Neutron Skin Effects in Mirror Energy Differences: The Case of ^{23}Mg-^{23}Na

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Charge radii and nuclear skin

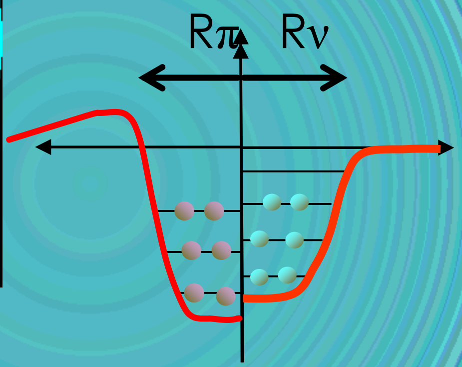
Charge radii are usually measured **via electron scattering**.

These measurements are limited to **stable nuclei**.

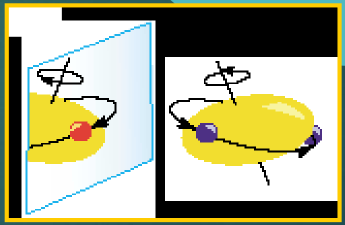
Laser spectroscopy allows to measure radial shifts along isotopic chains.

This applies to **ground states** or isomeric states.

Neutron skin is still more difficult to measure.



Can we get any information on the evolution of radii in excited states and on the neutron skin?



We will see that mirror energy differences are sensitive to the nuclear radius.

Charge invariance and isospin

In fact the nuclear force is **slightly asymmetric:**

e.g. scattering lengths a_{nn}**= -18.8±0.3 fm**

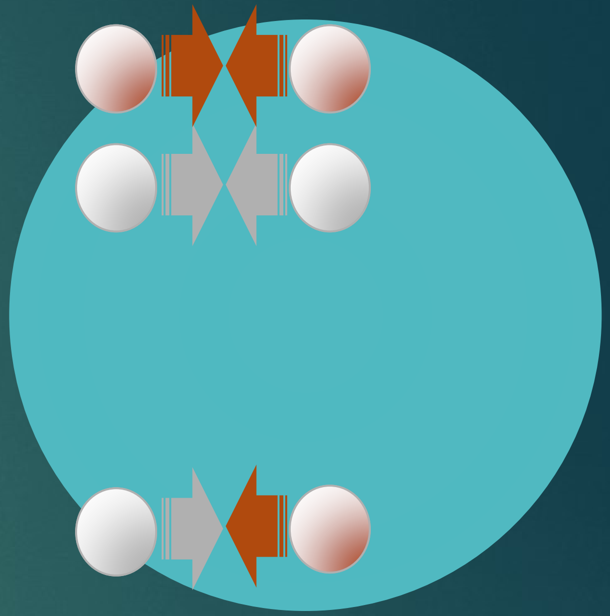
a_{pp}**= -17.3±0.4 fm**

→ the nn interaction is about 0.5% more attractive.

The nuclear force is also slightly **charge dependent**:

scattering length a_{np}**= -23.75±0.01 fm**

→ the np interaction is about **2.5% more attractive** than the average of nn and pp



- These will break symmetry slightly
- Coulomb force **also** breaks symmetry

BOTH can be though of as a perturbation – underlying symmetry will be retained.

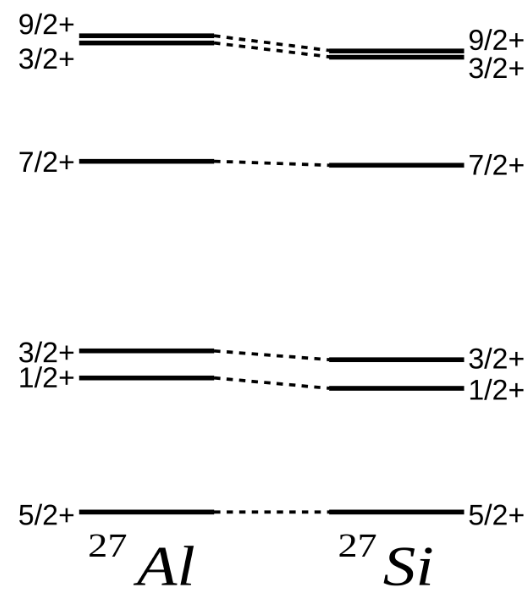
Energy differences along isospin multiplets

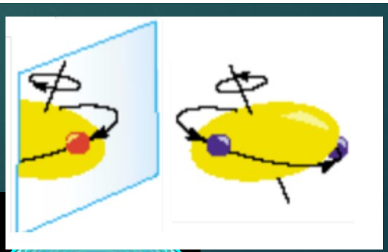
Mirror nuclei

- Same A, interchanged Z and N
- Differences in Binding energies
  - **CDE** Coulomb Displacement Energies
  - ~ tens of **MeV** – charged sphere
- Excitation energies
  - Binding energies normalized to the g.s.
  - ~ tens of **keV**
  - **Large Coulomb effects almost vanish**
- Charge Symmetry $V_{pp} = V_{nn}$
  - **Identical level scheme**

Mirror Energy Differences

$$\mathrm{MED}_J = \mathrm{Ex}_{J,T_z=-1/2} - \mathrm{Ex}_{J,T_z=+1/2} = -\Delta b_J$$



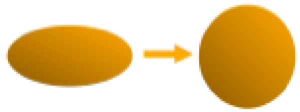


How do we calculate them?

