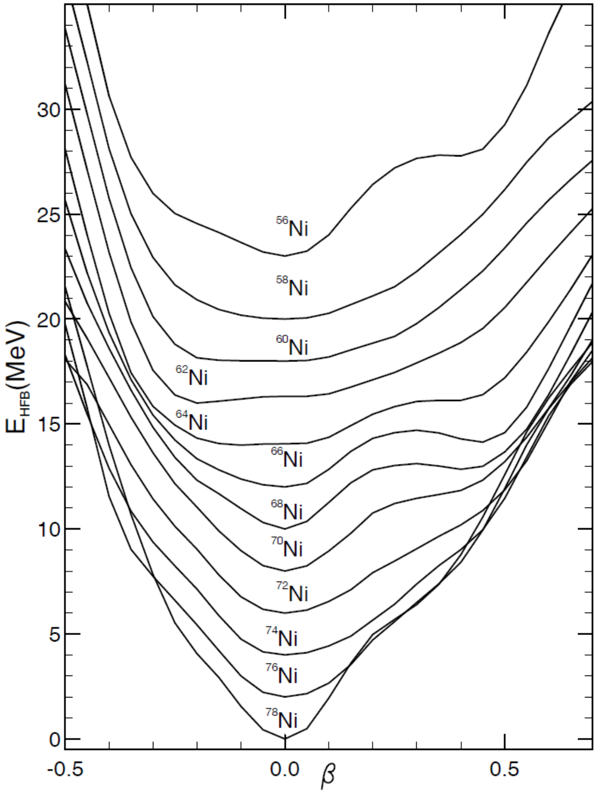
HFB+QRPA versus HFB+5DCH with the same interaction

Ni isotopes (Z=28)

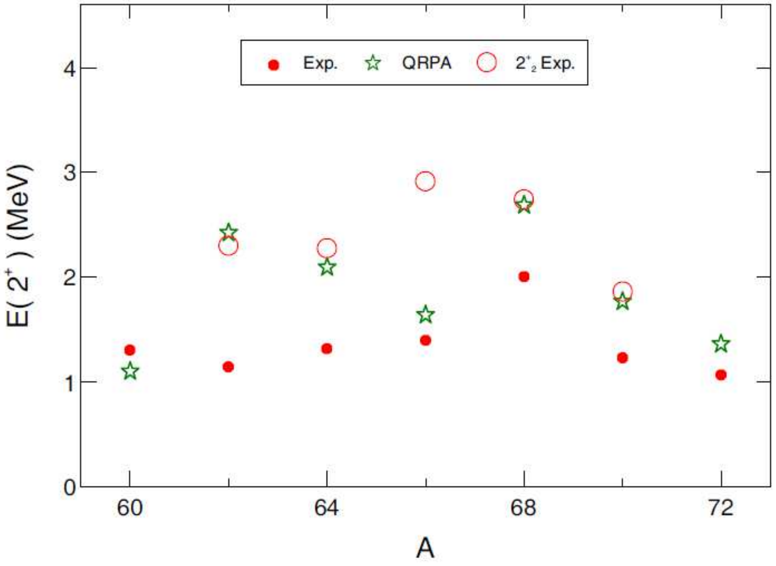
Two shell (N= 28, 50) and one sub-shell (N=40) closures







^{78}Ni is predicted doubly magic



For deformed nuclei the first 2^+ state is rotational

S. Péru and M. Martini, EPJA (2014) 50: 88.

Beyond mean field… with QRPA

RPA approaches describe

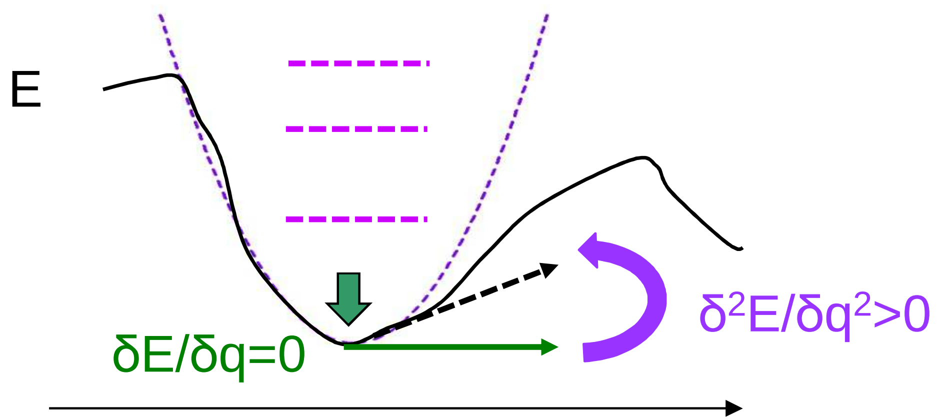
all multipolarties and all parities,

collective states and individual ones,

low energy and high energy states

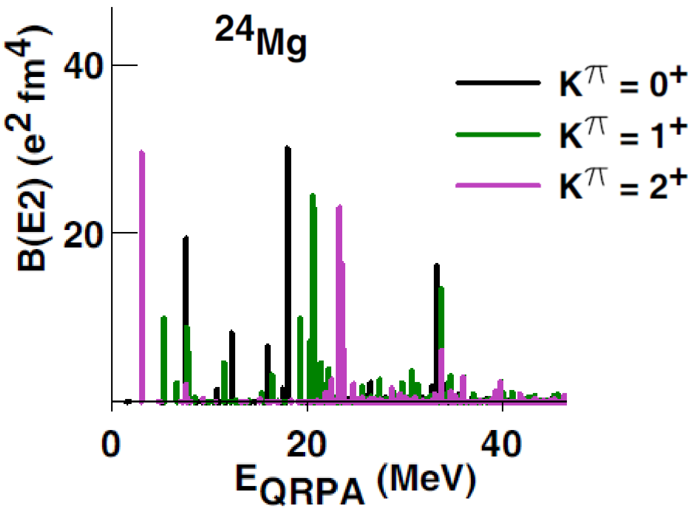
with the same accuracy.

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



<u>Spherical RPA with Gogny force</u>

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



<u>Axially symetric deformed QRPA with Gogny force</u>

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)

RPA approaches describe all multipolarties and all parities

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

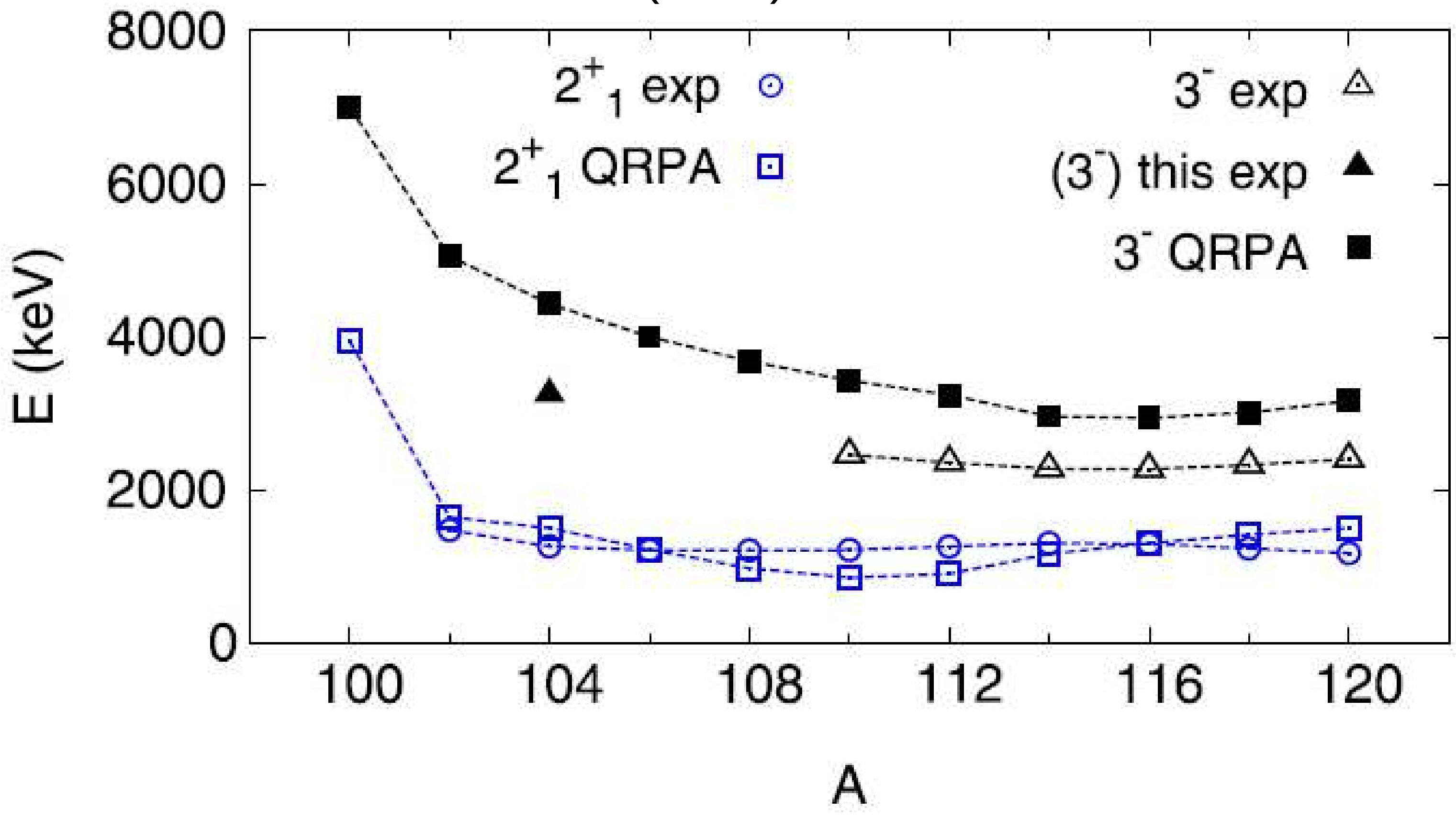
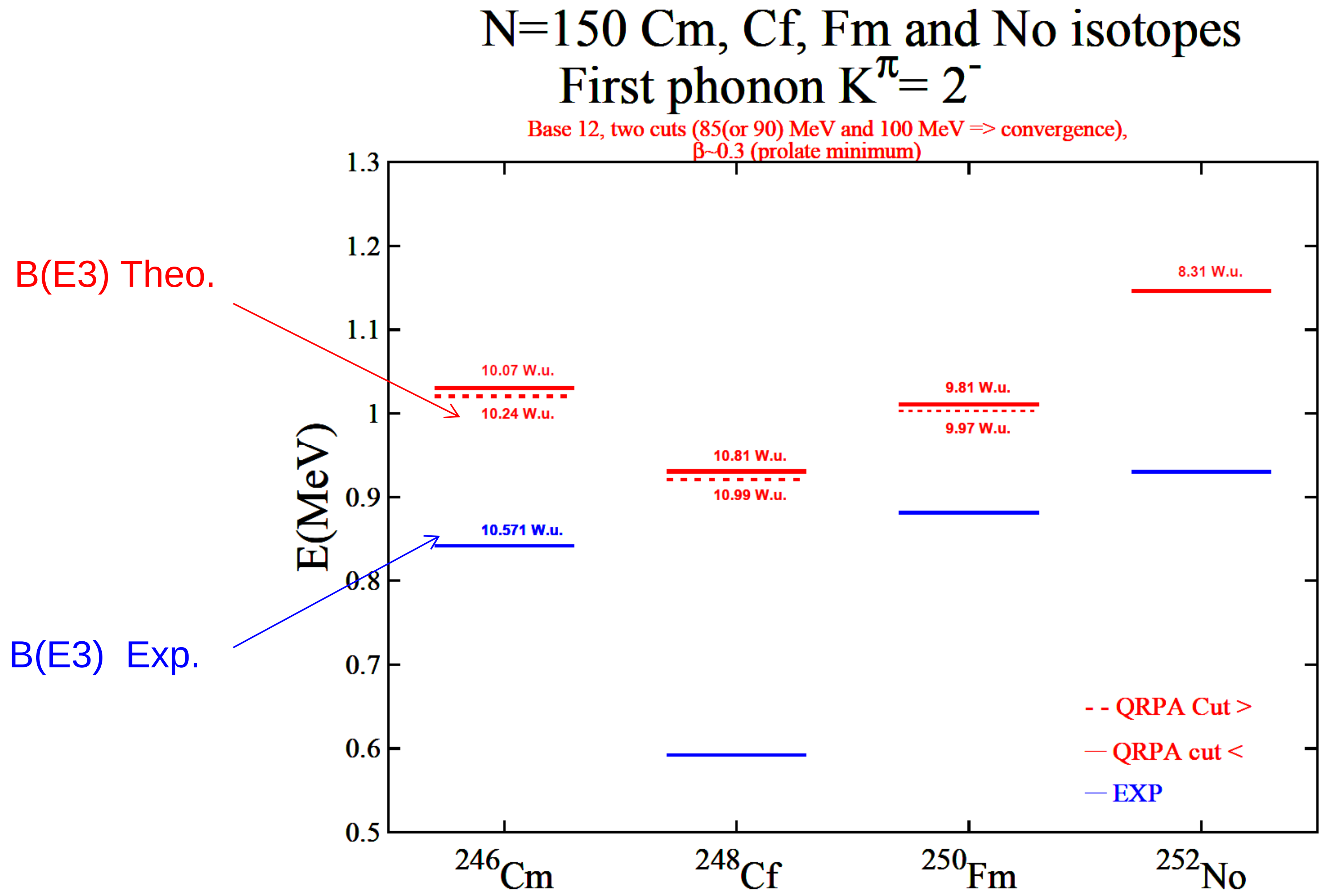


