Shape coexistence at the neutron rich edge; The cases of N=20, 28 and 40.

ALFREDO POVES

Departamento de Física Teórica and IFT, UAM-CSIC, Madrid (Spain)

EURORIB'12, Abano Terme, May 21-25 2012

OUTLINE

- Spherical mean field and correlations
- The physics of very neutron rich nuclei at N=20 and N=28
- The new island of deformation south of ^{68}Ni

Monopole Anomalies and Multipole Universality

- The different facets of the nuclear dynamics depend on the balance of the two main components of the nuclear hamiltonian; the Monopole which produces the effective spherical mean field and the Multipole responsible for the correlations
- Large scale shell model calculations have unveiled the monopole anomalies of the two-body realistic interactions, *i*.*e* that they tend to produce effective single particle energies which are not compatible with the experimental data and which, if used without modifications, produce spectroscopic catastrophes
- The Multipole Hamiltonian of the realistic two body interactions (dominated by L=0 pairings, quadrupole and octupole) does not seem to require any modification and it is ”universal” in the sense that all the effective interactions produce equivalent multipole hamiltonians

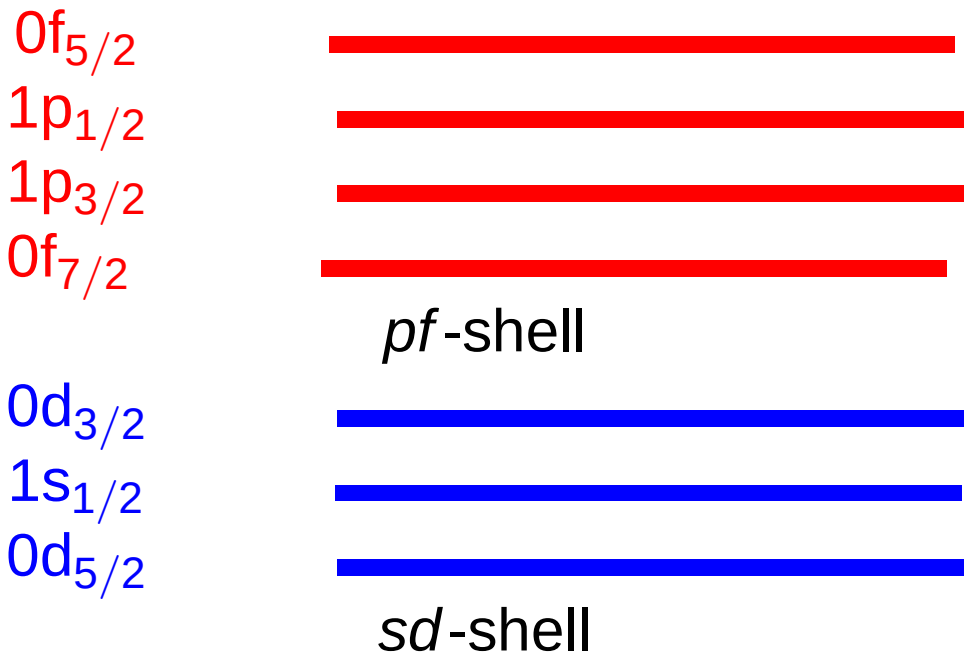
The Fate of the Magic Closures

- Magic numbers are associated to energy gaps in the spherical mean field. Therefore, to promote particles above the Fermi level costs energy.
- However, some intruder configurations can overwhelm their loss of monopole energy with their huge gain in correlation energy.
- Several examples of this phenomenon exist in stable magic nuclei in the form of coexisting spherical, deformed and superdeformed states in a very narrow energy range, Nuclear Allotropy? In the case of ^{40}Ca they have been described in the spherical shell model framework
- At the very neutron rich edge, around N=8, 20, 28 and 40, the intruder configurations, usually deformed, become the ground states, giving rise to the so called ”islands of inversion”.

Spherical Mean Field and Correlations

Let’s go through a fully worked-out example of the competition between spherical mean field and correlations; the physics at the N=20 ”island of inversion” described in the *sd*-*pf* valence space encompassing from the Oxygen to the Calcium isotopes.

Valence Space; *sd*-*pf*

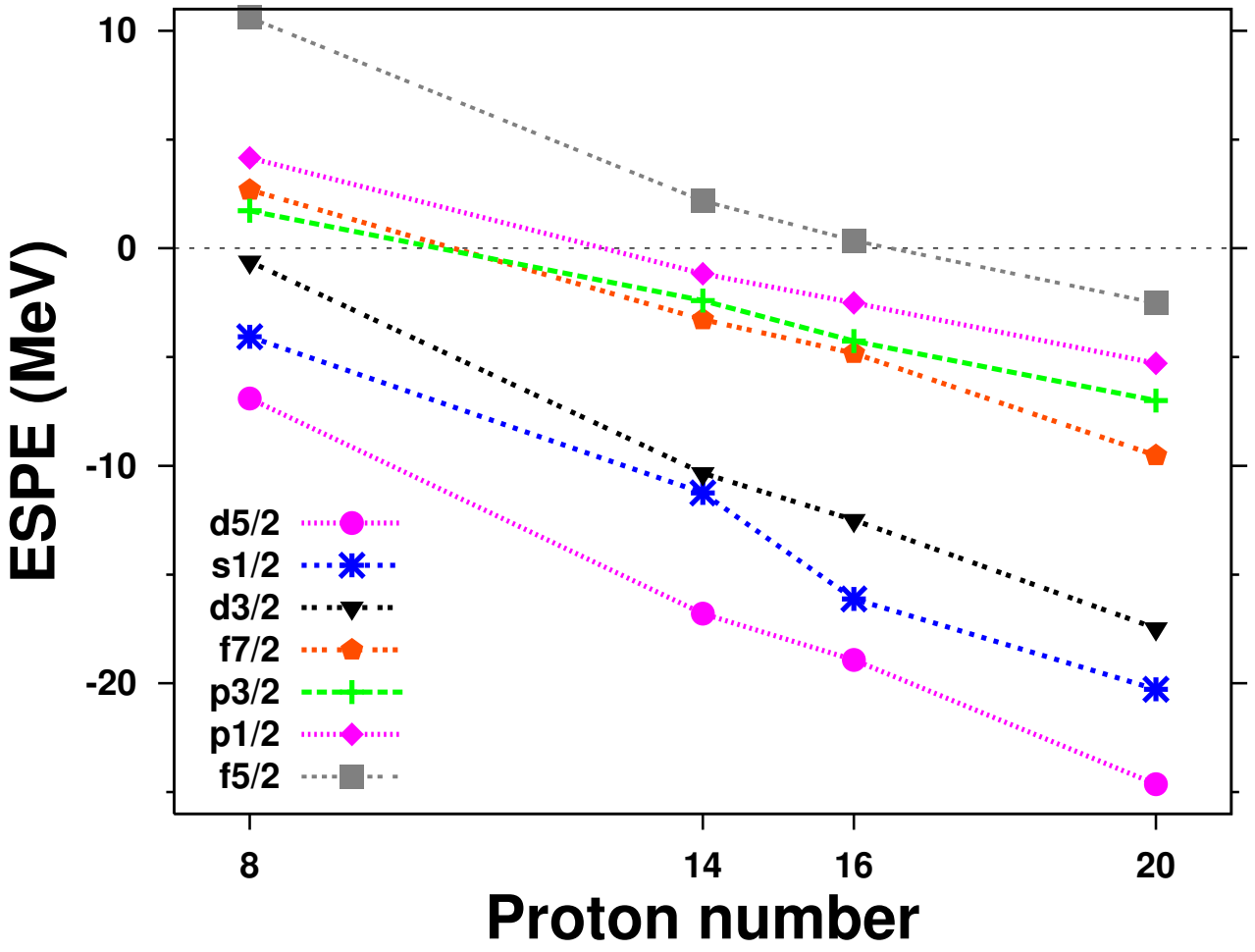


EFFECTIVE INTERACTION SDPF-U-MIX

Effective Single Particle Energies

- The effective single particle energies are the eigenvalues of the Monopole Hamiltonian
- Or, equivalently, the spherical Hartree-Fock single particle energies in the uniform filling approximation

Neutron Effective Single Particle Energies: N=20 (phenomenological)

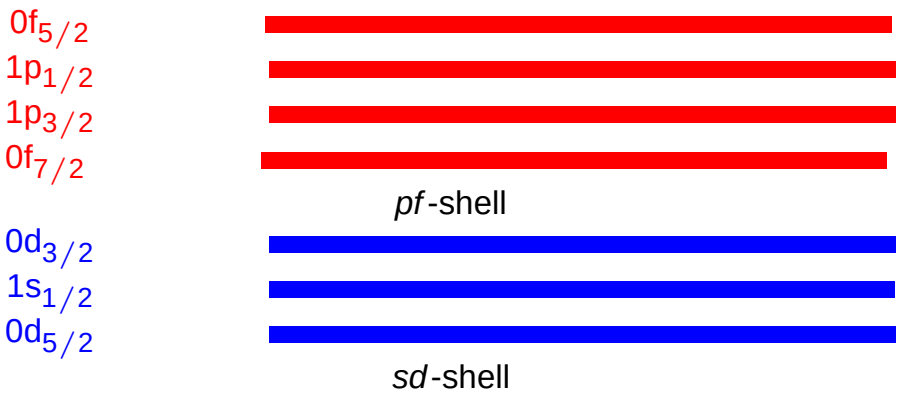


Effective Single Particle Energies: Trends

- At the neutron drip line, Z=8, the ESPE's of ^{28}O are completely at variance with those of ^{40}Ca at the stability valley. The change from the standard ESPE's of ^{17}O to the anomalous ones in ^{28}O is totally due to the interactions of the *sd* shell neutrons among themselves.
- Notice that the *sd*-shell orbits remain always below the *pf*-shell, while the $\nu f_{7/2}$ and $\nu p_{3/2}$ orbitals do get inverted
- The monopole part of the neutron-proton interaction restores the N=20 shell gap when the valley of stability is approached

When do the quadrupole correlations thrive?