Contributions to the MED

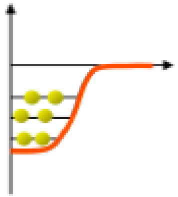
Monopole Term

Radius Variation with J



Related to **orbitals occupation numbers**

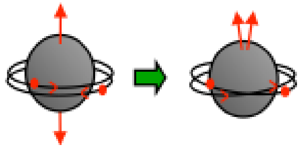
Single Particle Energies



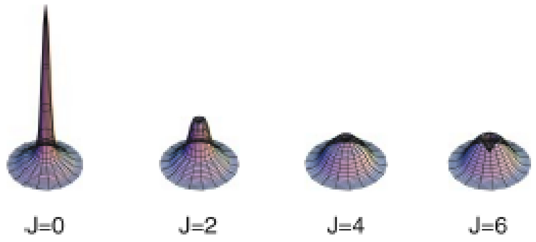
Electromagnetic Spin Orbit
Thomas precession

Multipole Term

Nucleon Alignment with increasing Angular Momentum J



W.f. overlap decreases with increasing J



Calculated in the harmonic oscillator basis

Calculation of Mirror Energy Differences

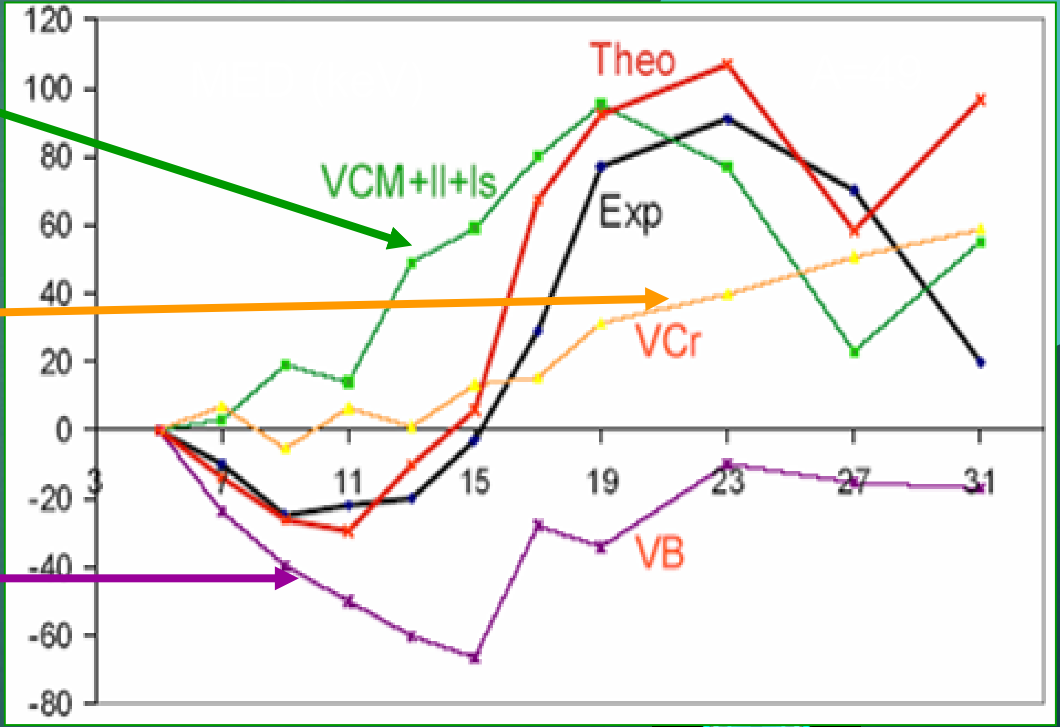
$$MED_J^{exp} = E_J^*(Z_>) - E_J^*(Z_>)$$

$$MED_J^{theo} = \Delta_M \langle V_{Cm} \rangle_J + \Delta_M \langle V_{CM} \rangle_J + \Delta_M \langle V_B \rangle_J$$