Fig. 3. (Color online.) Systematics of 2^+ and 3^- excitation energies in tin isotopes from experiment and HFB + QRPA calculations using the Gogny D1M interaction.

Octupole states in heavy nuclei

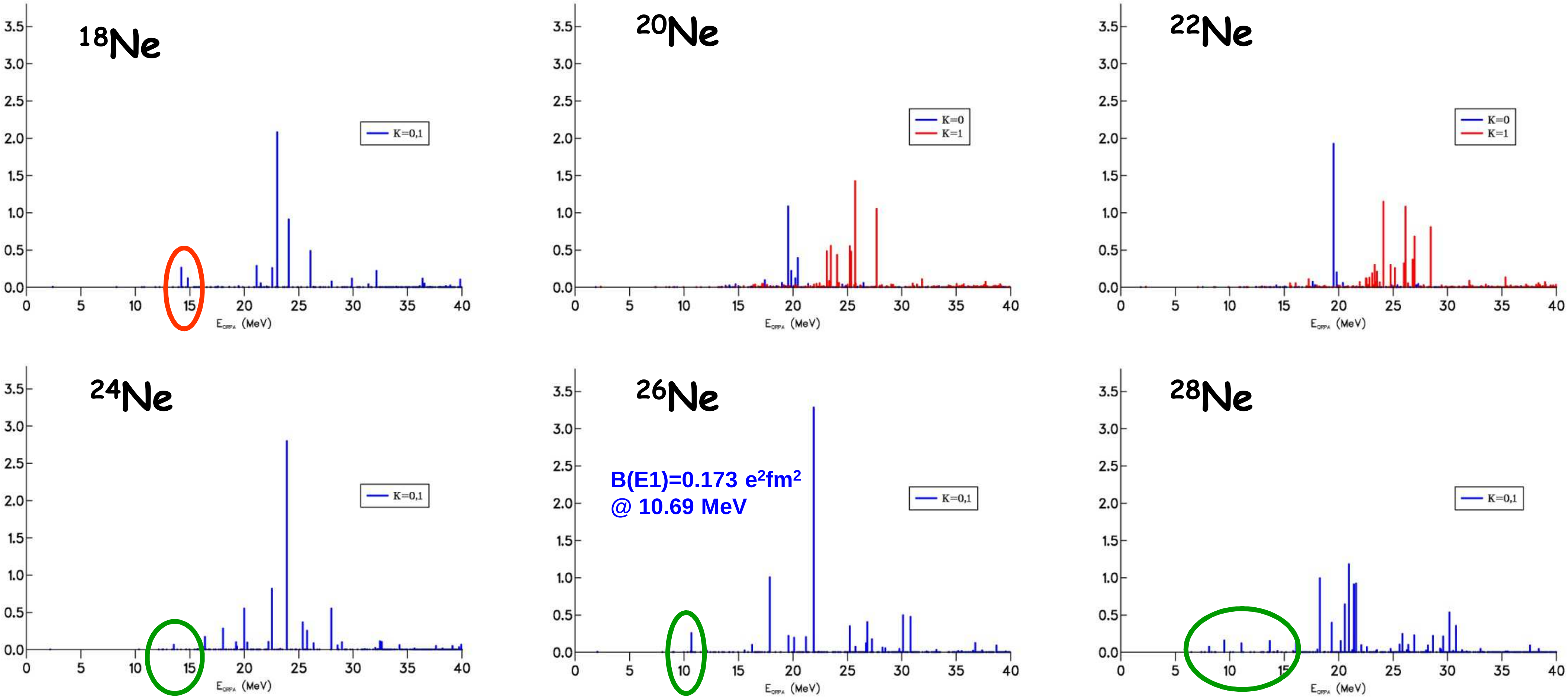


Dipole response for Neon isotopes

Increasing neutron number

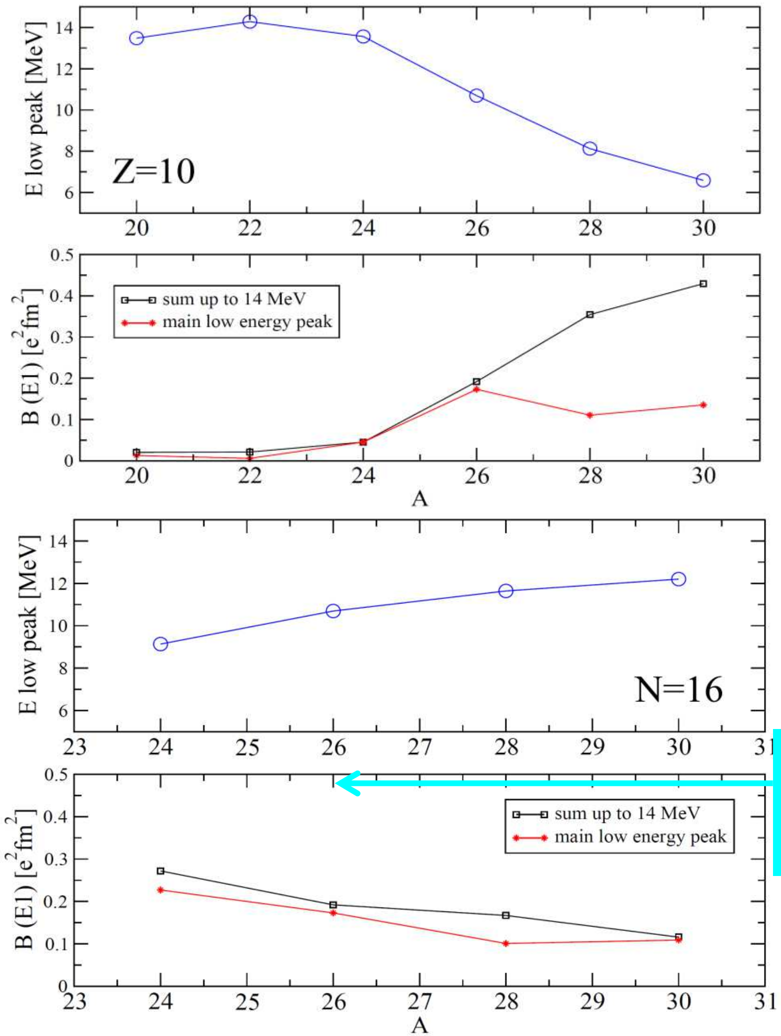
- Low energy dipole resonances and shift to low energies
- Increasing of fragmentation

^{26}Ne : B(E1) = 0.49 ± 0.16 e^2 fm^2 %STRK = 4.9 ± 1.6 @ 9 MeV
J. Gibelin et al, PRL 101, 212503 (2008)

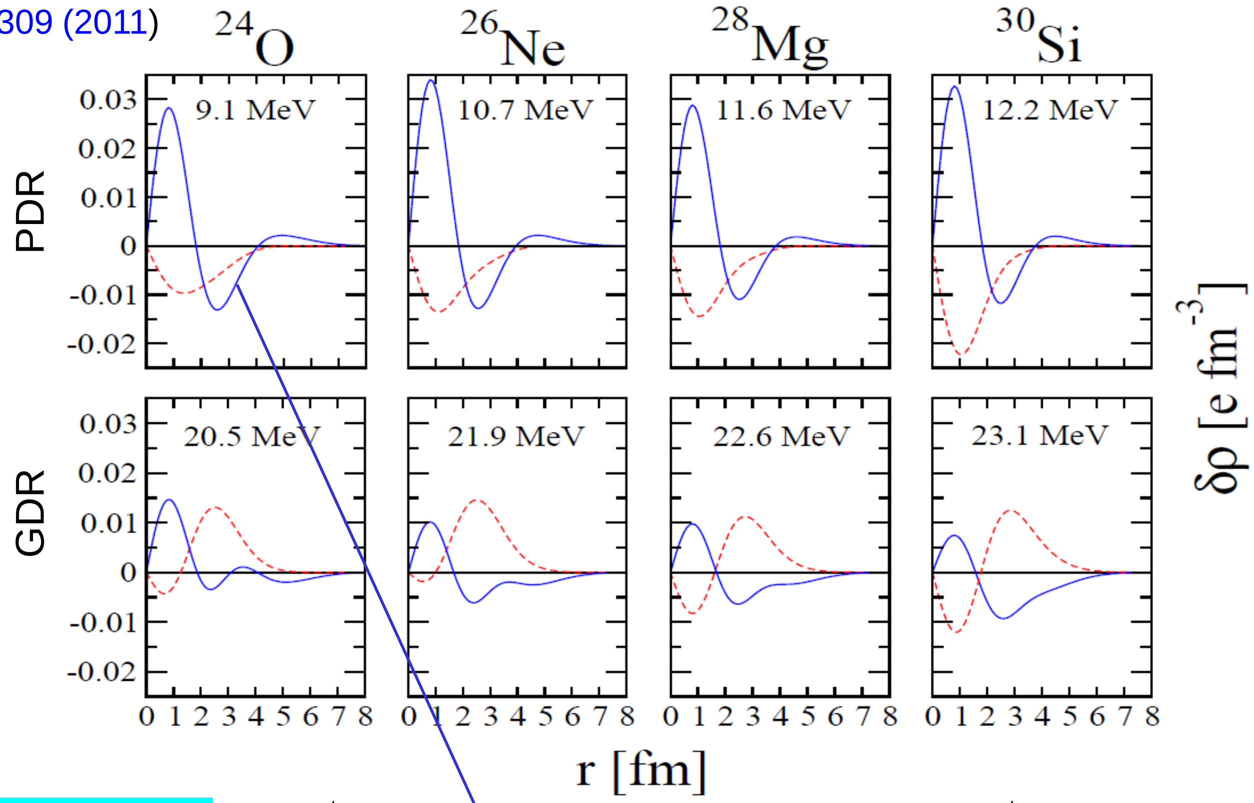


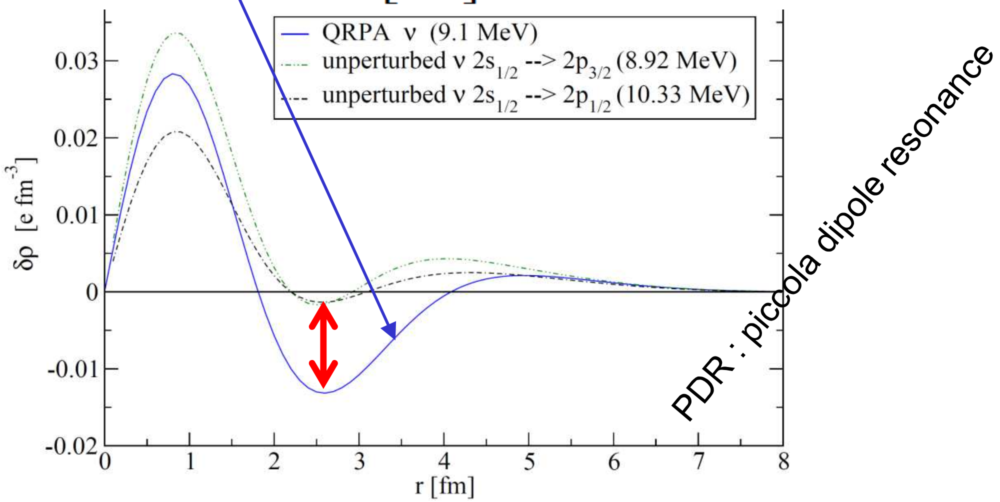
Dipole response for Neon isotopes and N=16 isotones