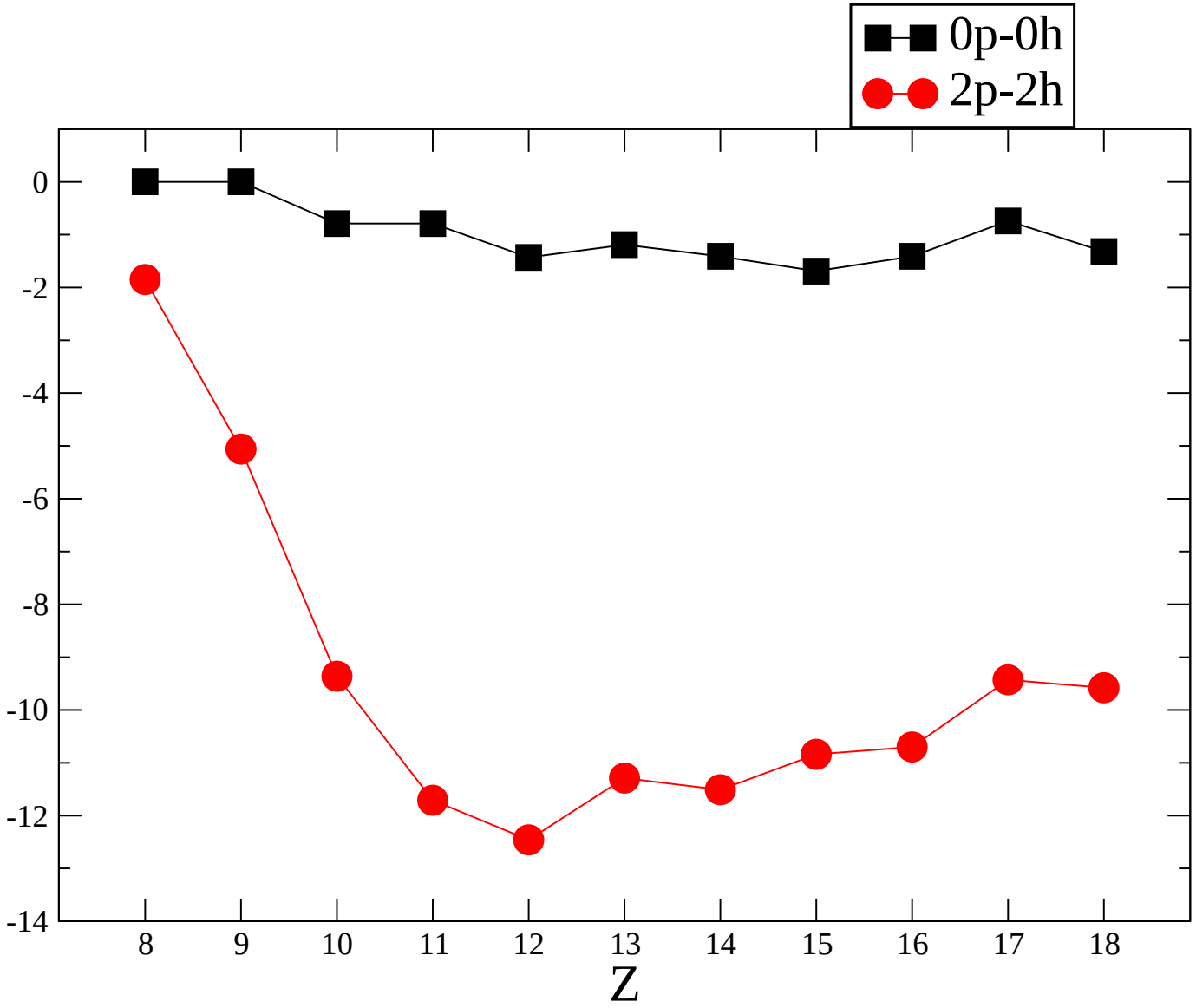
- When, both valence neutrons and protons, occupy quasi-degenerate orbits with $j_r - j_s$=2 and $l_r - l_s$=2, (Quasi-SU3), or quasi-spin doublets (Pseudo-SU3)
- For example, $0f_{7/2}$ and $1p_{3/2}$, or $0d_{5/2}$ and $1s_{1/2}$ form Q-SU3 doublets and $0d_{3/2}$ and $1s_{1/2}$ a P-SU3 doublet
- In the limit of vanishing spin-orbit splitting, all the orbits in a harmonic oscillator shell, form an SU3 multiplet.



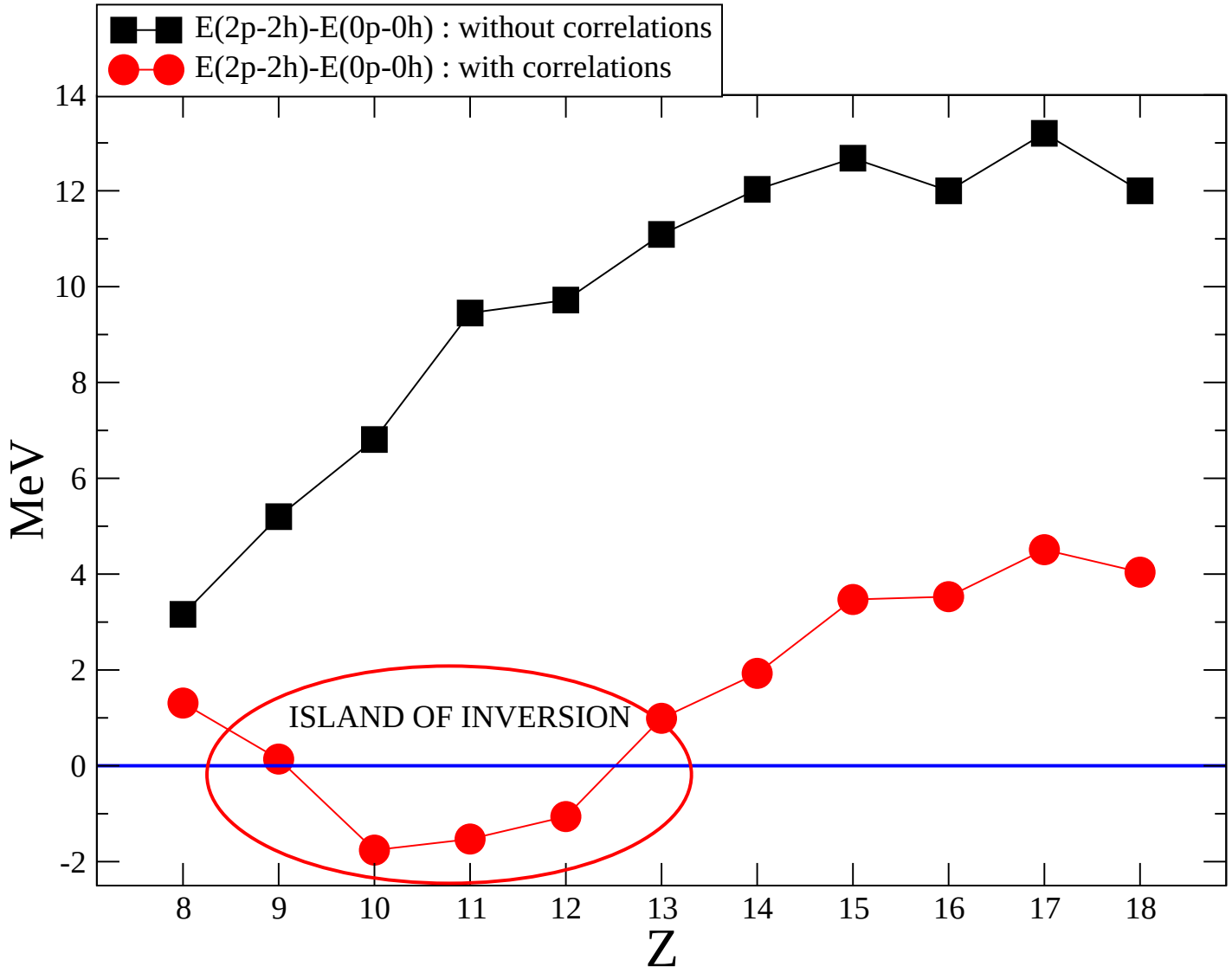
Correlation Energies

- Let's consider the configurations with closed N=20 ; $(sp)^{(8,8)}$ $(sd)^{(12,Z-8)}$ (normal filling) and the ones with two neutrons blocked in the pf-shell $(sp)^{(8,8)}$ $(sd)^{(10,Z-8)}$ $(pf)^{(2,0)}$ (intruder)
- And calculate the energy of the ground states at fixed configuration, with and without correlations