The multipole Coulomb contribution gives information on the nucleon alignment

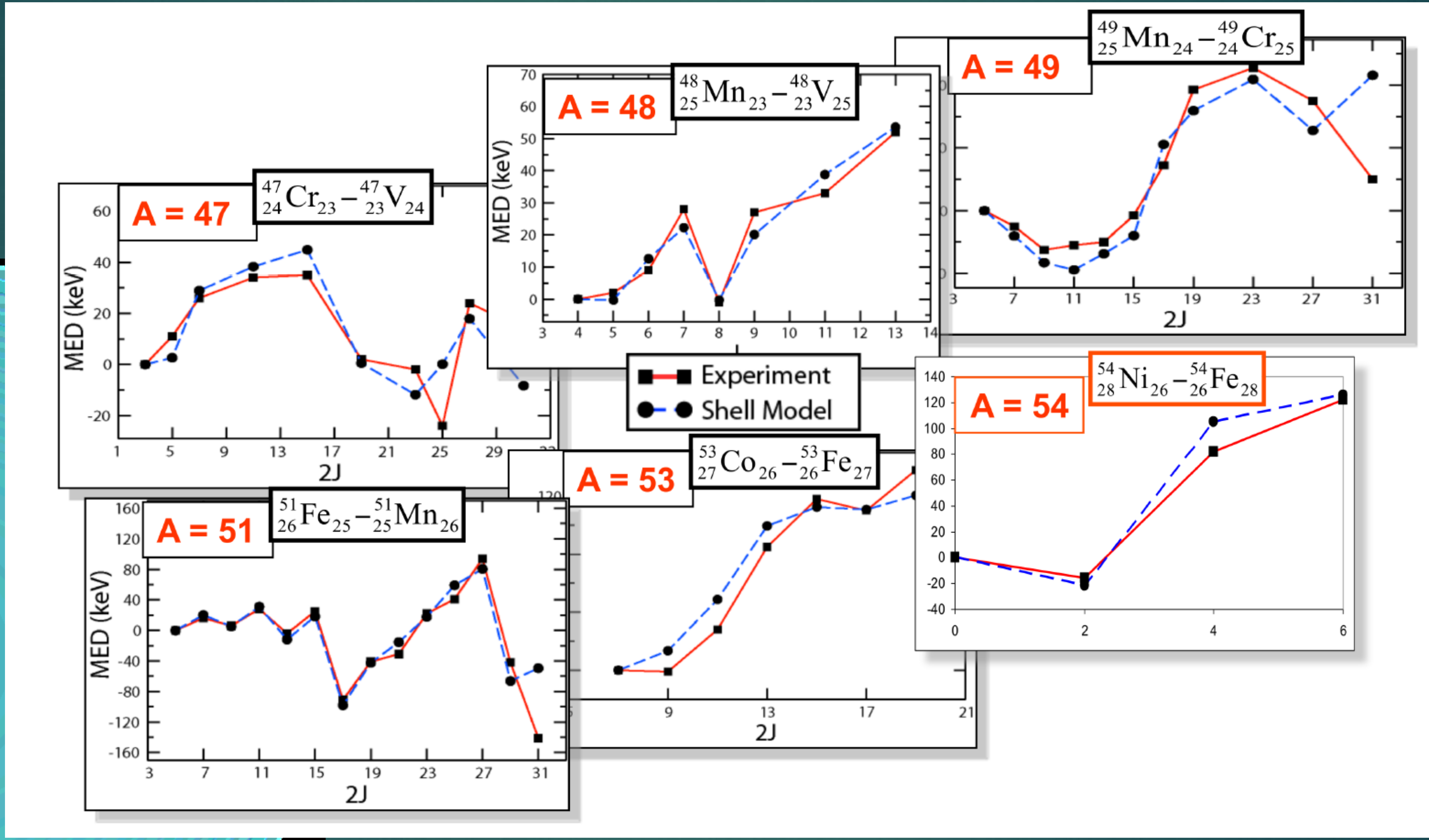
The monopole Coulomb contribution gives information on changes in the nuclear radius (deformation)

Important contribution from the "nuclear" ISB term,
of the same order as the Coulomb contributions!!!!!



Now, **without changing the parametrization**, see how the rest of the MED for nuclei along the f7/2 shell are described by the calculations…