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



B(E1) = 0.49 ± 0.16 e^2 fm^2
@ 9 MeV
J. Gibelin et al, PRL 101, 212503 (2008)



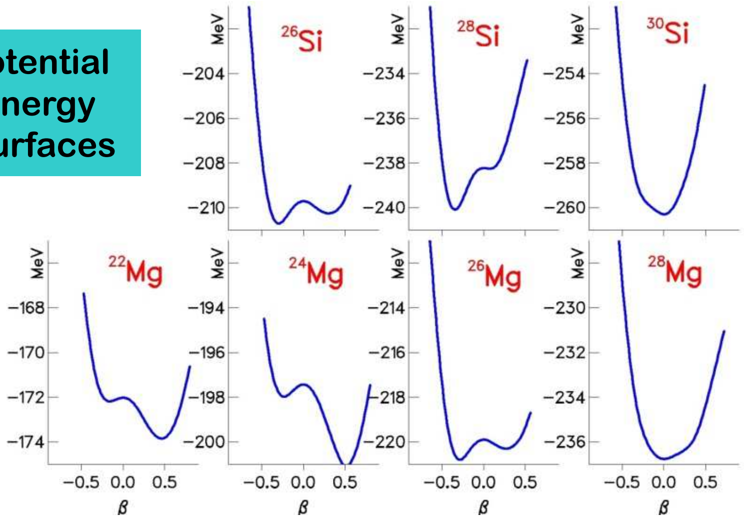


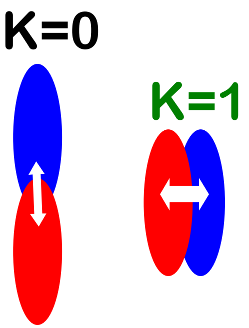
Increasing |N-Z| number :

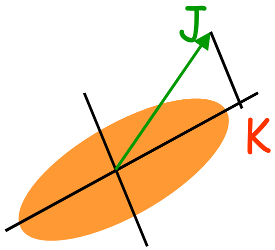
- Low energy dipole resonances shift to low energies
- Increasing of fragmentation and collectivity