Correlation energies: normal vs. 2p-2h intruder



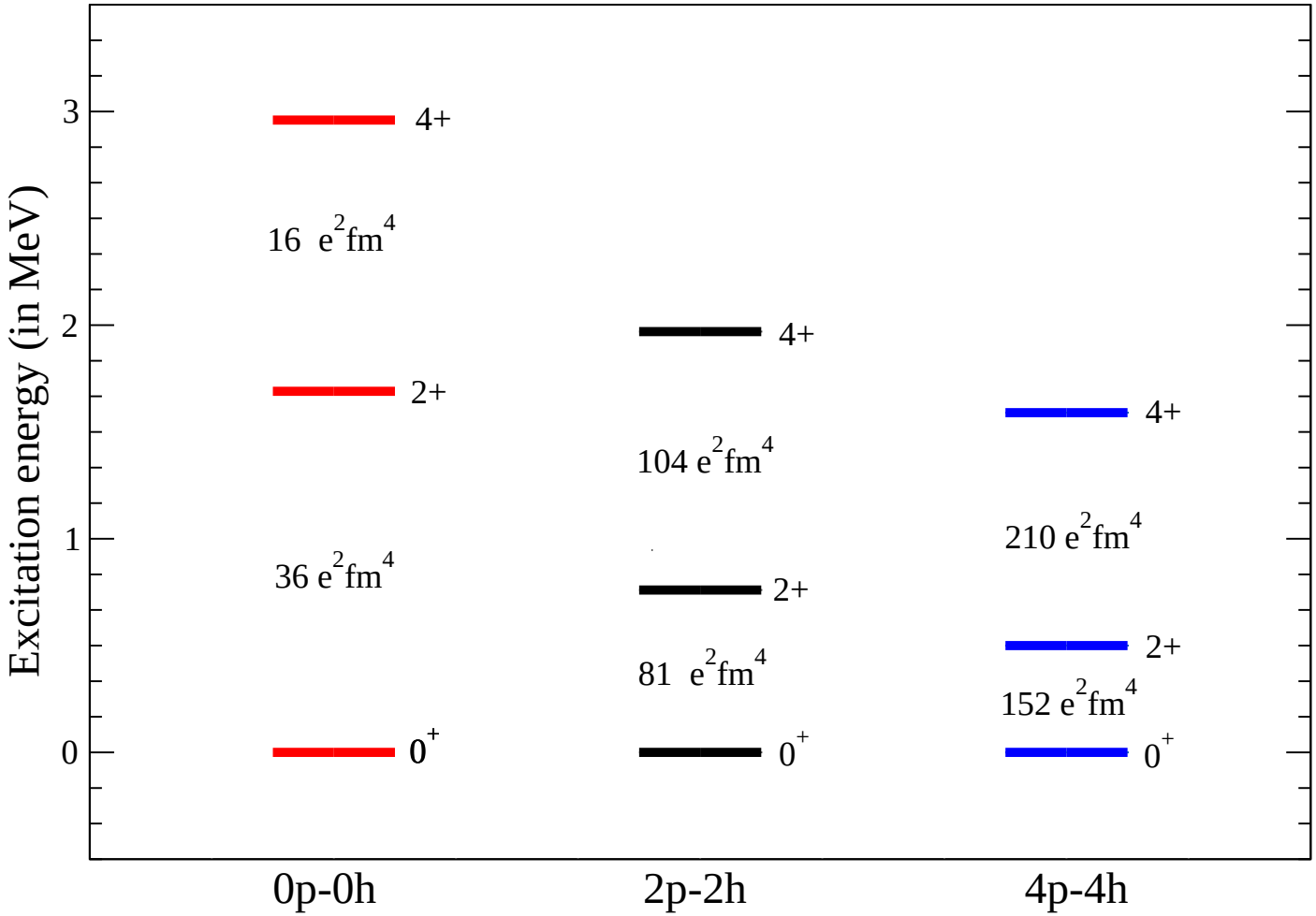
GAPS: normal vs. 2p2h intruder



ESPE's vs. Correlation Energies

- It is evident that the occurrence of the "islands of inversion" depends of subtle cancellations between monopole losses and correlations gains by the intruder states
- Notice that the correlation energies can be huge. For instance, in ^{32}Mg, the correlation energy of the lowest 0^+ state in the 0p-0h, 2p-2h and 4p-4h configurations is respectively, 1.5 MeV (spherical), 12.5 MeV (deformed) and 21 MeV !! (superdeformed)

Spherical, Deformed and Superdeformed states in ^{32}Mg



The superdeformed 4p-4h state in ^{32}Mg

- The 4p-4h state of of ^{32}Mg has an academic interest in itself even if the states belonging to its rotational band do not manifest themselves openly in the low energy spectrum, (as do their cousins in the superdeformed bands of ^{36}Ar and ^{40}Ca) because of its strong mixing with the 0p-0h and 2p-2h spherical and deformed states. They could become yrast at some higher spin, but, the experiments to find them are probably hopeless.

The superdeformed 4p-4h state in ^{32}Mg

- In fact one can understand why this configuration can produce such superdeformed structure in the context of SU3 and it variants. Let's assume that the four pf-shell neutrons be in Quasi-SU3 and the four neutron holes in sd in Pseudo-SU3, then the neutrons will contribute with $23b^2$ (x effective charge) to the intrinsic quadrupole moment. If we go to the SU3 limit in the pf-shell sector this number increases to $25b^2$. The value from the shell model calculation is $24.7b^2$. For the protons, the SU3 limit gives $13b^2$ against $9.7b^2$ (x effective charge) of the shell model calculation.
- This is in my opinion a result of a great intellectual beauty and Elliott deserves the credit for it. With effective charges 0.35/1.35 these values lead to β=0.6/0.7 depending of the definition of β.

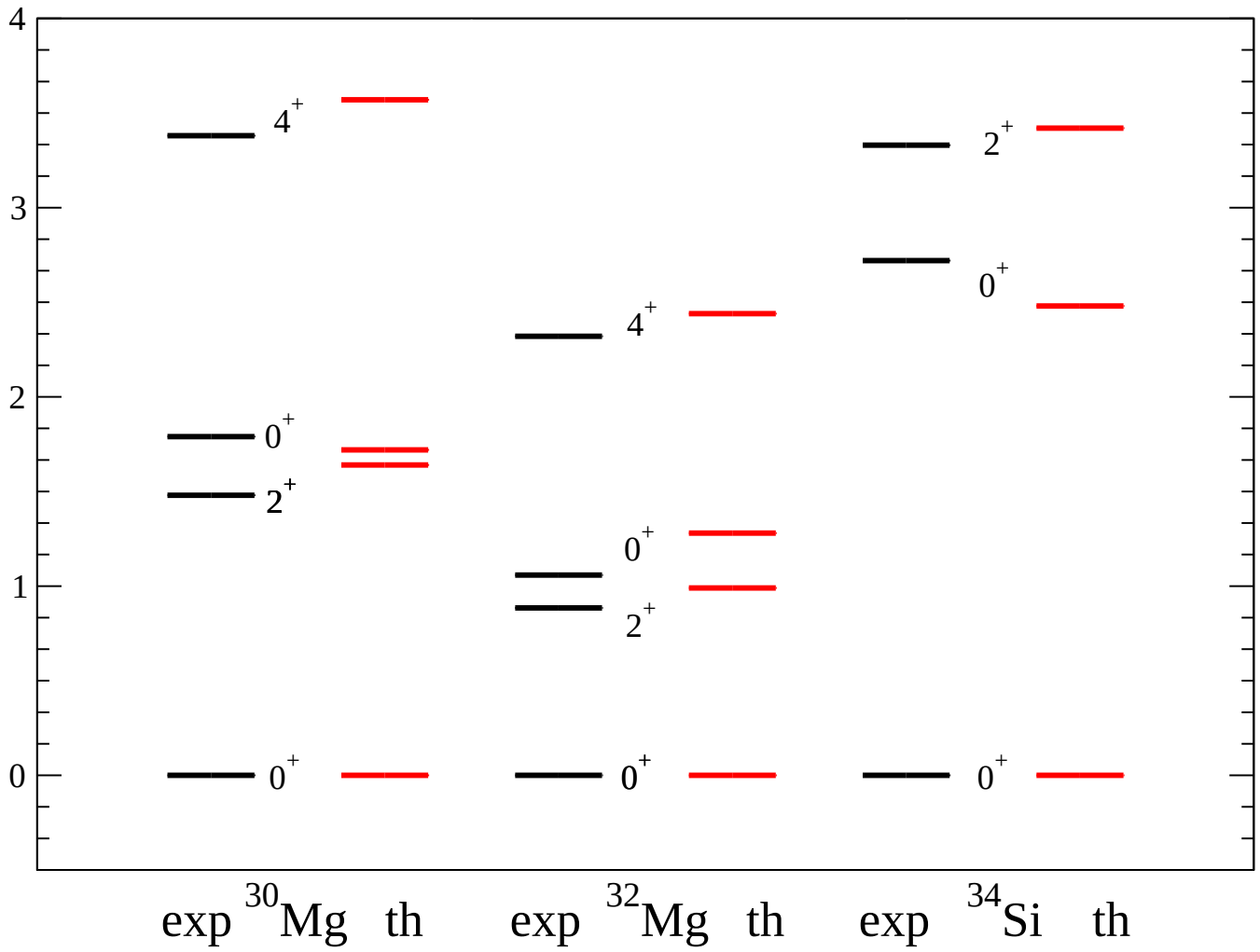
Quadrupole Collectivity vs. Magic Closures N=20

- Four protons away from doubly magic ^{40}Ca, ^{34}Si is a new doubly magic nucleus because the normal filling configuration dominates the ground state with the deformed 2p-2h being the first excited state at 2.72 MeV. The first excited 2^+ at 3.33 MeV is also of 2p-2h nature.
- To go even more neutron rich, one needs to remove protons from the $0d_{5/2}$ orbit.
- This causes a small reduction of the N=20 neutron gap, and an increase of the correlation energy of the intruder which is enough to make it the ground state.
- In this way we suddenly land in the Island of Inversion in which Deformed Intruder states become ground states, as in ^{32}Mg, ^{31}Na and ^{30}Ne.