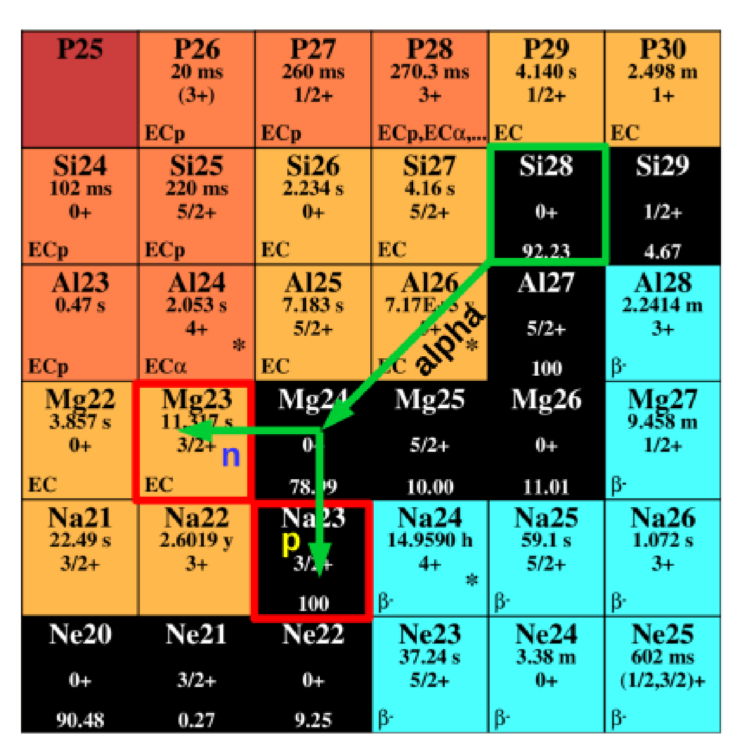
$f_{7/2}$ shell: "Classical" MEDs



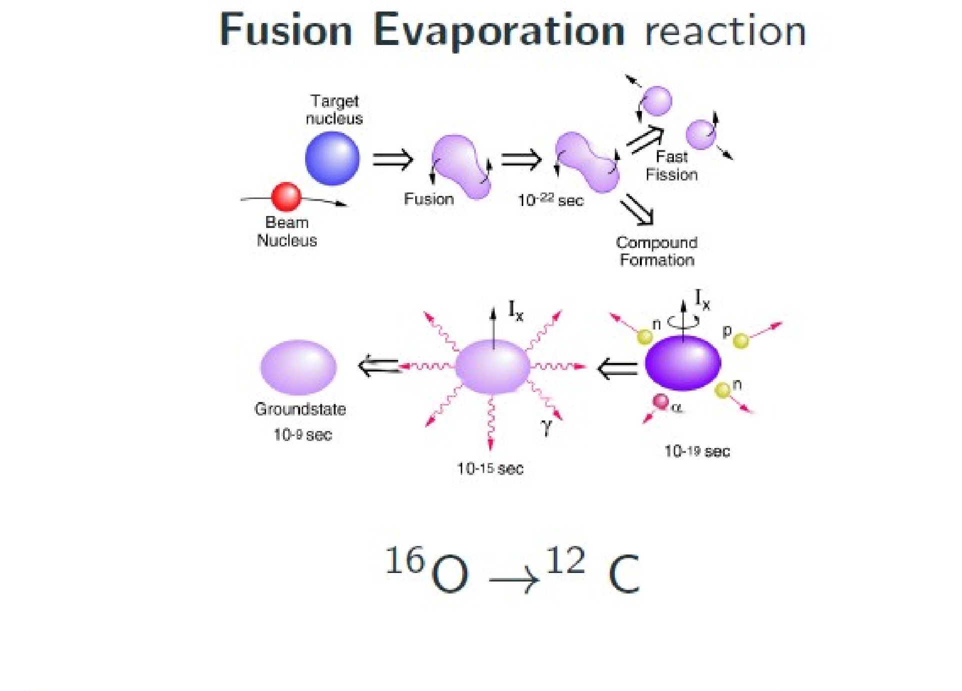
Is the V_B term needed also in **other mass regions**?

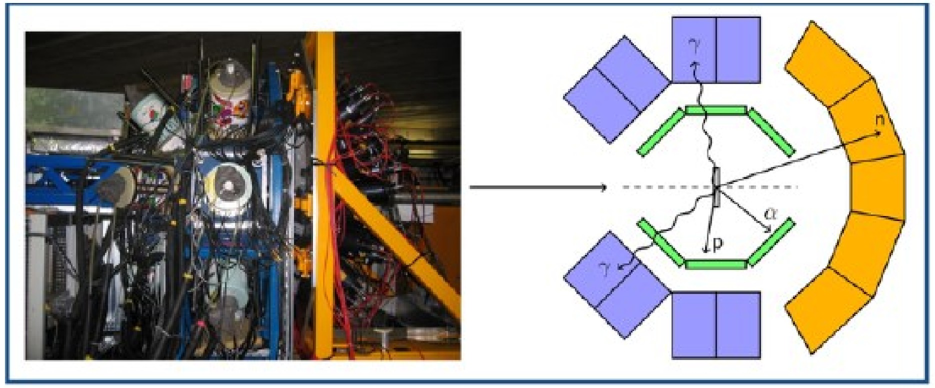
The answer went much beyond the scope of the question

The experiment: $^{16}O+^{12}C$



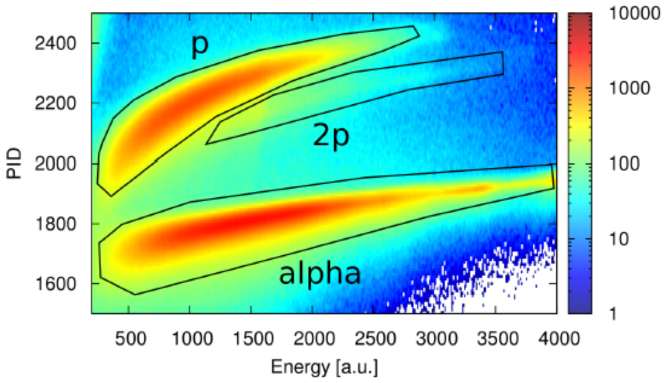
- EXOGAM
- DIAMANT
- NEUTRON-WALL





Selection of the channel

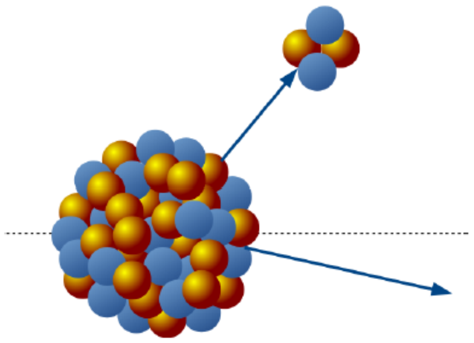
Channel selection
Pulse Shape vs. Energy



Efficiency estimate
From γ spectra

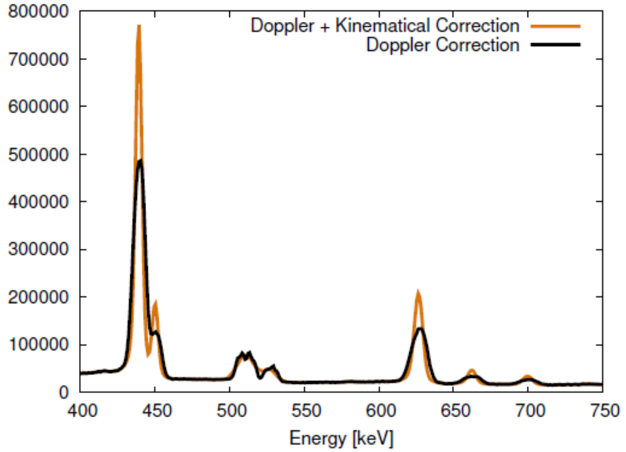
^{23}Na - αp channel				
γ energy	$I_{\alpha p}/I_p$	ϵ_α	$I_{\alpha p}/I_\alpha$	ϵ_p
440	0.32	24 %	0.63	39 %
627	0.29	22 %	0.60	38 %