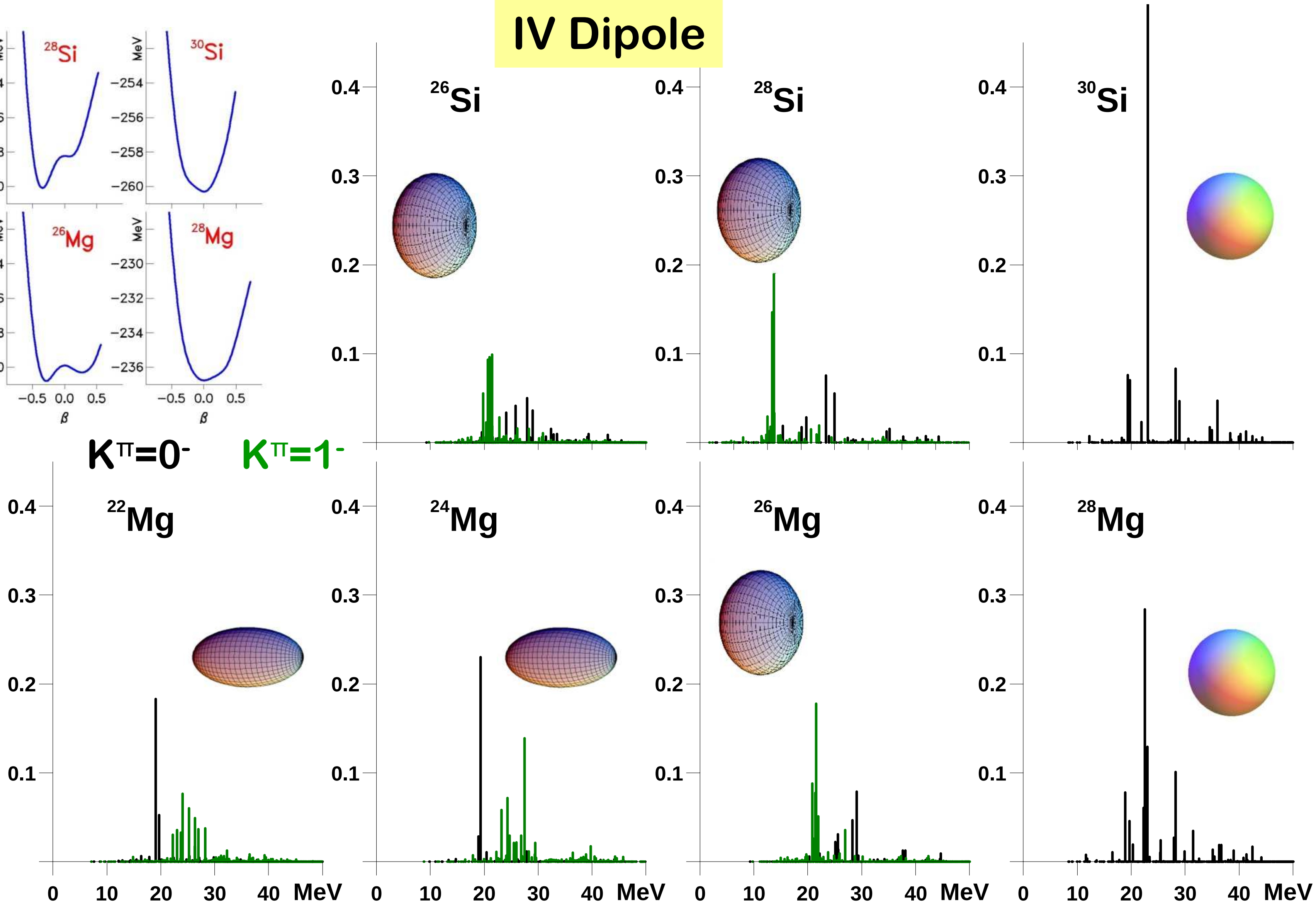
First study with QRPA in axial symmetry

Potential Energy Surfaces



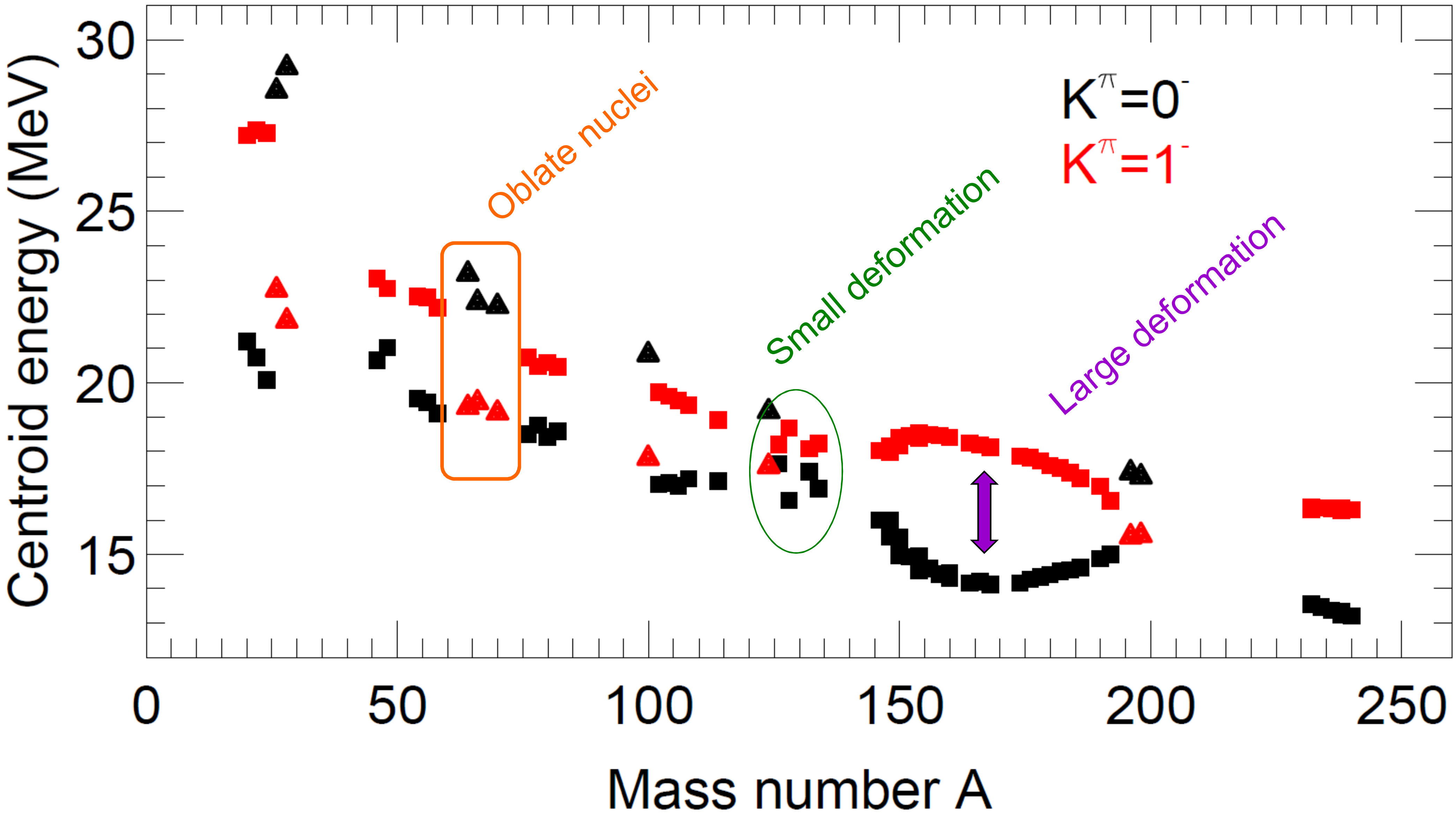






S. Péru and H. Goutte, Phys. Rev. C 77, 044313 (2008).

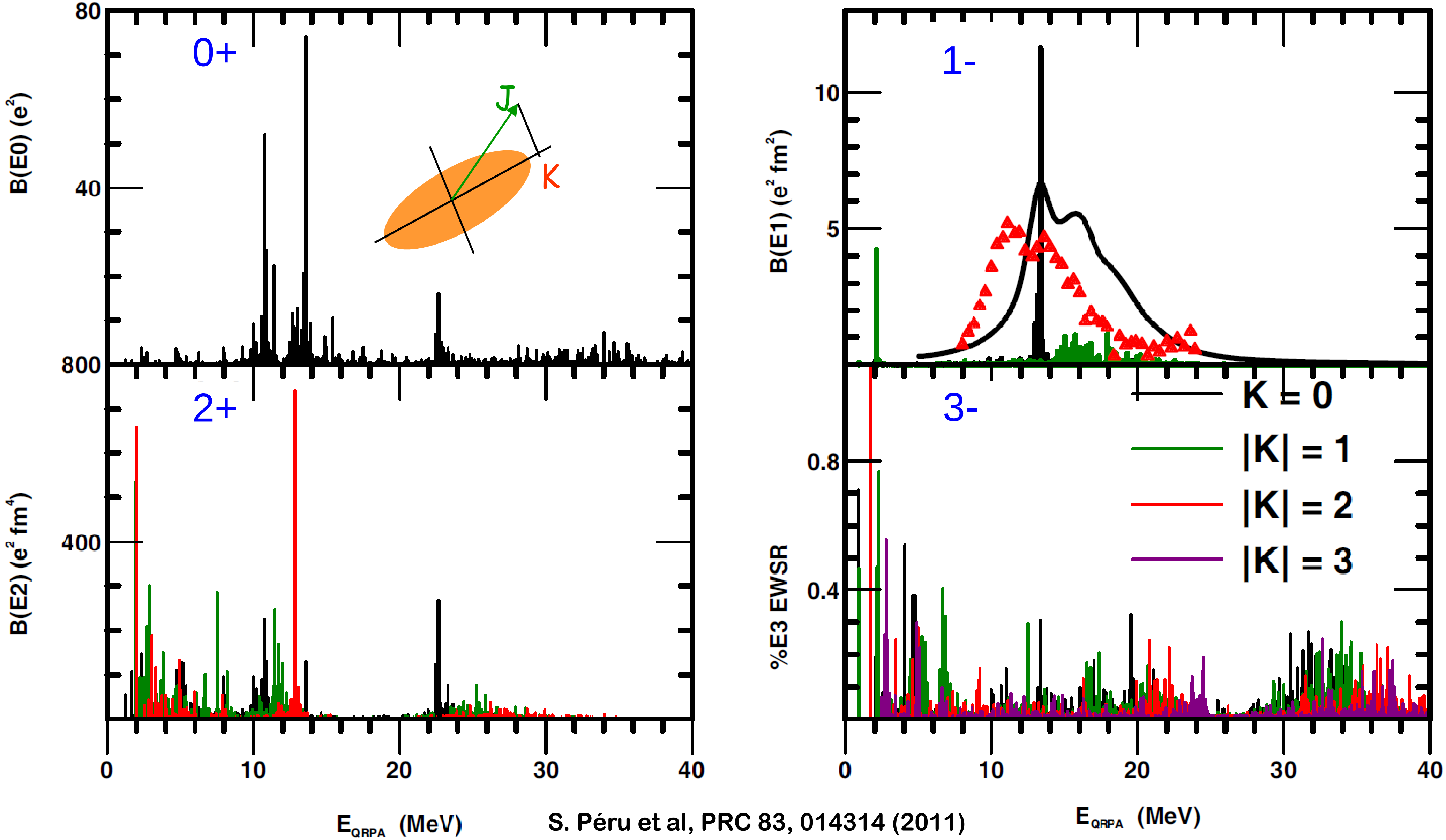
Impact of the deformation on dipole resonances