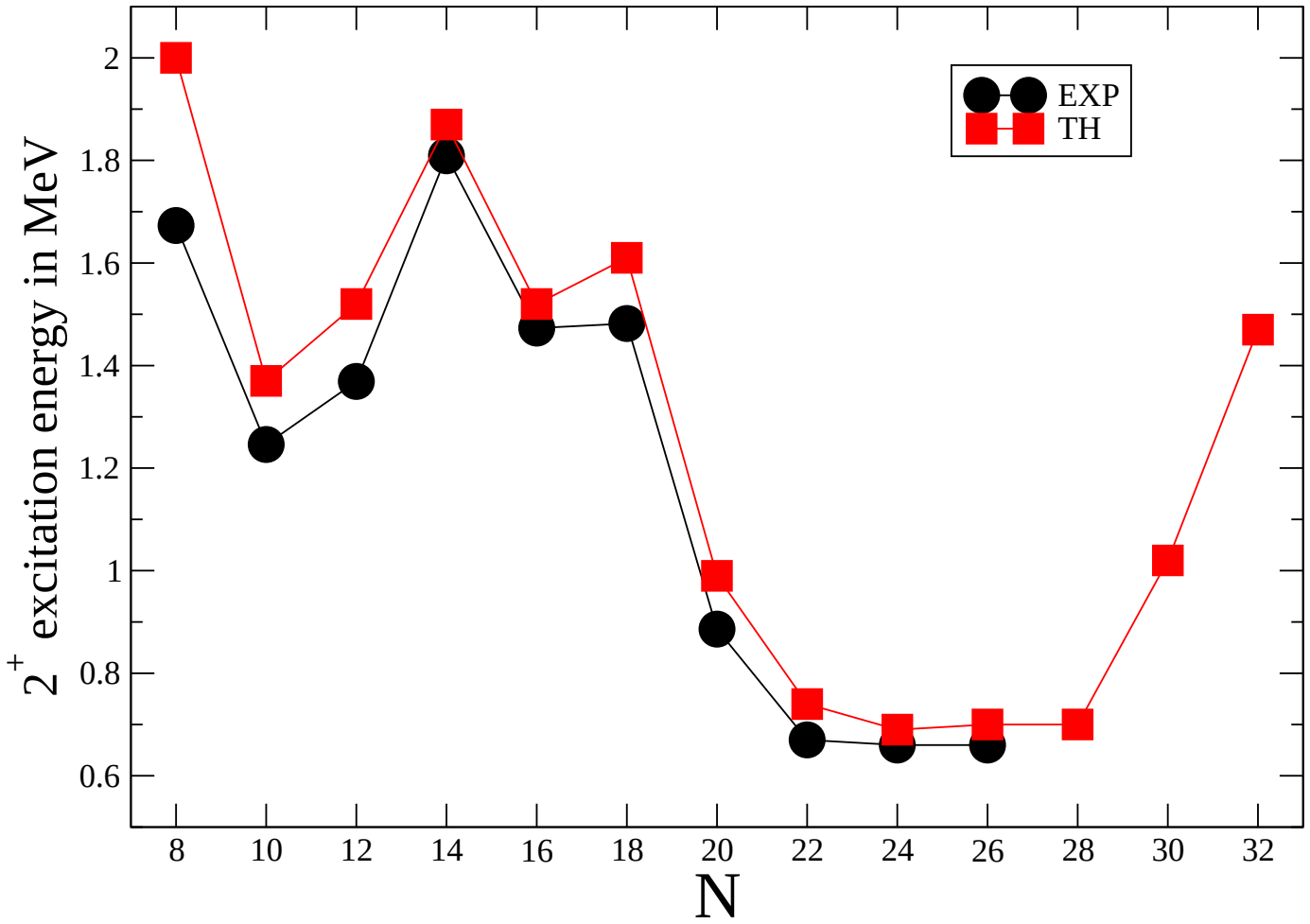
The 0^+ states in ^{30}Mg, ^{32}Mg, and ^{34}Si

- Among the recent crop of experimental results in nuclei far for stability I would surely highlight the discovery of the long sought excited 0^+ states in ^{32}Mg , and ^{34}Si, made at Isolde (Wimmer, et al.) and Ganil (Rotaru, et al.)
- At the same time there has been a certain uneasiness in the community because some (oversimplified) models claim that ^{32}Mg may not belong to the ”island of inversion” the 2p.2h state being in fact the newly discovered excited state at 1.06 MeV
- Our large scale shell model calculations, which explain the physics in the full N=20-28 region, do not support this heterodox view.

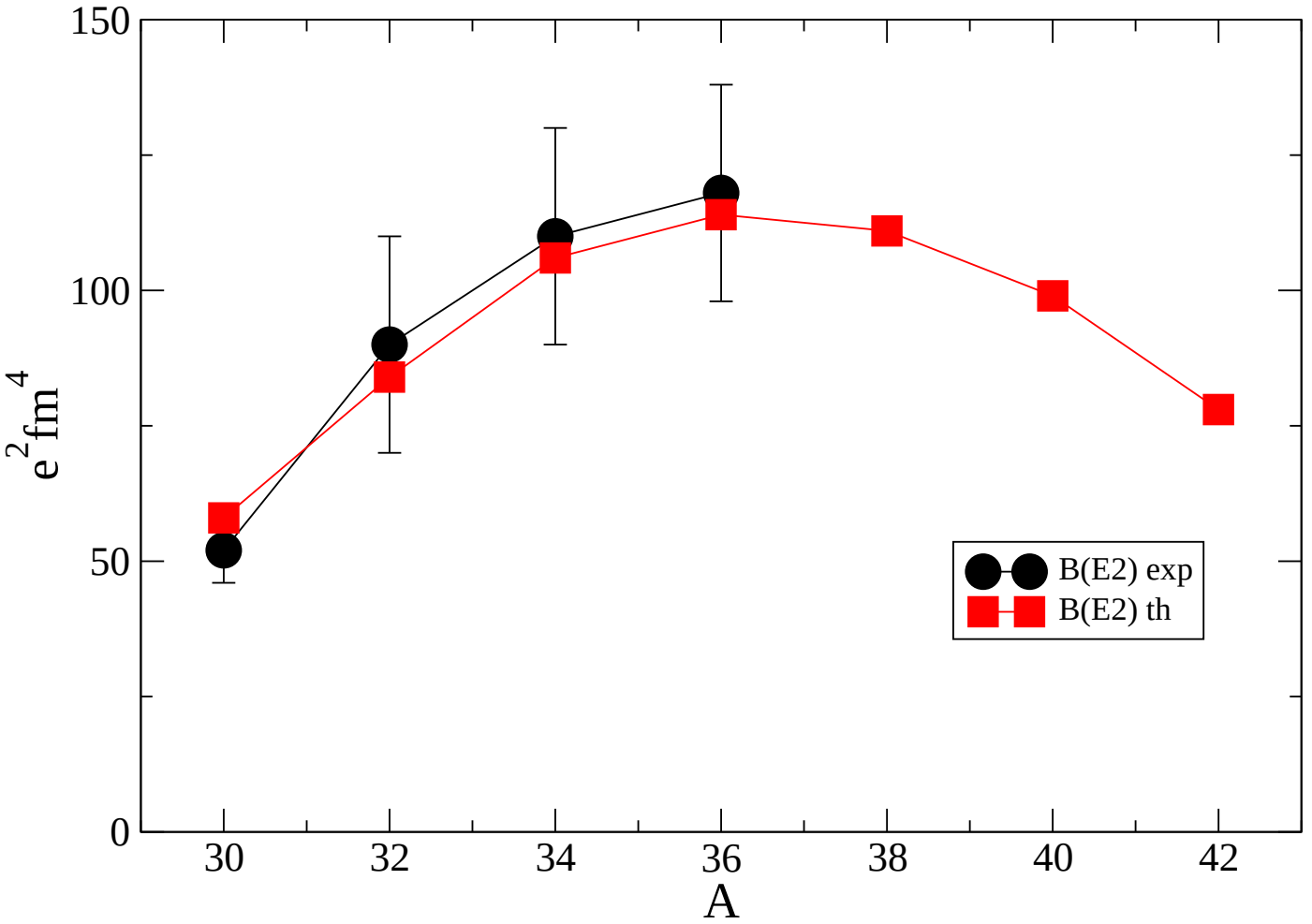
The isotonic and the Isotopic courses to ^{32}Mg



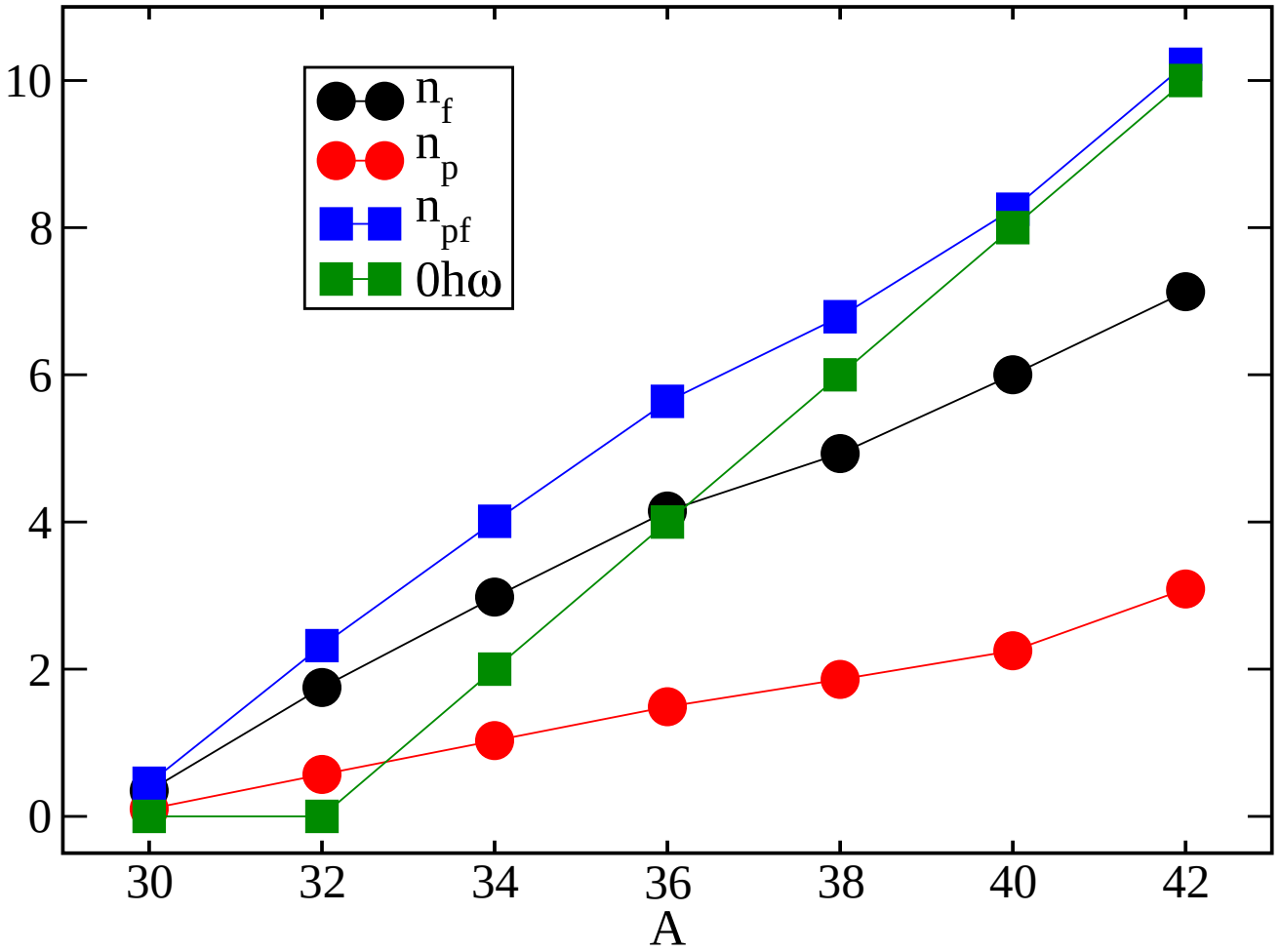
The Magnesium isotopes from the proton to the neutron dripline; SDPF-U interaction