Kinematical correction

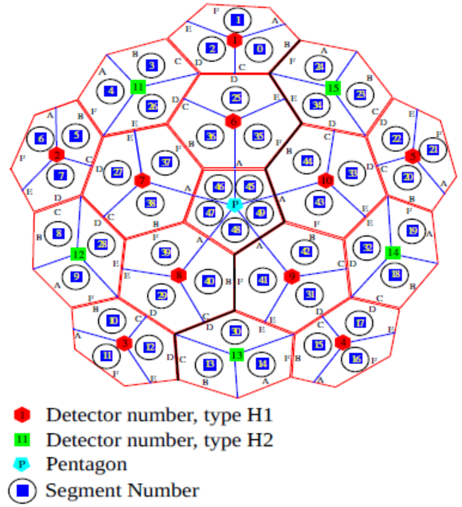


Trajectory reconstructed from the angle of the evaporated particles

Resolution improvement: 1.6



Selection of the channel



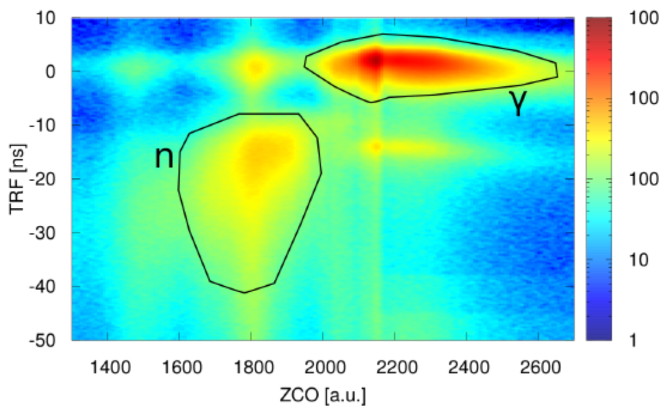
50 BC501A liquid scintillators

Neutron Wall was placed at forward angle to maximize the efficiency

Pulsed beam allows to discriminate between single γ and neutron hits

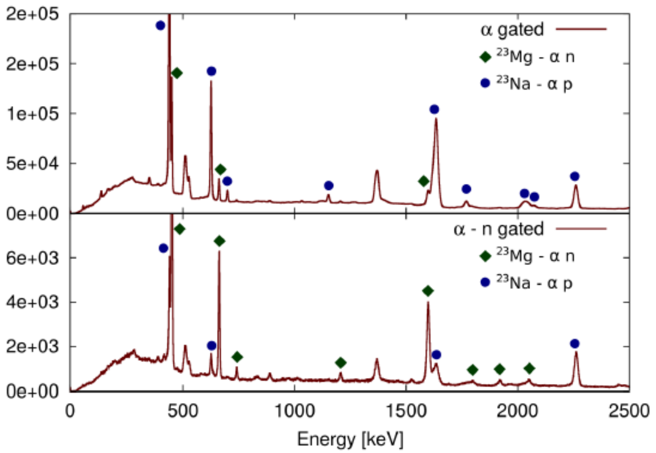
1n neutron efficiency estimated to be $\sim 21\%$