M. Martini, et al, accepted to PRC

Multipolar responses for ^{238}U

Heavy deformed nucleus → massively parallel computation

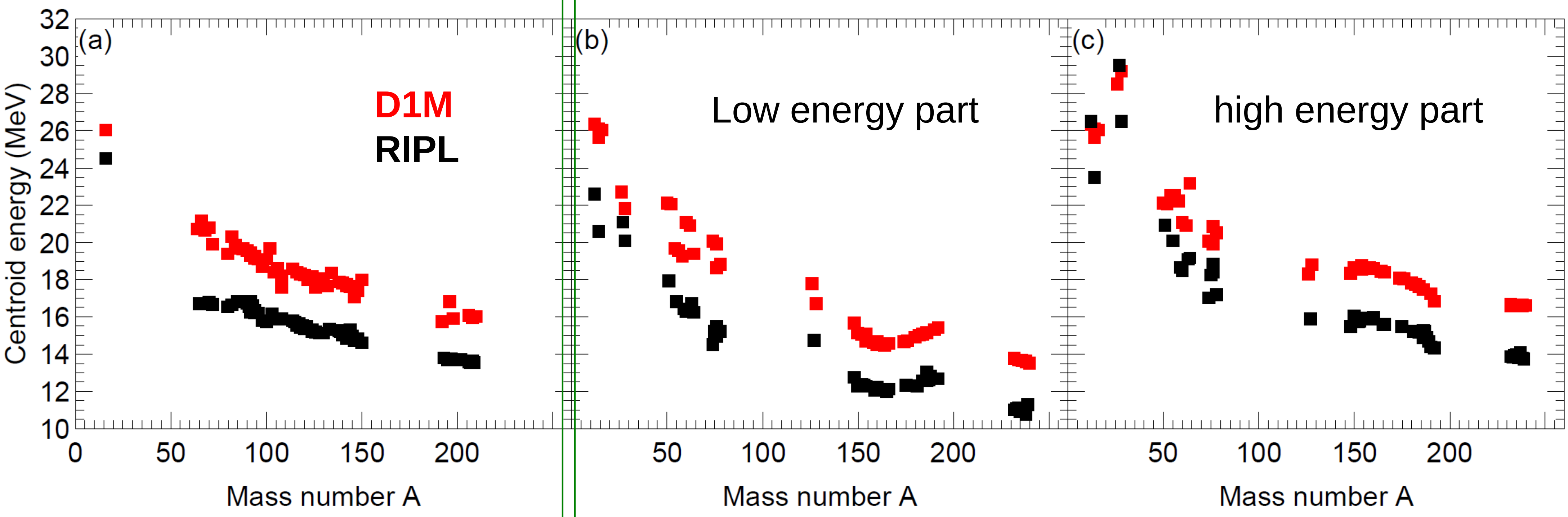


S. Péru et al, PRC 83, 014314 (2011)

Comparison with experimental data

One Lorentzian in RIPL

Two Lorentzians in RIPL



Systematic overestimation of the centroid energies :~ 2MeV

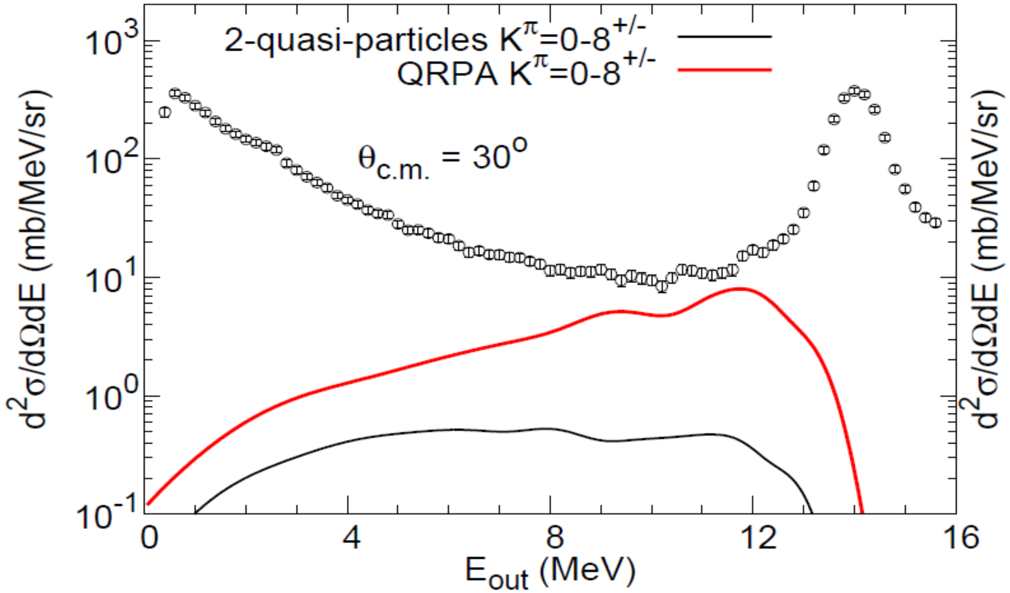
M. Martini, et al, accepted to PRC

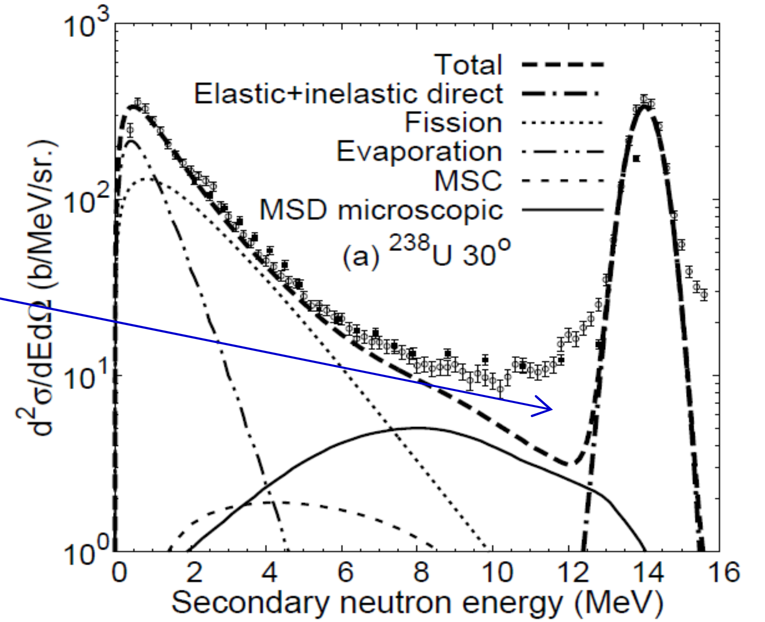
Beyond the nuclear structure

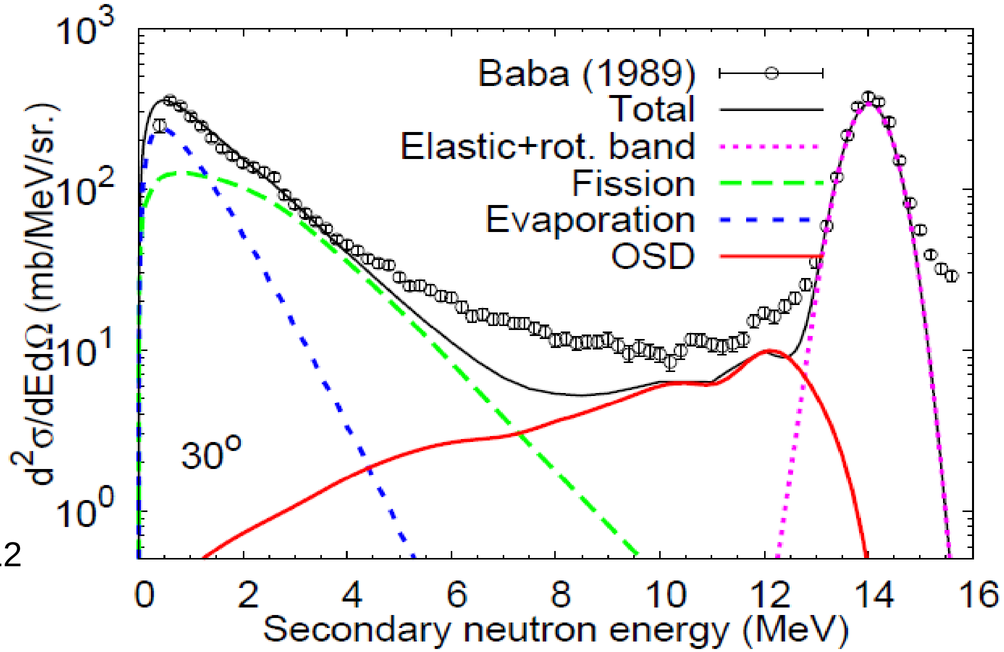
(n, *x* n) cross section on ^{238}U

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

Photoneutron cross sections for Mo isotopes

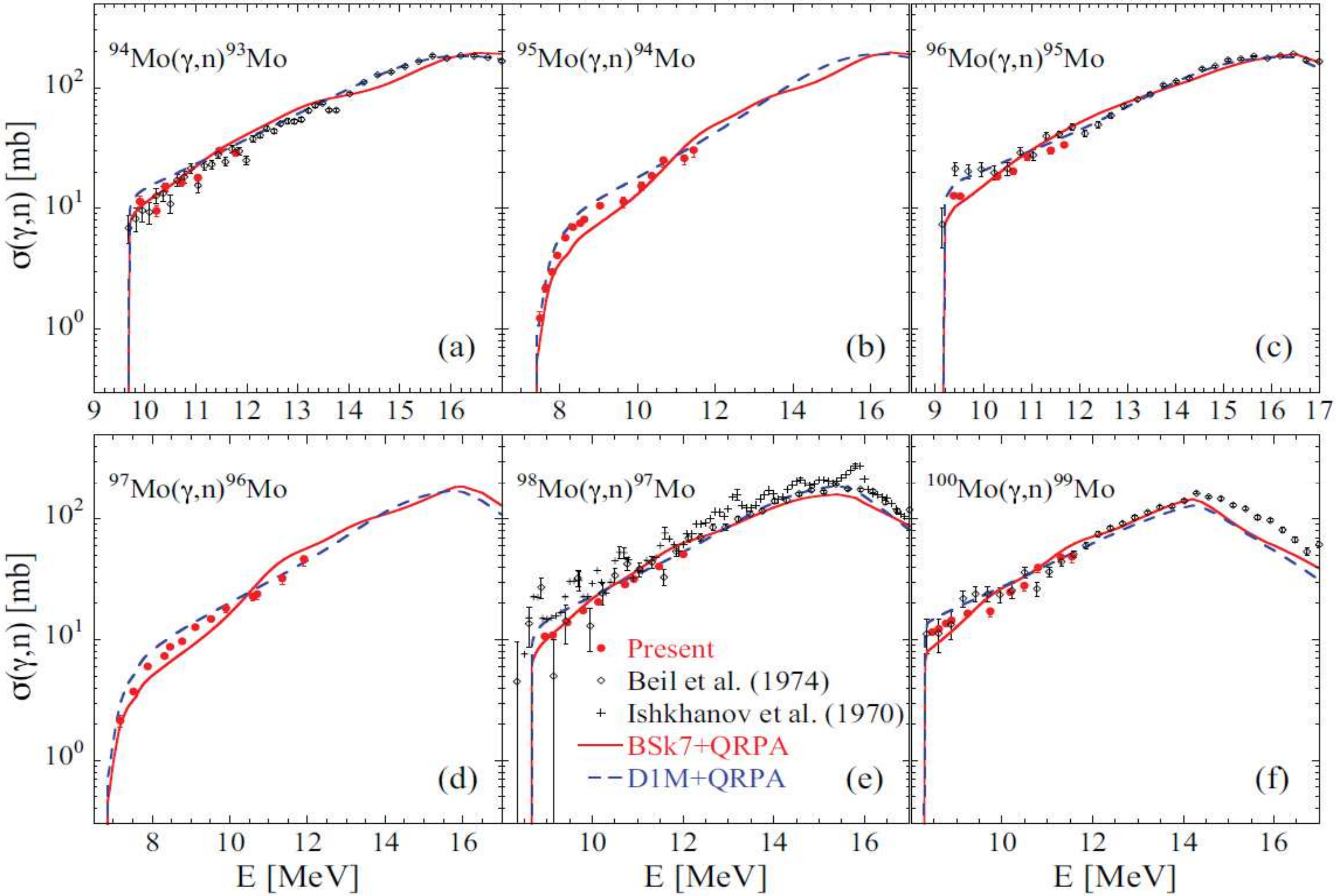
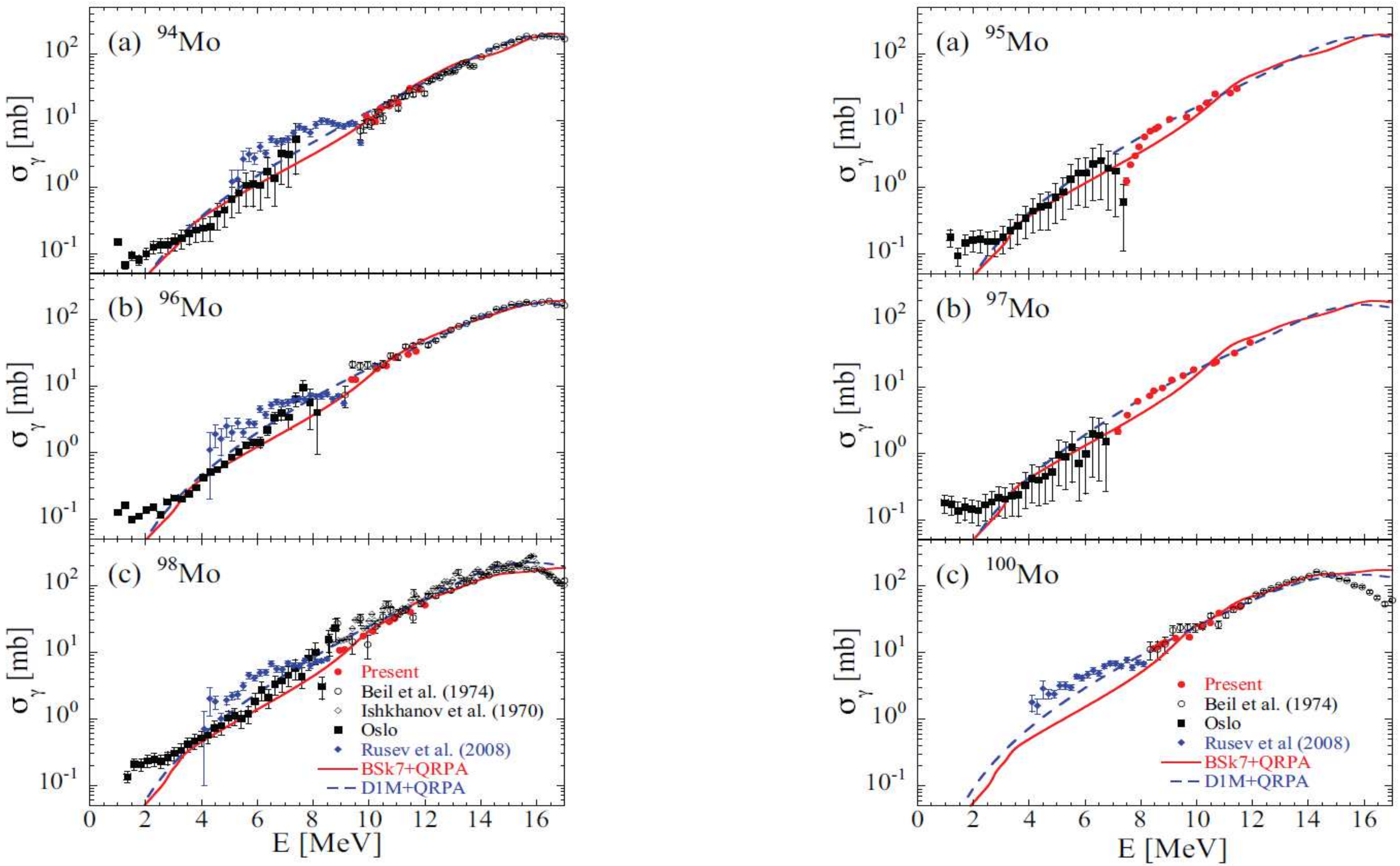


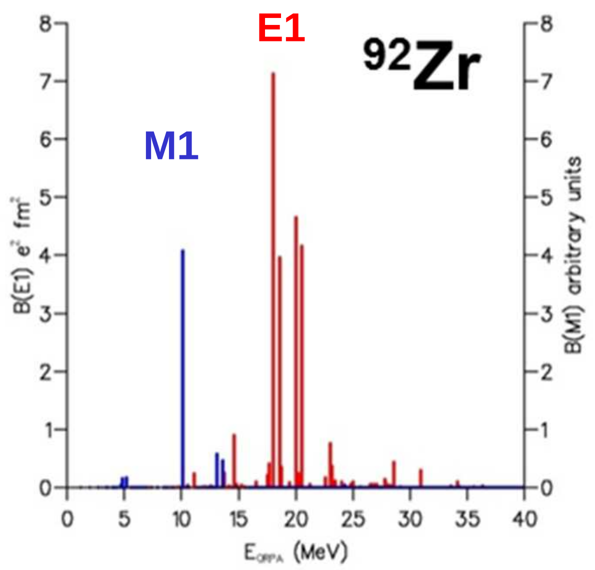
FIG. 3. (Color online) Comparison between the present photoneutron emission cross sections and previously measured ones [17,18] for six Mo isotopes, ^{94}Mo (a), ^{95}Mo (b), ^{96}Mo (c), ^{97}Mo (d), ^{98}Mo (e), and ^{100}Mo (f). Also included are the predictions from Skyrme HFB + QRPA (based on the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

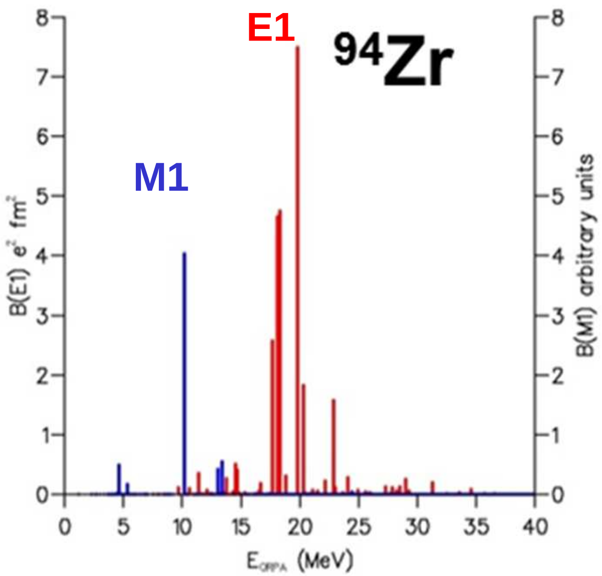
Photo-absorption cross sections for Mo isotopes