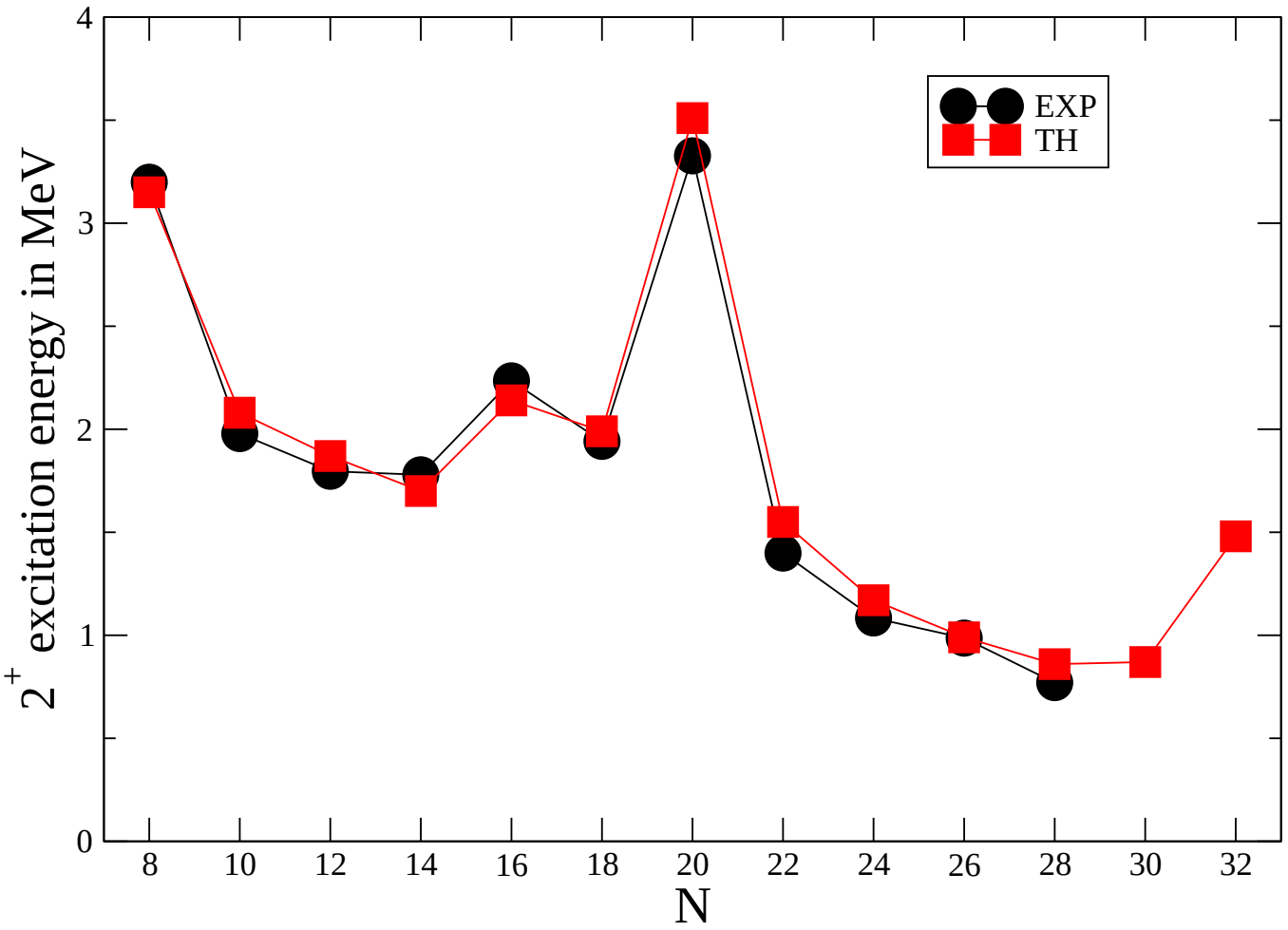
The Magnesium isotopes; B(E2)'s



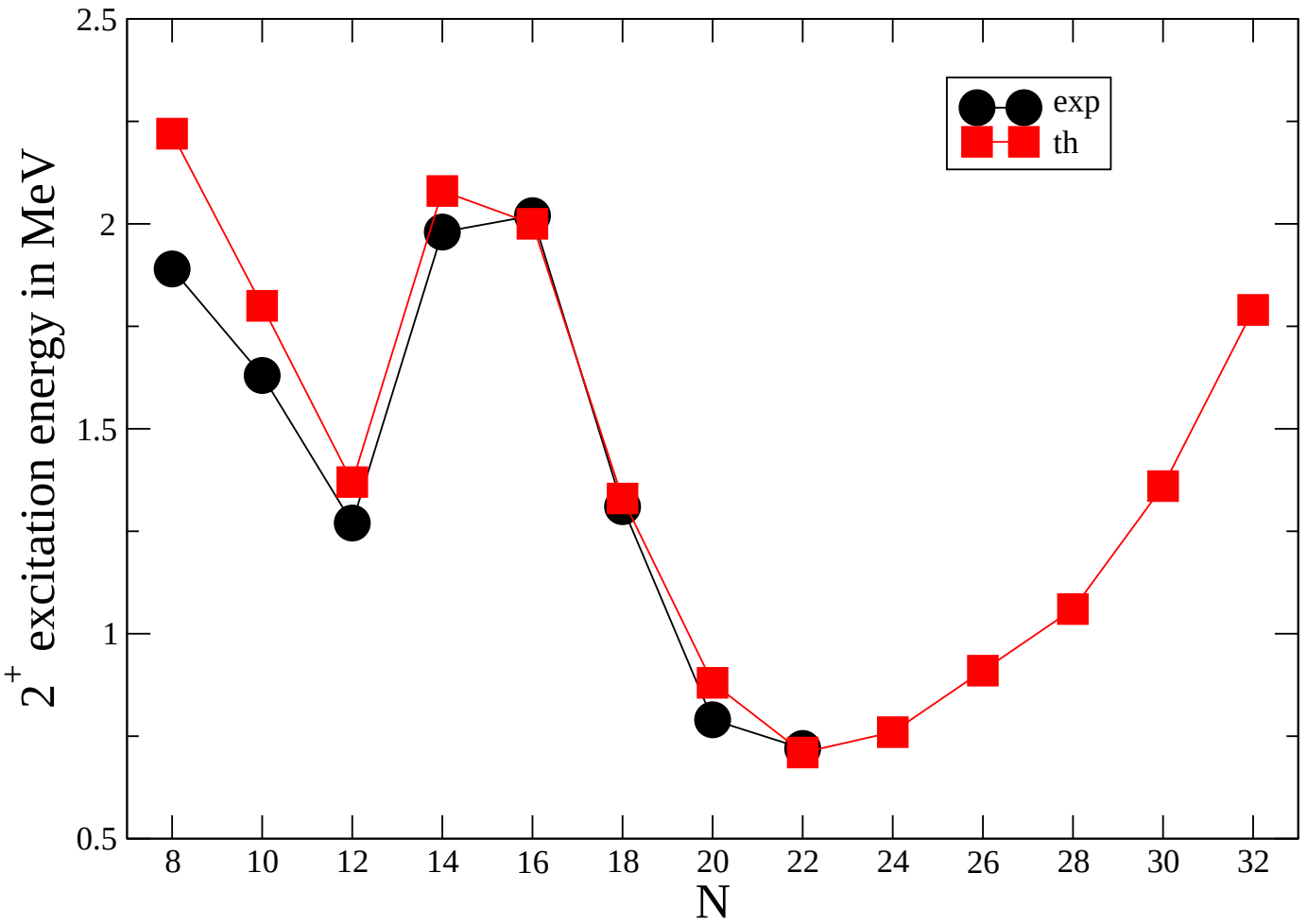
The Magnesium isotopes; Occupation numbers



The Silicon isotopes from the proton to the neutron dripline; SDPF-U interaction



The Neon isotopes from the proton to the neutron dripline; SDPF-U interaction



Coexistence

- The N=20-28 region offers a wealth of coexisting configurations
- The ground state of ^{30}Mg is ”normal” whereas the intruder deformed state lies at 1.8 MeV
- In ^{32}Mg the ground state is deformed; a very low excited 0^+ has been recently found at 1.1 MeV. Naively one could think of it as the ”normal” semimagic partner, but the calculations seem to point toward more exotic structures.
- In doubly magic ^{34}Si, the first excited 0^+, recently measured at 2.72 MeV seems to be the intruder bandhead
- The ”islands of inversion” at N=20 and N=28 seem to have merged in the Magnesium isotopes.