n-γ discrimination

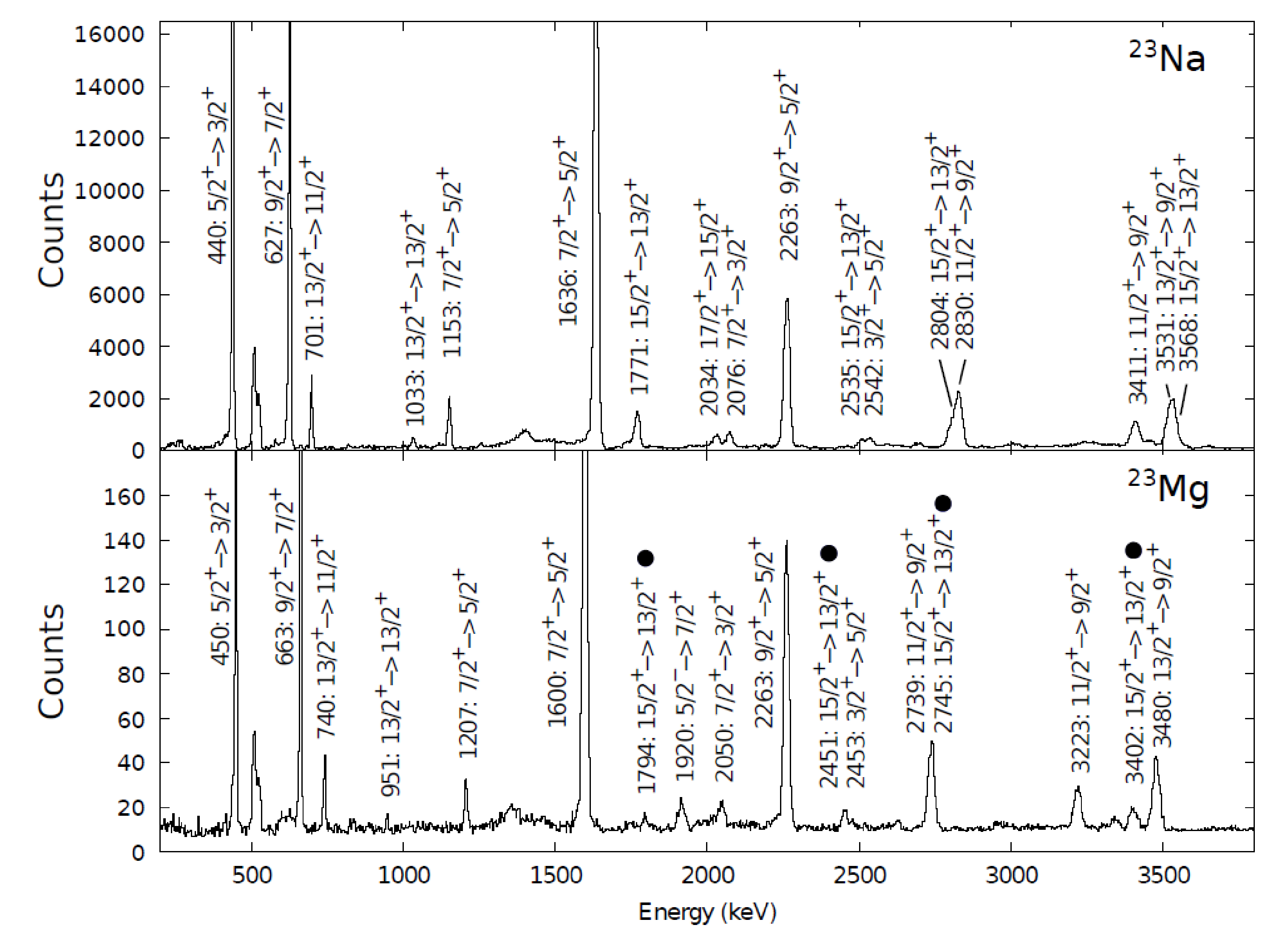


TRF vs ZCO

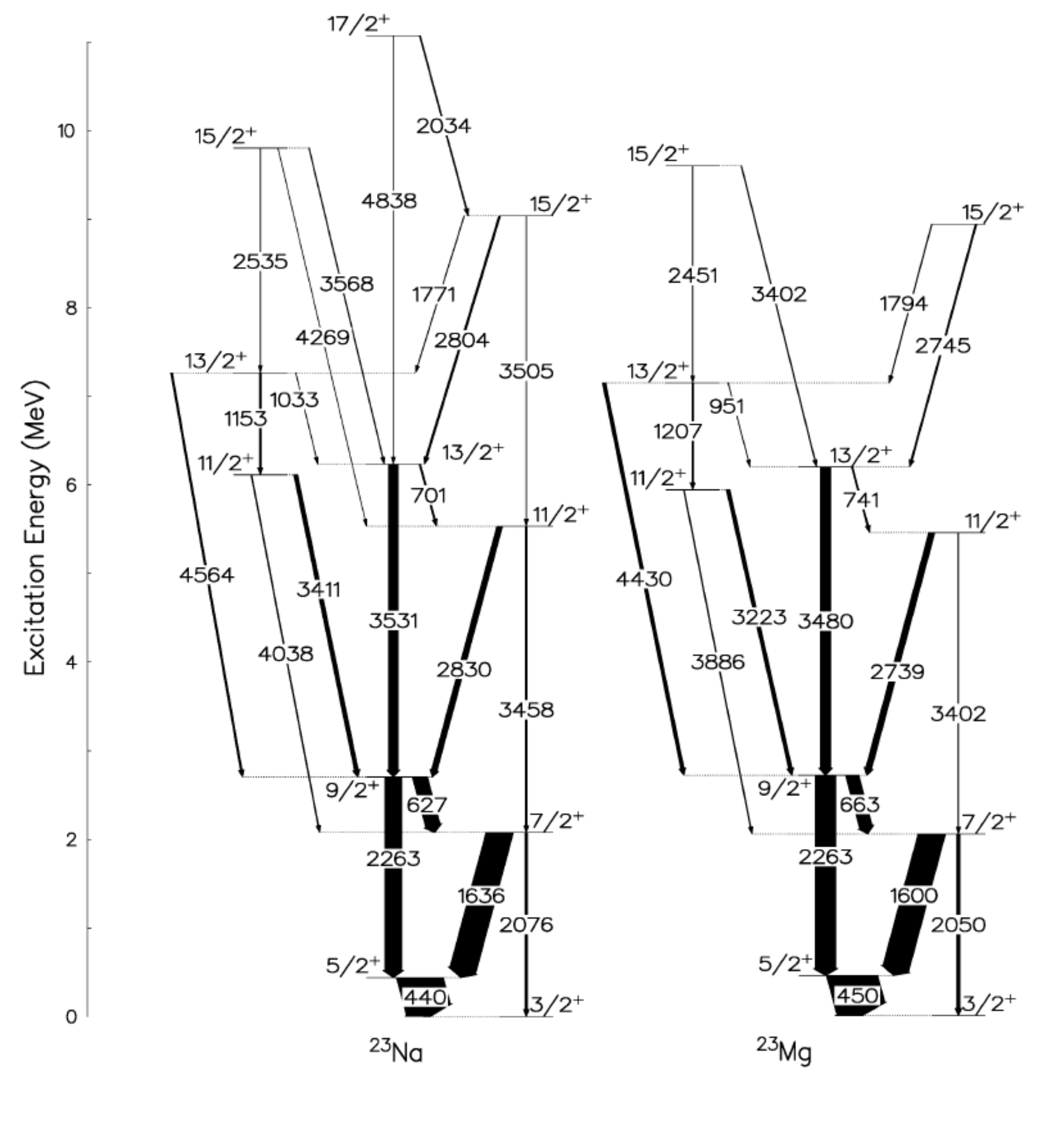
Channel selectivity



Mirror symmetry at work



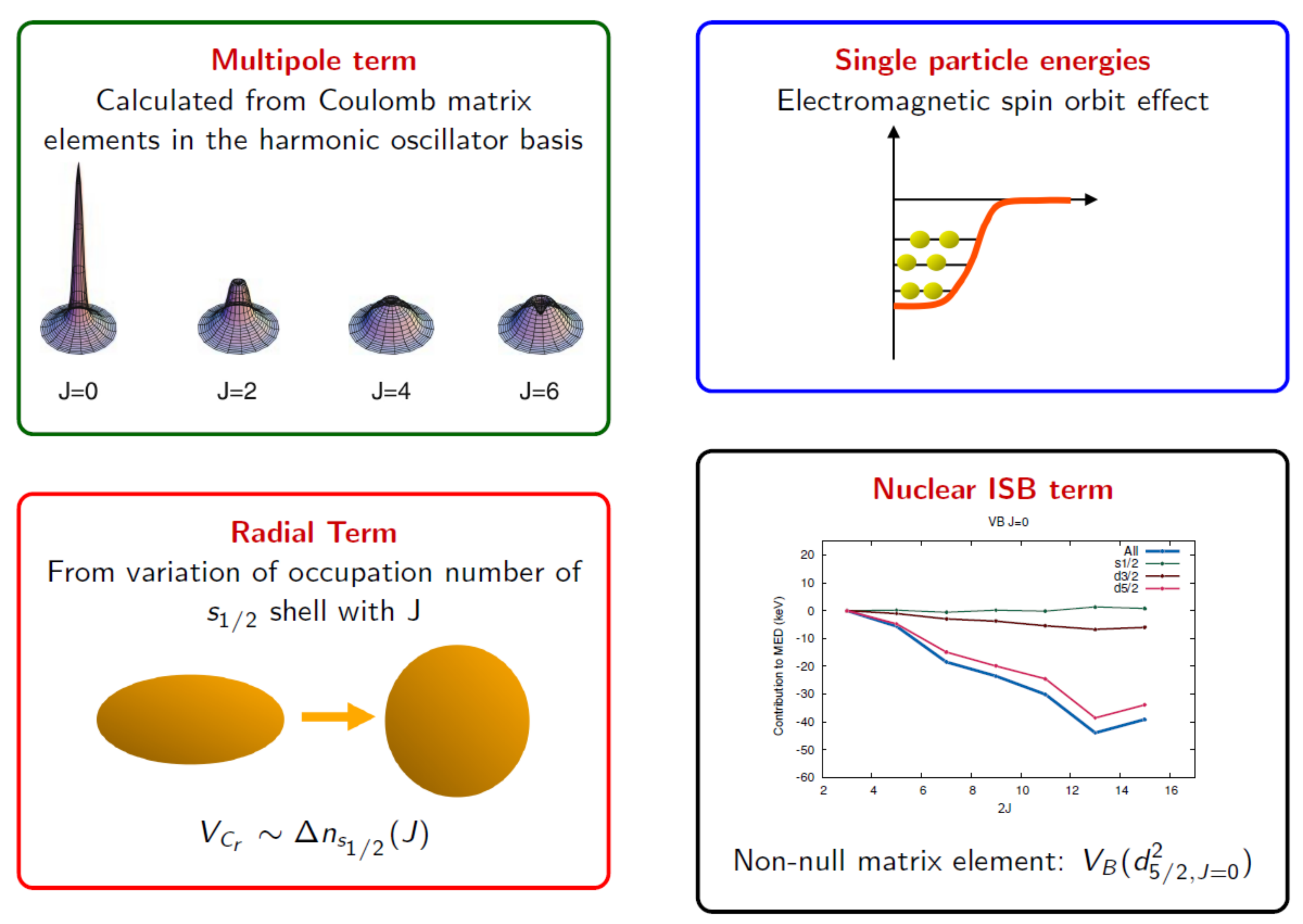
Level schemes