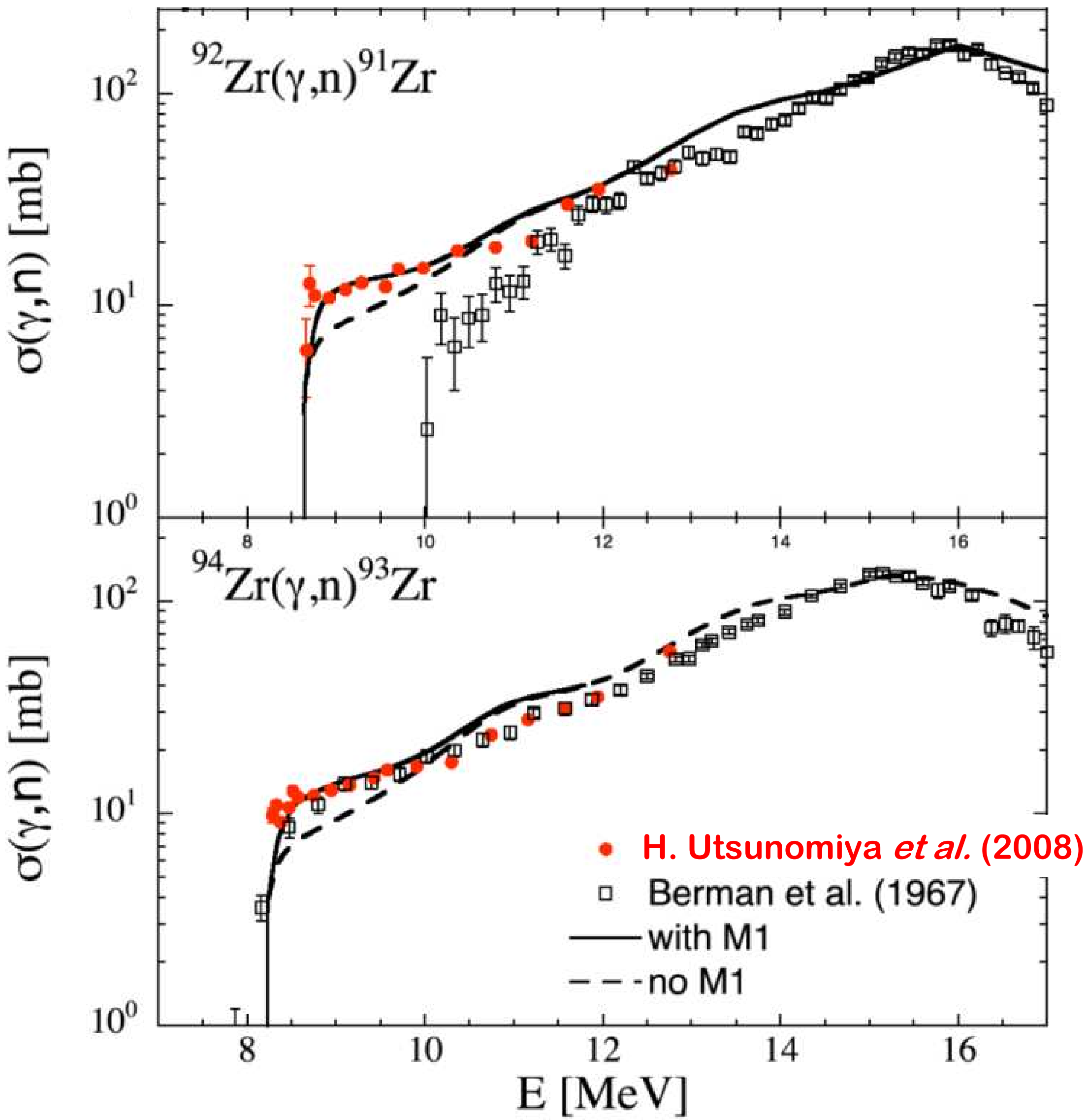
H. UTSUNOMIYA *et al.* PHYSICAL REVIEW C **88**, 015805 (2013)



Dipole electric and magnetic excitations for Zr isotopes

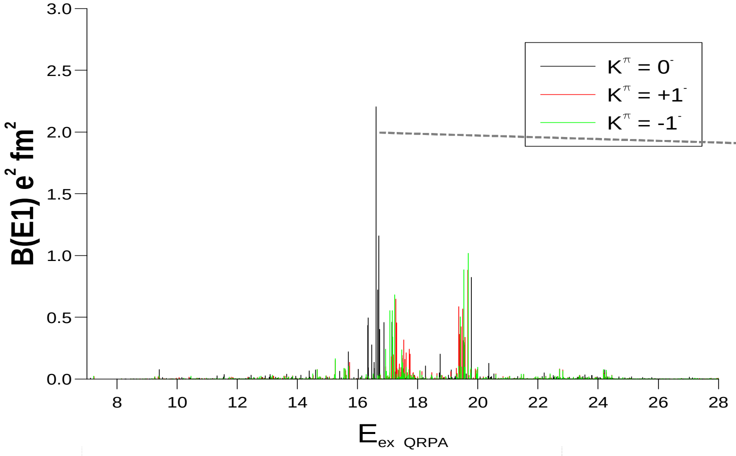


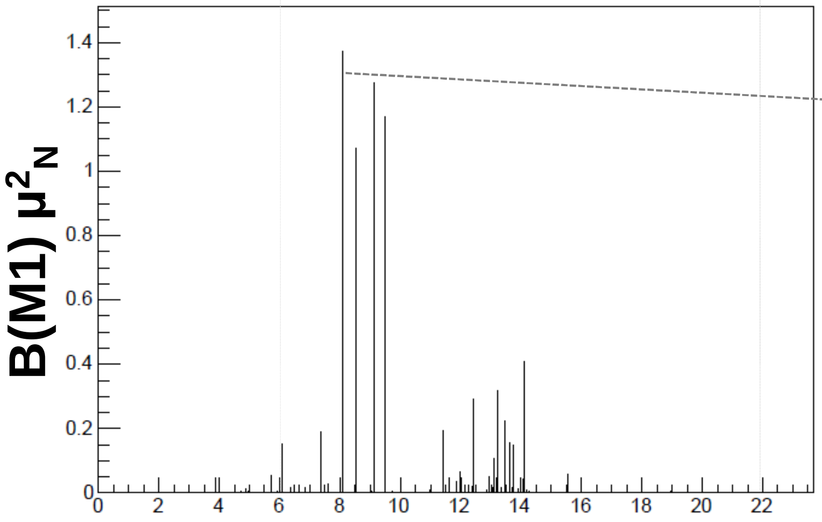


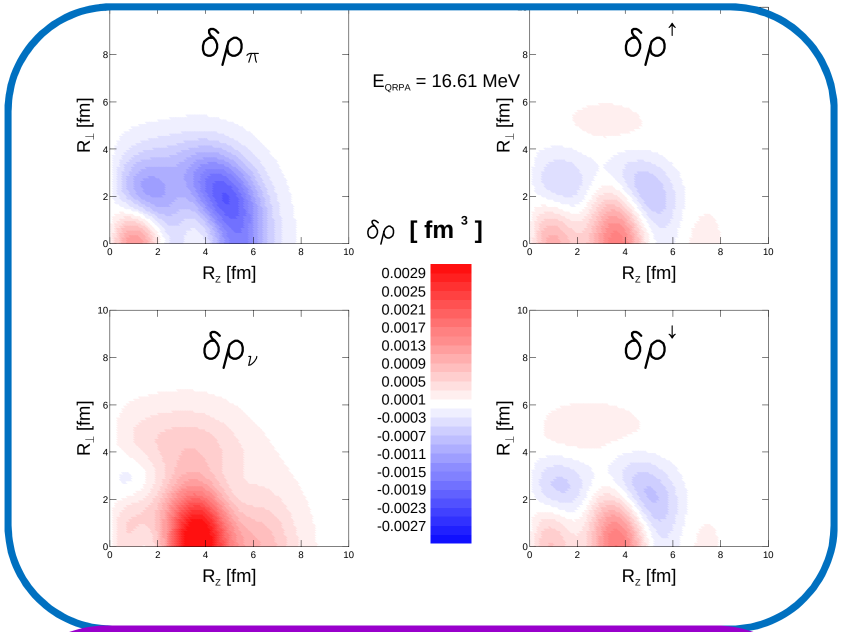


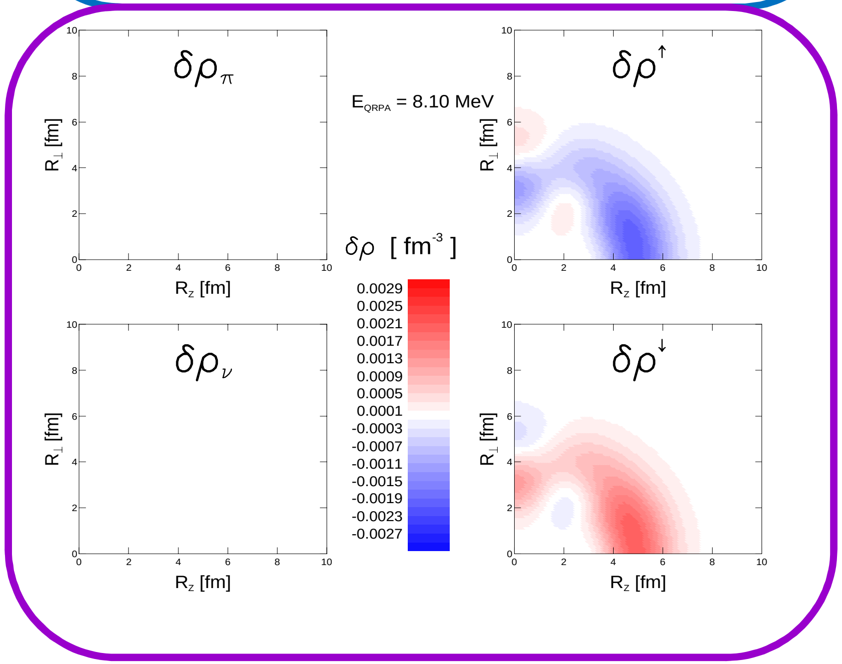
H. Utsunomiya et al, PRL 100, 162502 (2008)

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





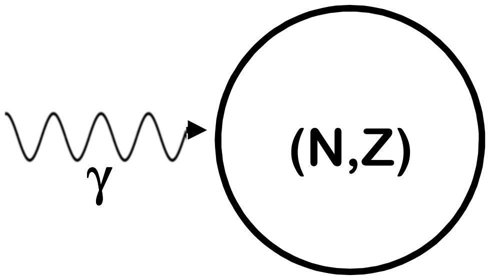




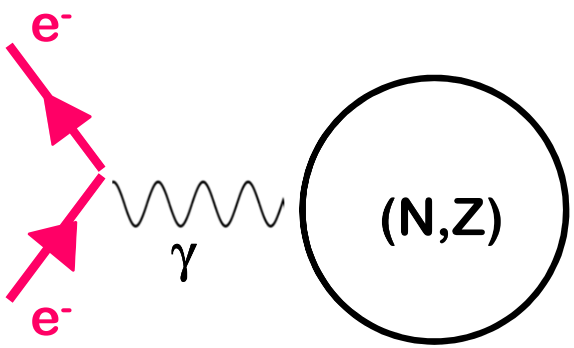
M. Versteegen et al, submitted in PLB

Nuclear Excitations

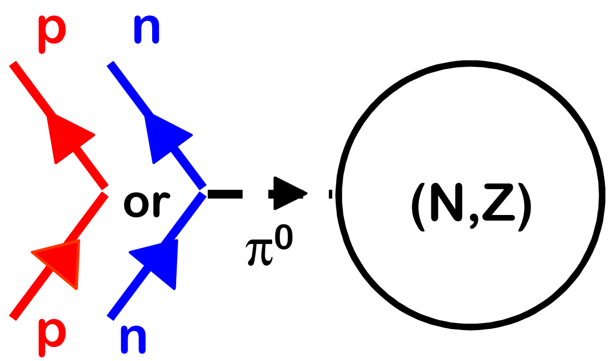
Photo-absorption

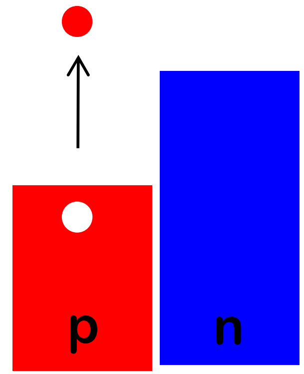


Electron scattering



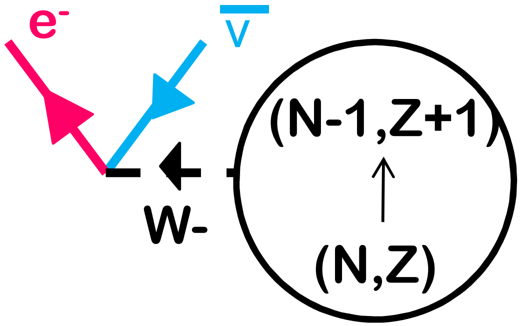
(p,p) or (n,n)