The island of deformation south of ^{68}Ni

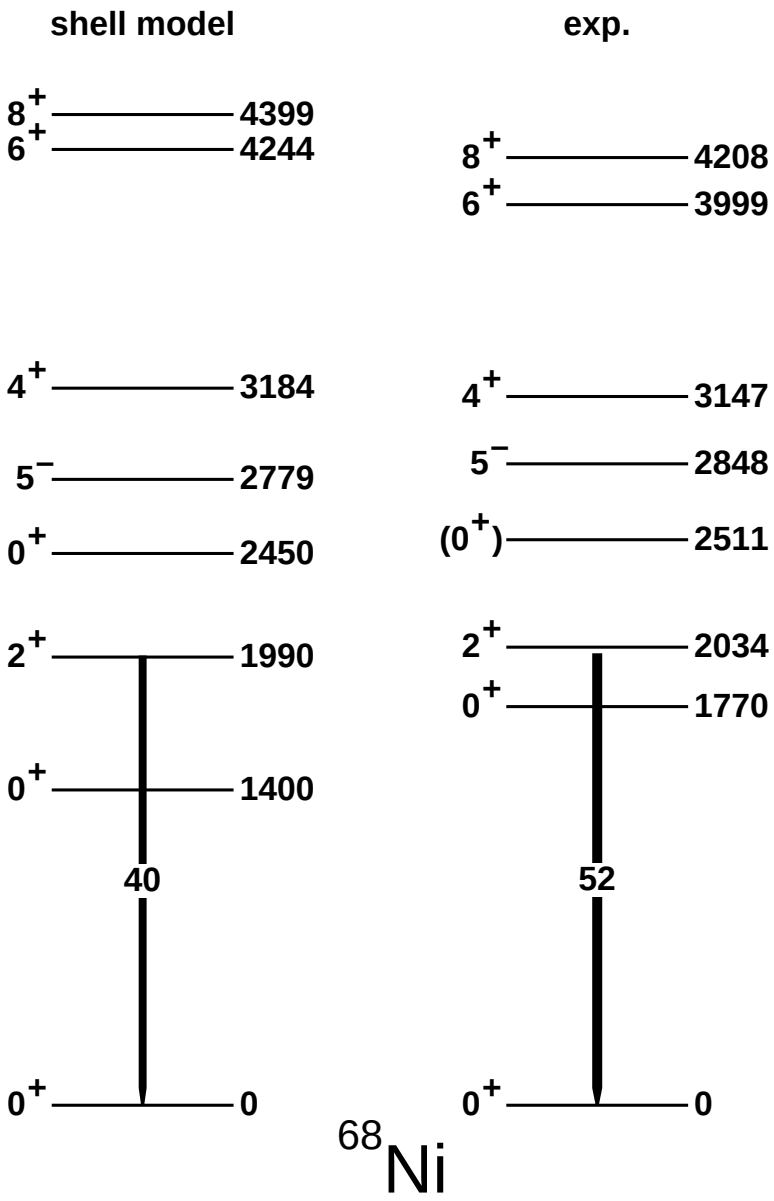
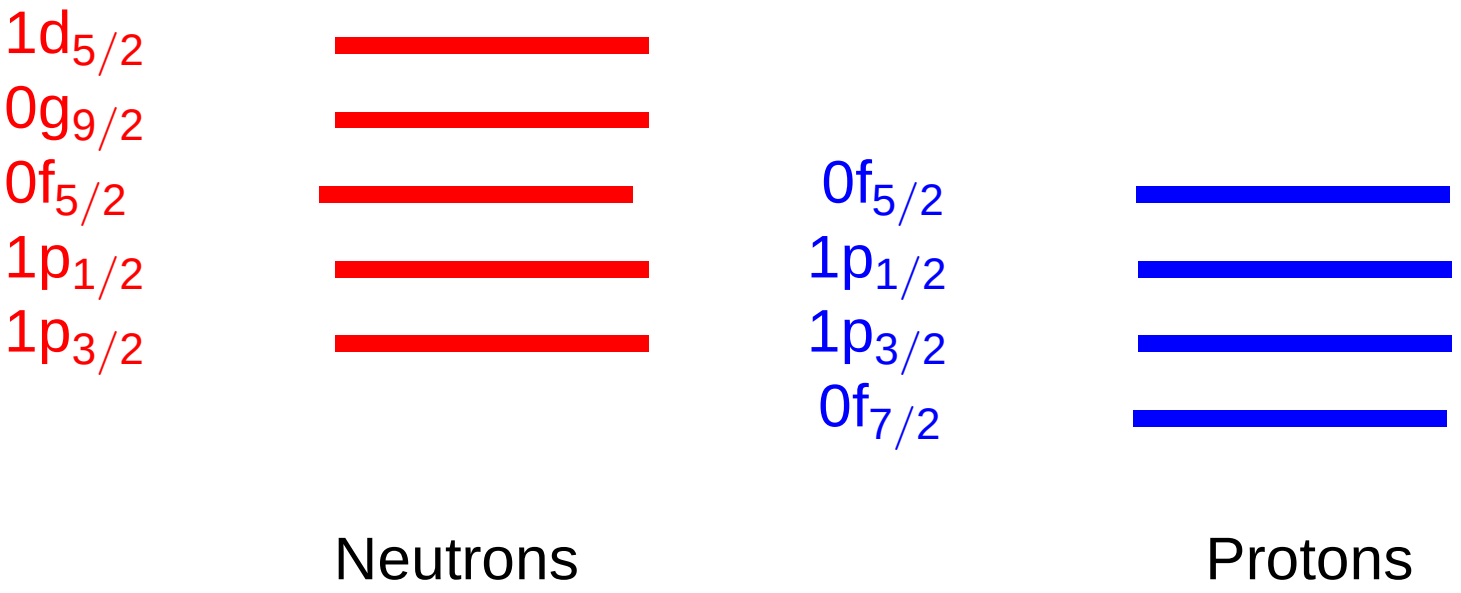