Previously known level scheme confirmed and extended:

- 2 new levels
- 4 new transitions

Theory I: USD interaction



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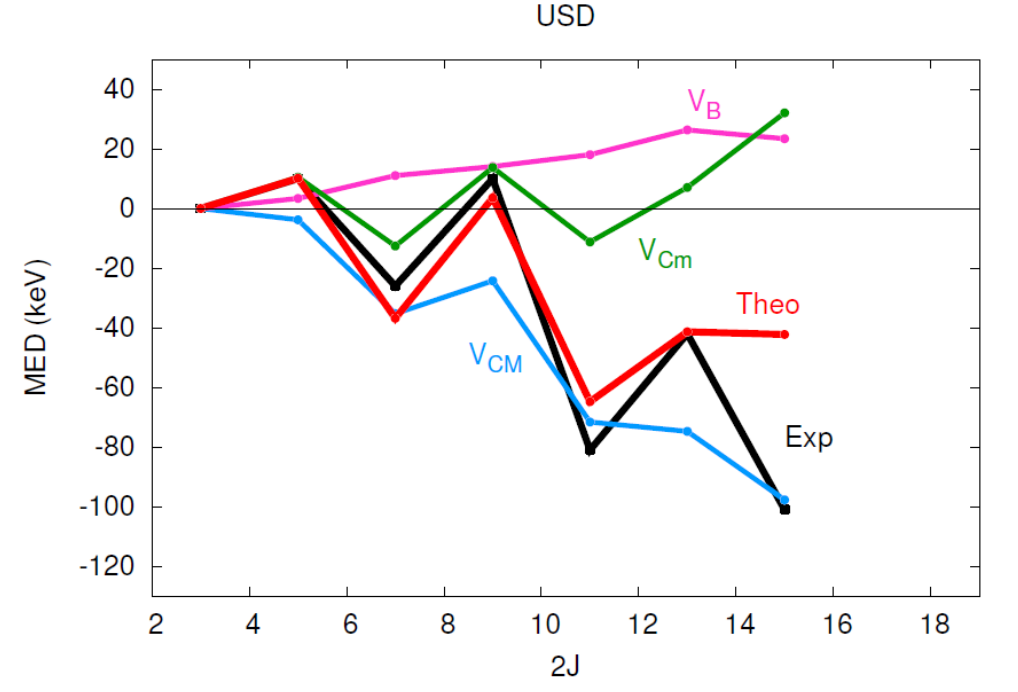