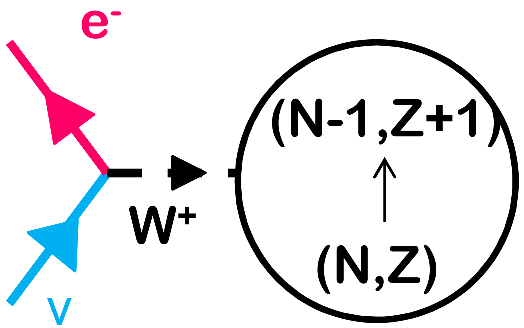


Charge exchange:

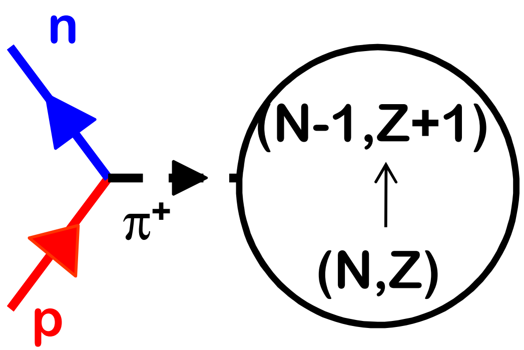
β decay

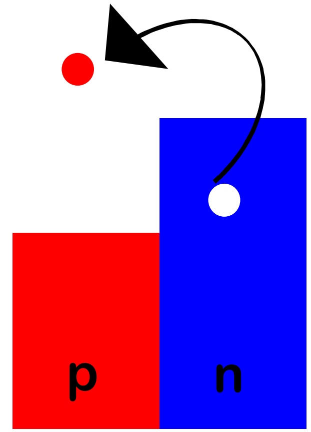


Neutrino scattering



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

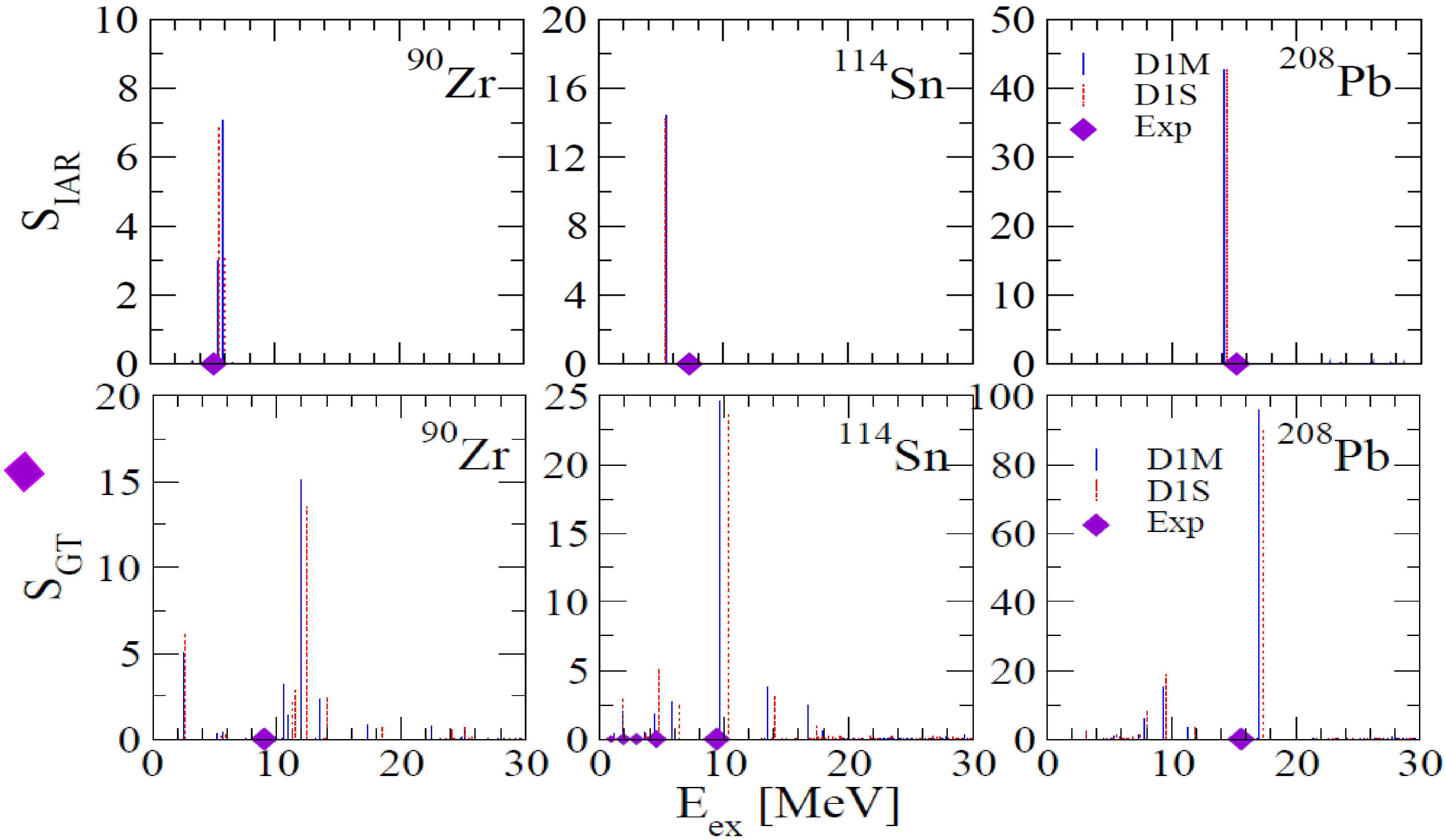




Gogny pnQRPA Strength Distributions

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

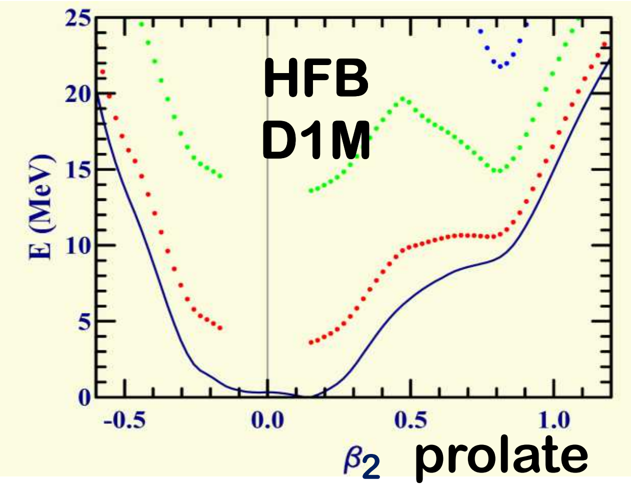
Good agreement with experimental data

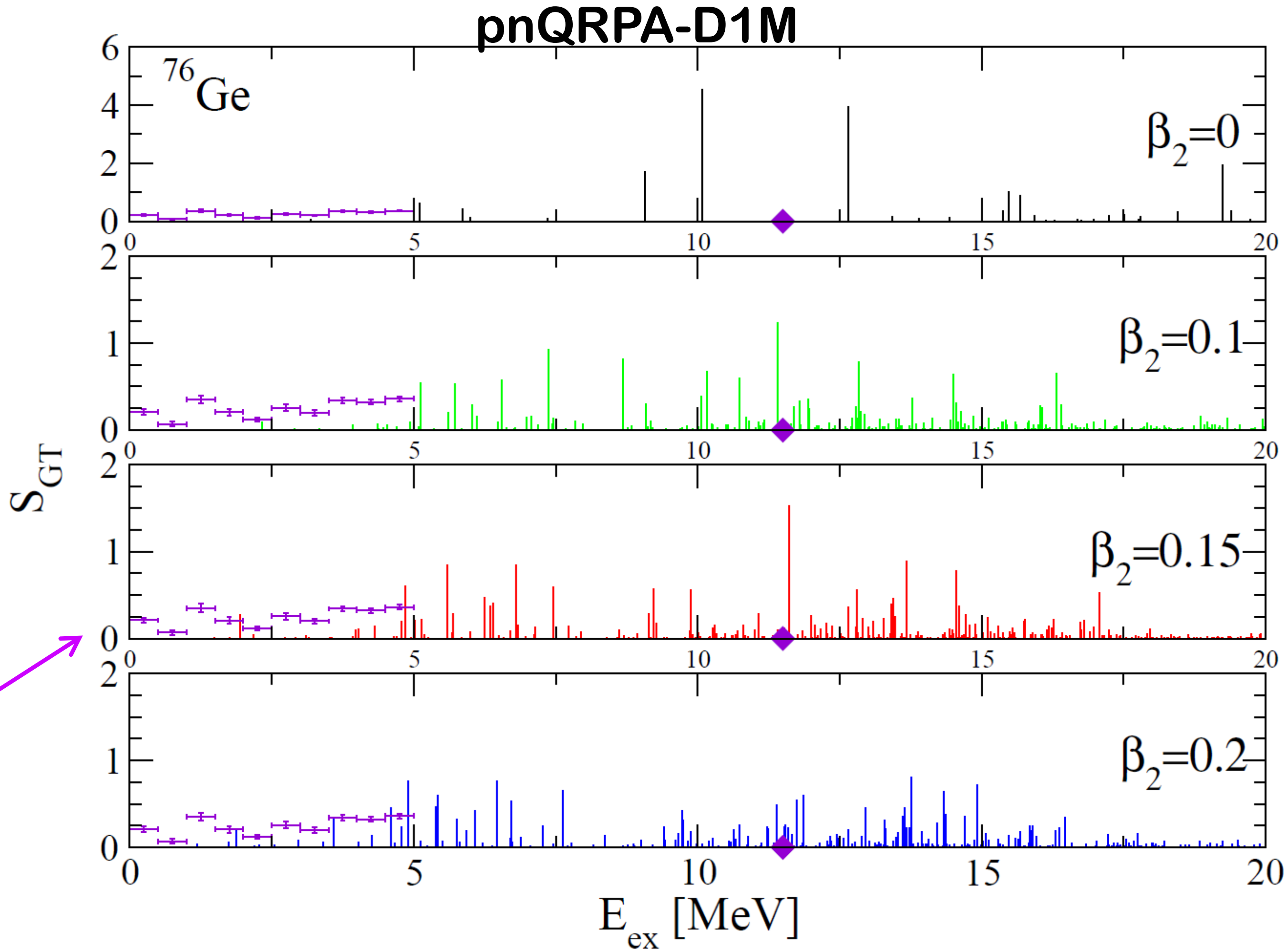


Here, the reference energy corresponds to the lowest 2-qp excitation associated with the ground state of the odd-odd daughter nucleus in which the quantum numbers of the single quasi-proton and neutron states are obtained from the self-consistent HFB calculation of the odd-odd system.