Figure credit, Carin Cain

The Valence Space for ^{68}Ni and its neighbors

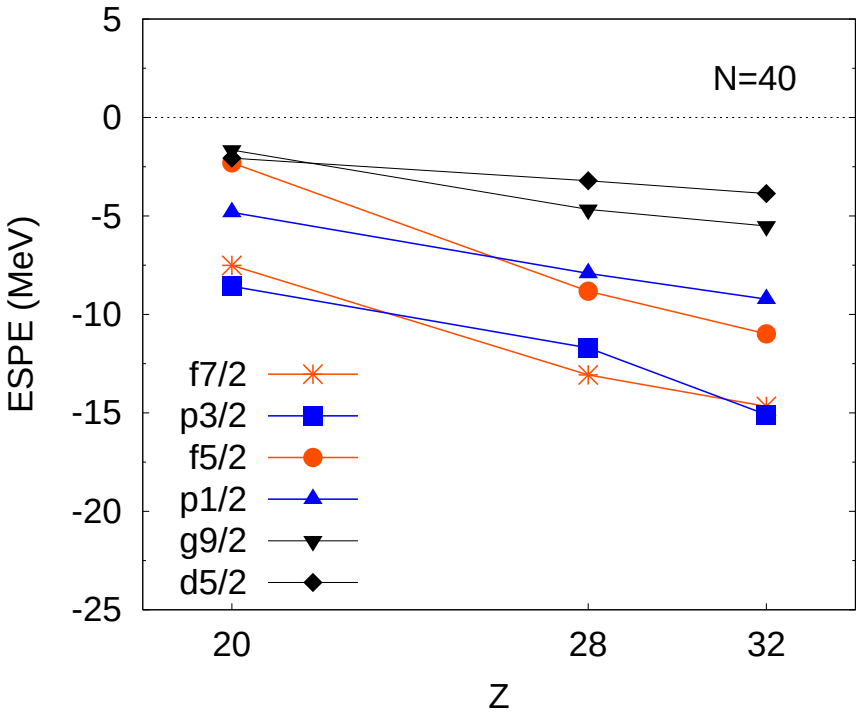


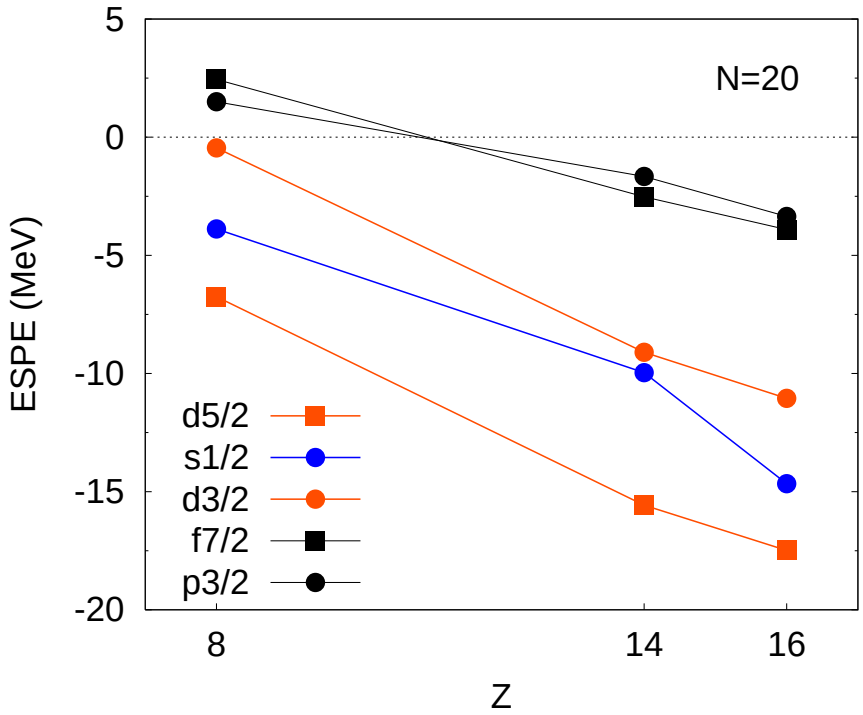
^{48}Ca acts as the inert core

The island of deformation south of ^{68}Ni

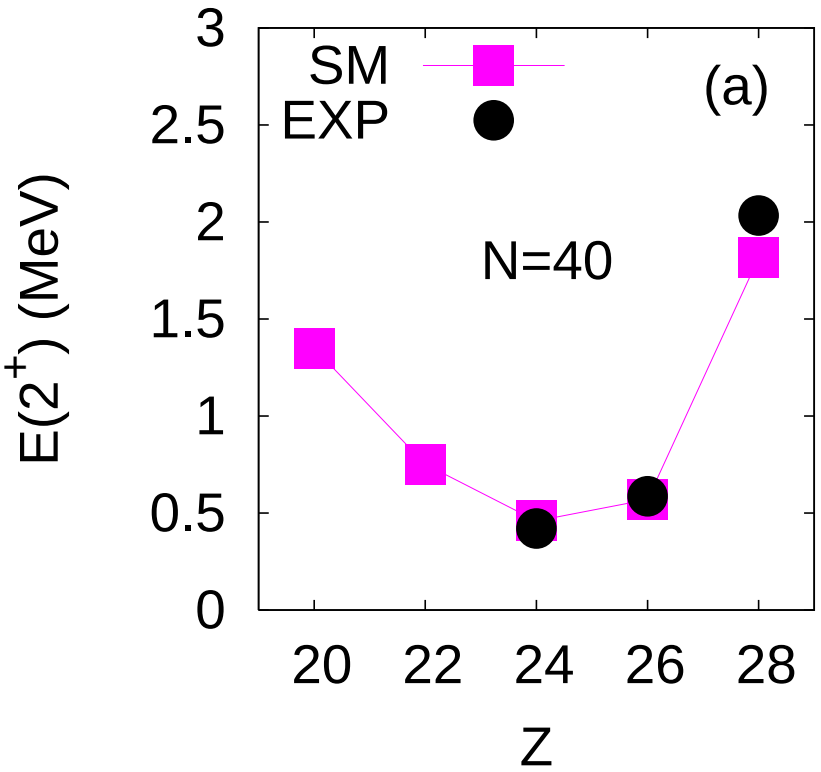
- The situation at N=40 is similar to the one found at N=20 except that ^{68}Ni is not a “bona fide” magic nucleus.
- Removing protons from the $0f_{7/2}$ orbit, activates the quadrupole collectivity, which, in turn, favors the np-nh neutron configurations across N=40, that take advantage of the quasi-SU3 coherence of the doublet $0g_{9/2}$- $1d_{5/2}$.
- Large scale SM calculations in the valence space of the full *pf*-shell for the protons and the $0f_{5/2}$ $1p_{3/2}$ $1p_{1/2}$ $0g_{9/2}$ and $1d_{5/2}$ orbits for the neutrons, predict a new region of deformation centered at ^{64}Cr.