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





β_2(min. HFB) = 0.15 γ(min.HFB) = 0°

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

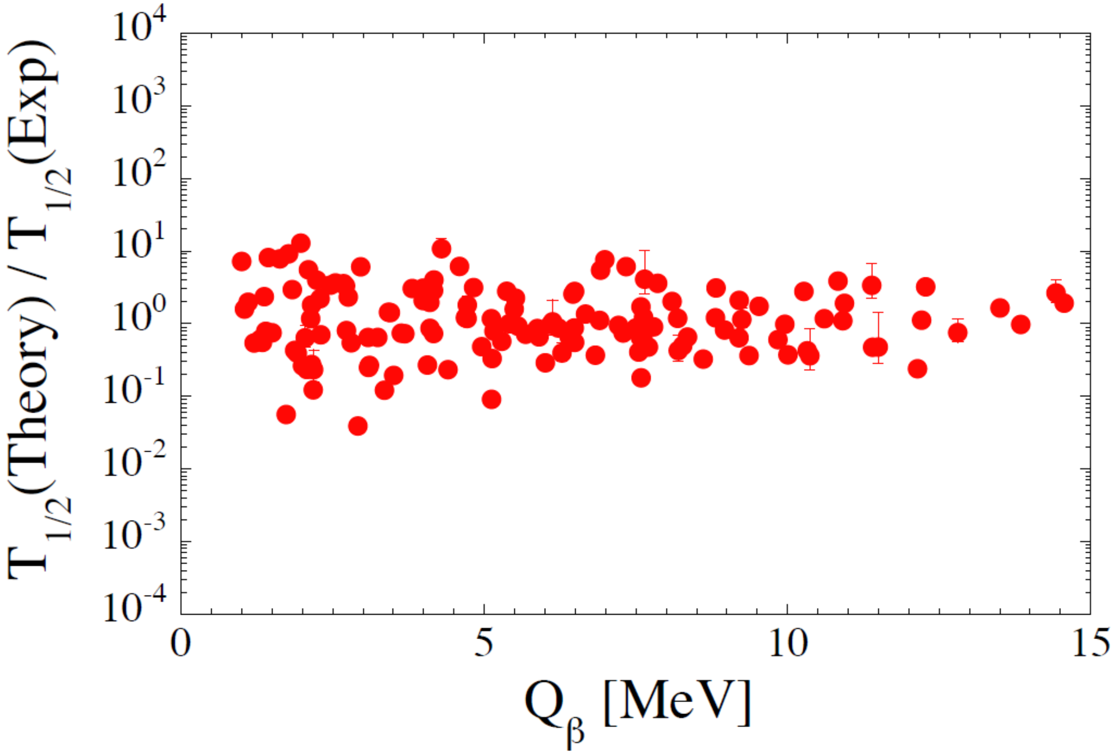
Experiment
Thies et al., Phys. Rev. C 86, 014304 (2012)

- 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

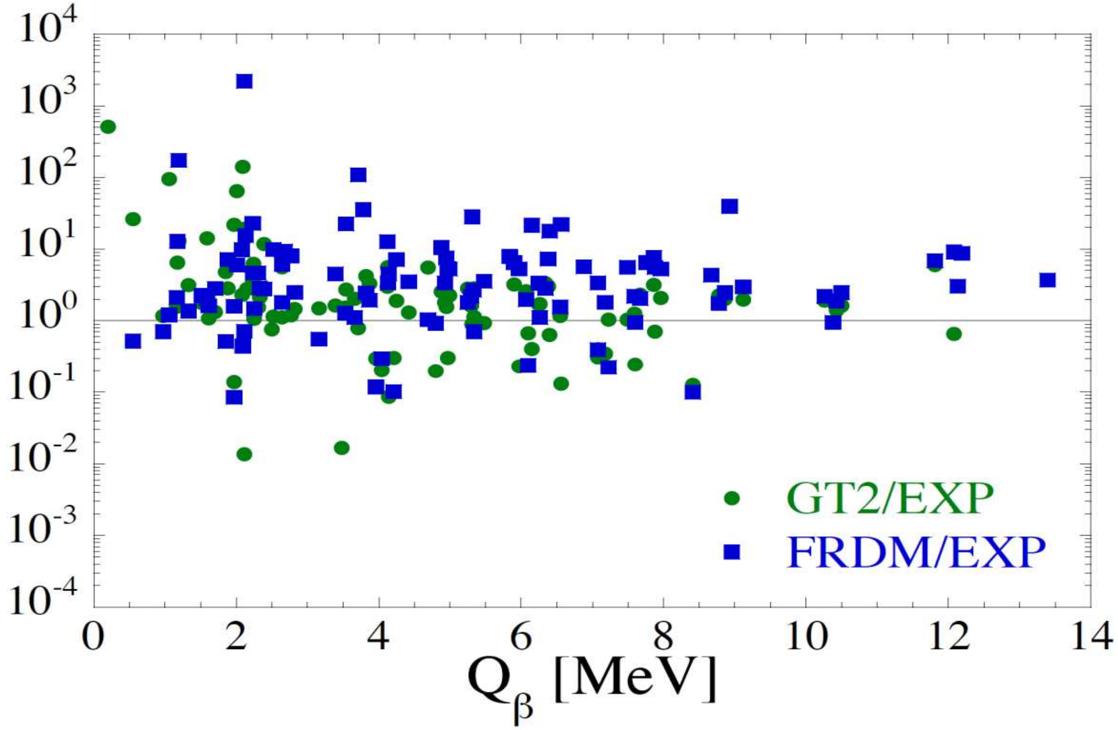
β^- decay half-life $T_{1/2}$: Comparison with other models

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

Our model



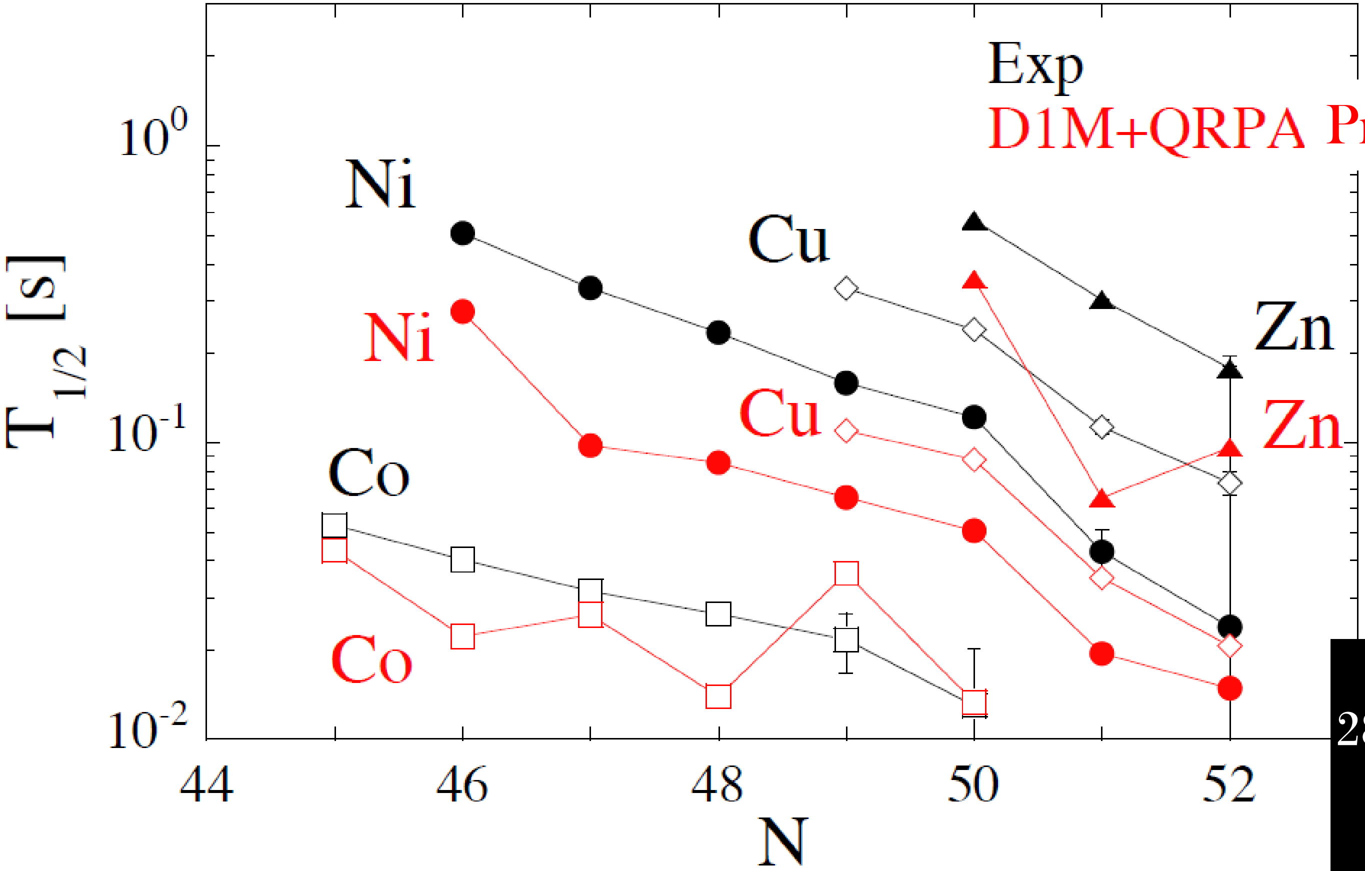
Other models



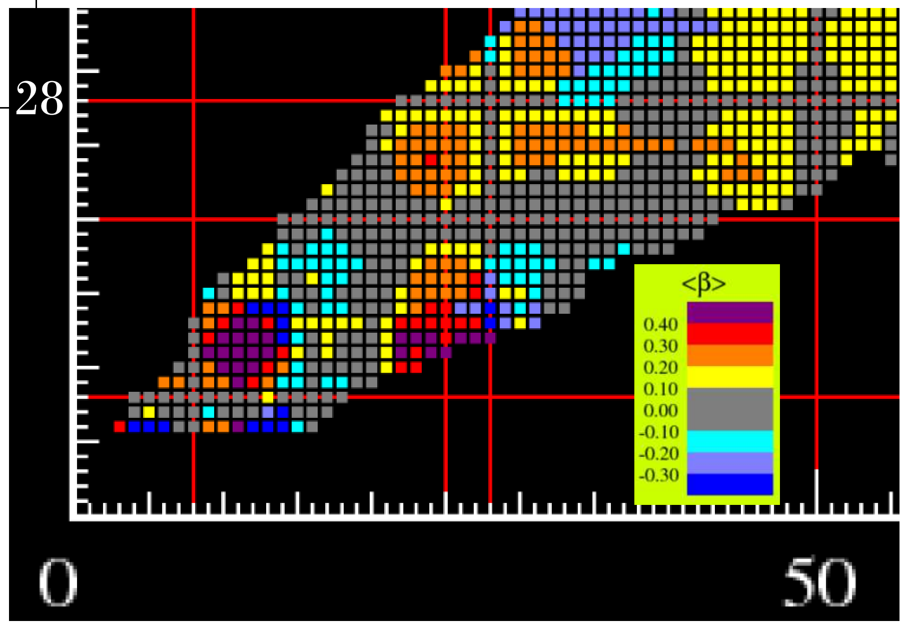
FRDM: Moller et al., ADNDT, 66,131 (1997)

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

Even and odd systems, deformed and spherical nuclei



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}Co, ^{79,80}Ni and ^{81}Cu :

Experimental indication of a Doubly Magic ^{78}Ni

To summarize

Beyond static mean field with the Gogny finite range force:

- 5DCH: good reproduction of collective low energy spectra and shell effects; QRPA : good description of pygmy and giant resonances in spherical or deformed nuclei
- QRPA and 5DCH complete each other.
- Self-consistent QRPA approach has been 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 :

- For magic spherical nuclei, IAR and GT results in good agreement with data.
- 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.