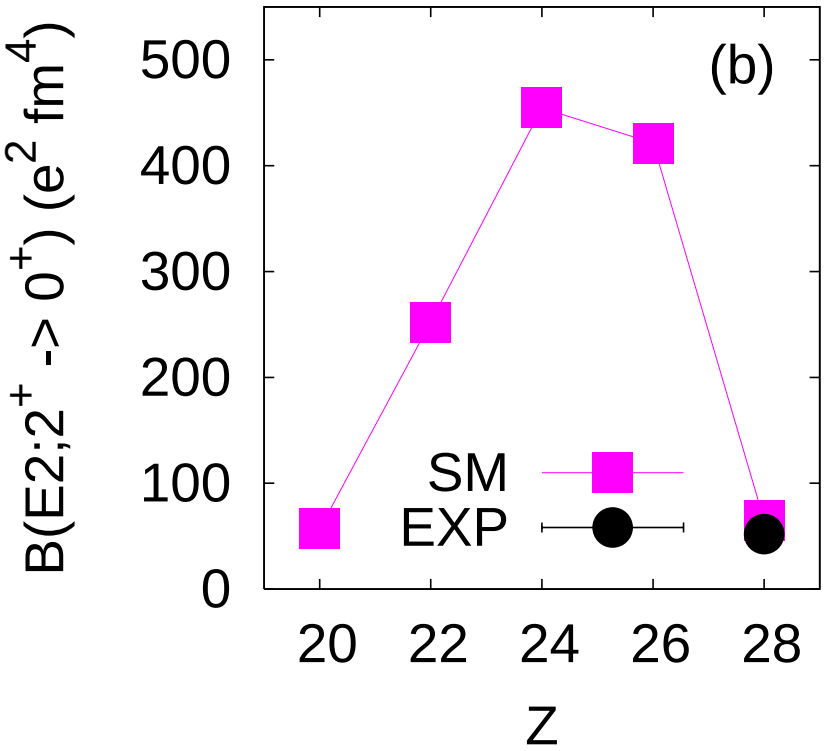
The neutron ESPES at N=40 and N=20



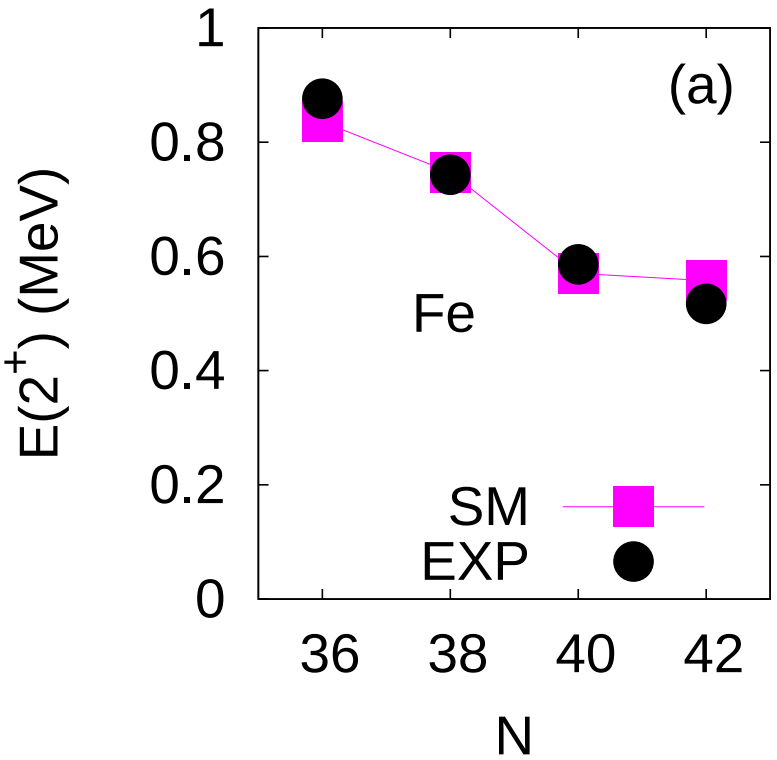


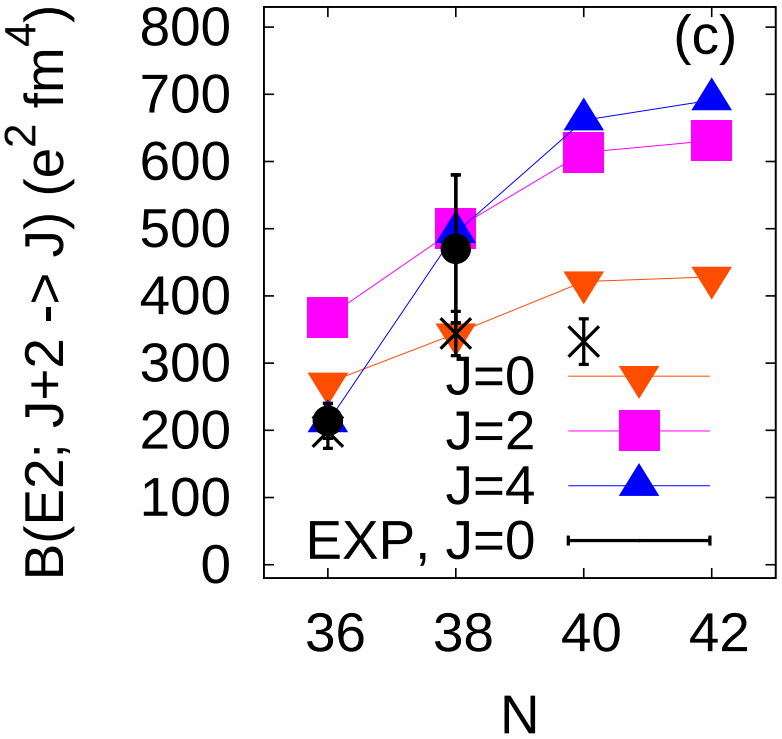
The N=40 isotones



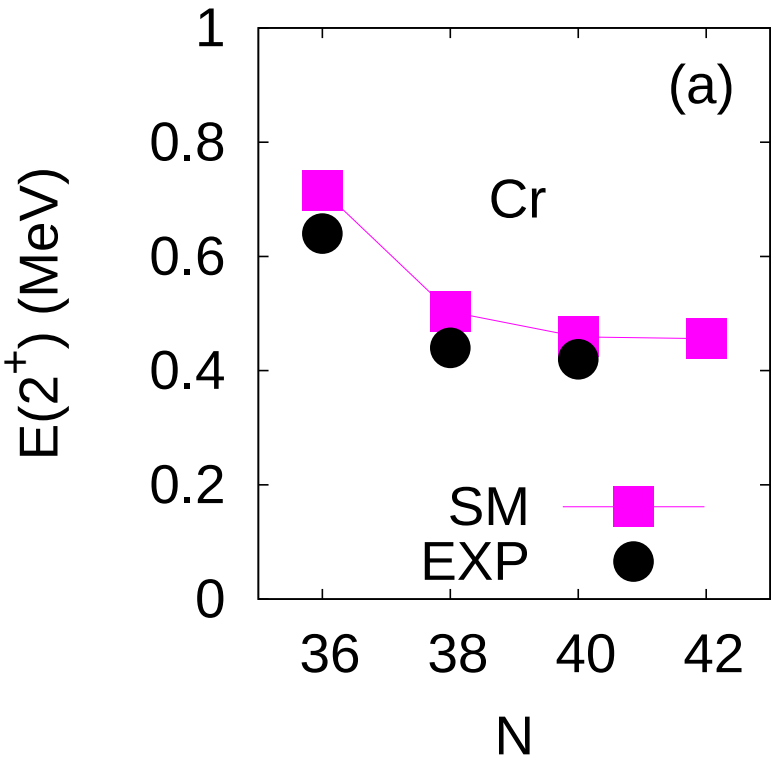


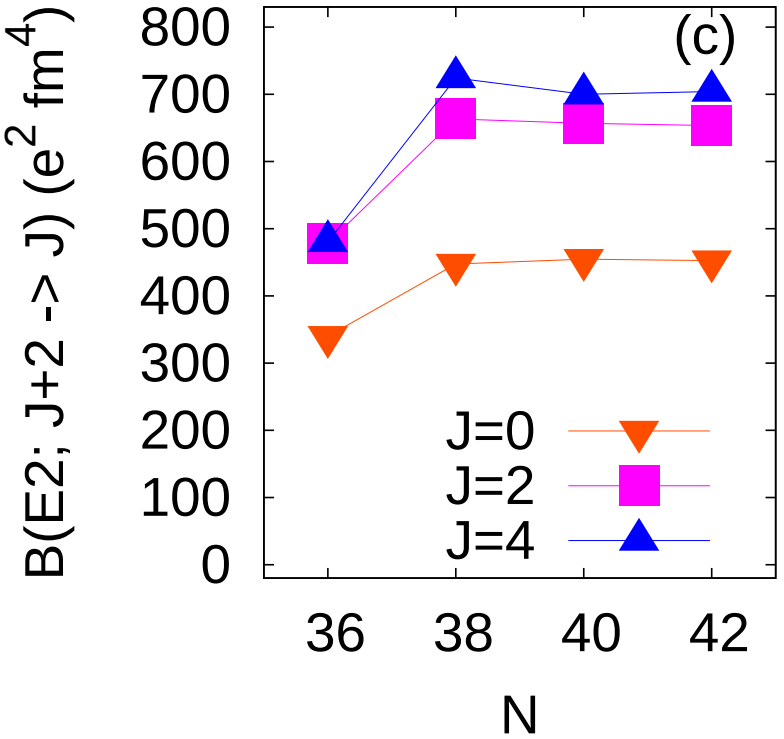
The Iron Isotopes



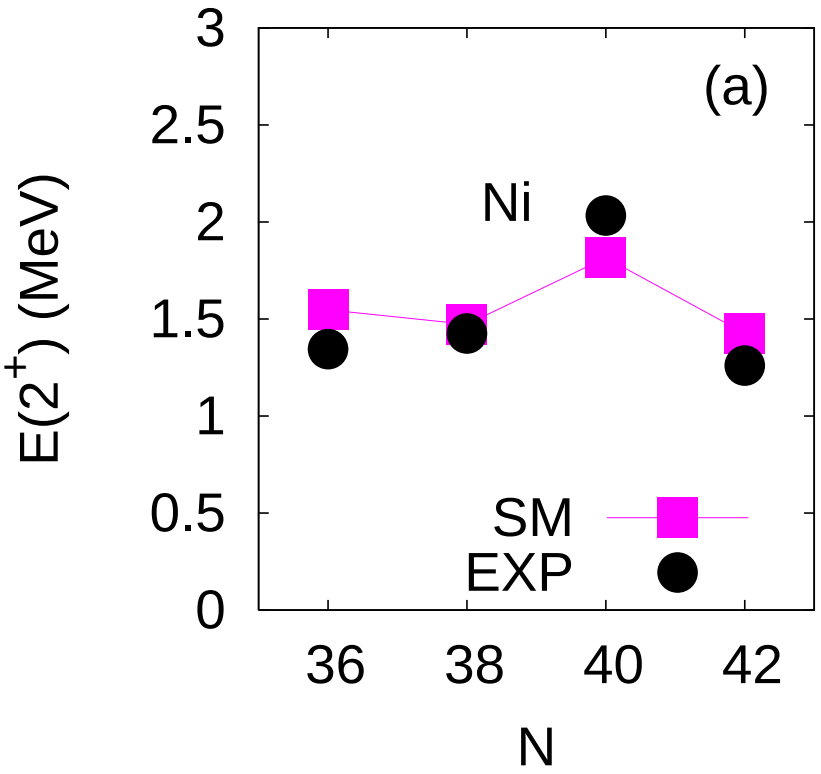


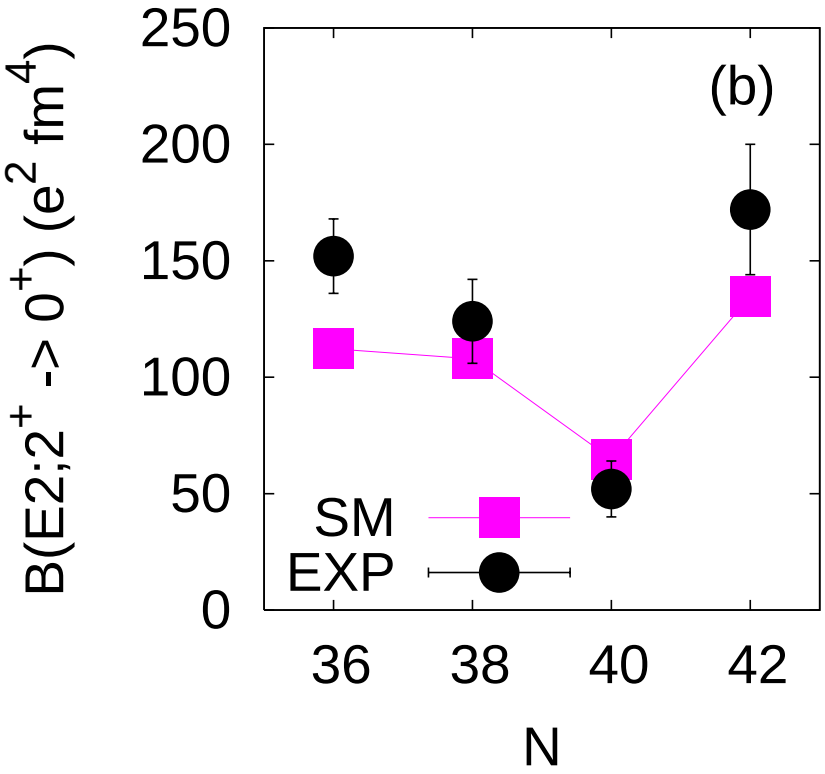
The Chromium Isotopes



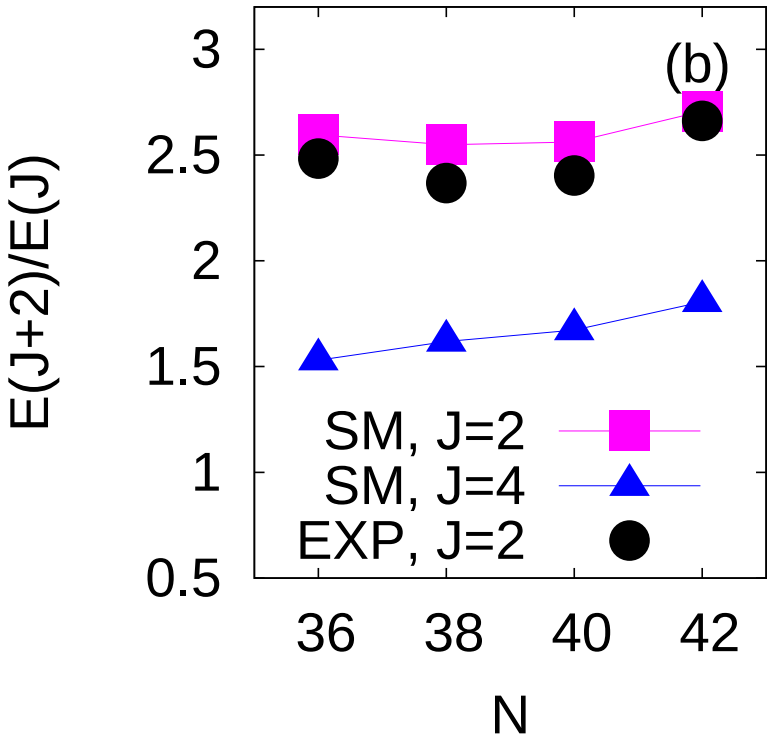


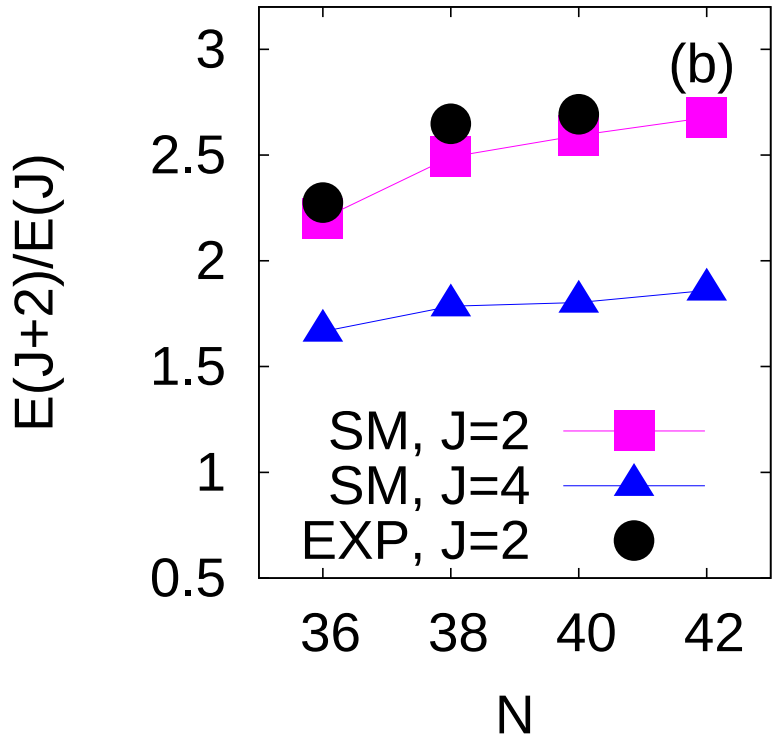
The Nickel Isotopes





The yrast bands, Iron and Chromium





Conclusions

- At the very neutron rich edge, when the T=1 part of the NN (or NNN) interaction becomes dominant, the spherical mean field may have a shell structure at variance with the one at the stability valley
- The physics around magic or semi-magic closures depends of subtle balances between the monopole and the the correlation energies of the configurations at play
- At N=20 the correlation energies of the 2p-2h states are very large (10 MeV) and rather constant

Conclusions

- The ”islands of inversion” at N=20 and N=28 seem to have merged in the Magnesium isotopes.
- These ”islands of inversion” appear due to the effect of the correlations, hence they could also be called ”islands of enhanced collectivity”. As quadrupole correlations are dominant in this region, most of their inhabitants are deformed rotors. Shape transitions and coexistence show up everywhere.