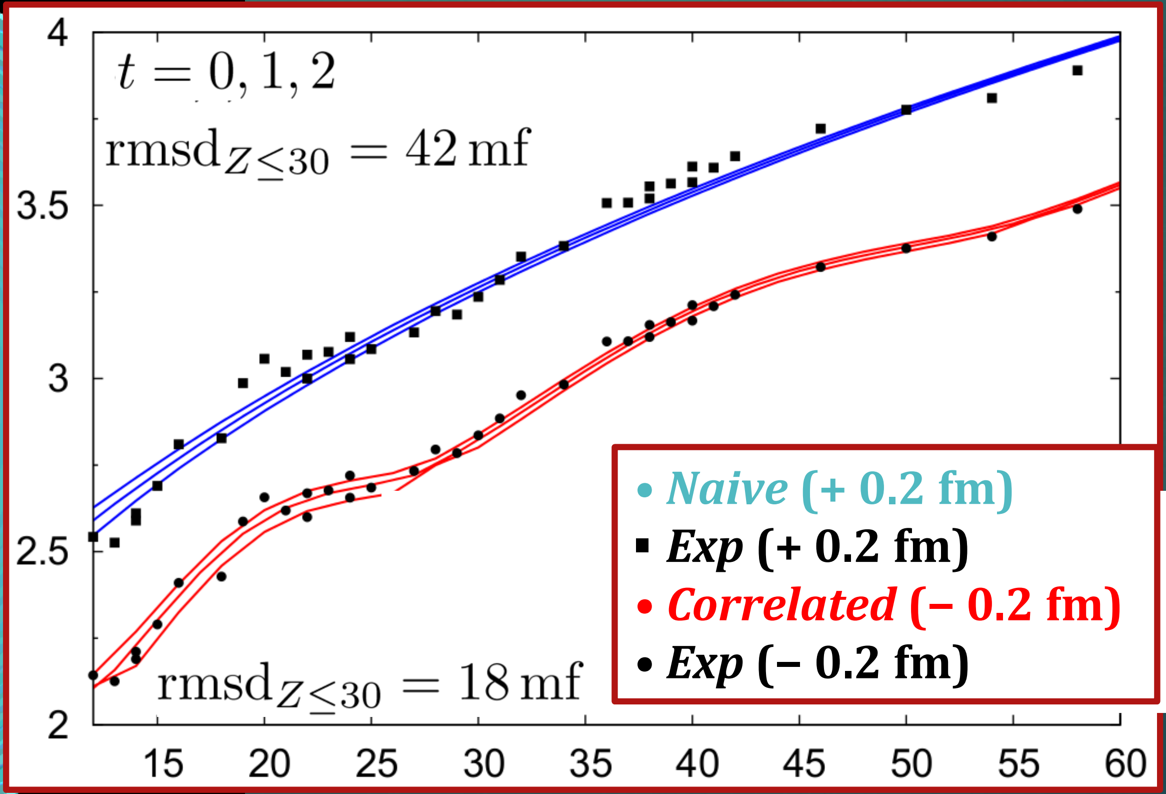
- Calculations performed as in the classical in $f_{7/2}$ shell
  - **Important multipole term** (alignment)
  - Improved by radial term correction
  - V_B needed: ~ 30 keV
    - → **What is the origin?** From NN interaction?

New Approach for fit to the charge radii: Duflo-Zuker formula

Courtesy of J. Bonnard

$$\sqrt{\langle r_\pi^2\rangle} = \rho_\pi = A^{1/3}\left[\rho_0 - \frac{\zeta}{2}\frac{t}{A^{4/3}} - \frac{\upsilon}{2}\left(\frac{t}{A}\right)^2\right] e^{g/A} + \lambda\left[\frac{z(D_\pi - z)}{D_\pi^2}\times\frac{n(D_\nu - n)}{D_\nu^2}\right] A^{-1/3}$$

- Fit yield **very good results** for A<60 N>Z nuclei
- The quality of the DZ fit **does not depend on ζ** = Isovector monopole polarizability – thickness of nuclear skin



How to understand Z>N radii?

- Mirror nuclei seen as core+p or core+n
  - charged sphere + particle yield severe underestimation of MDE → Nolen-Schiffer Anomaly (NSA)
- MDE depends strongly on the radii
  - **Let's play with the radii to reproduce MDE, solving NSA**

Isovector monopole polarizability

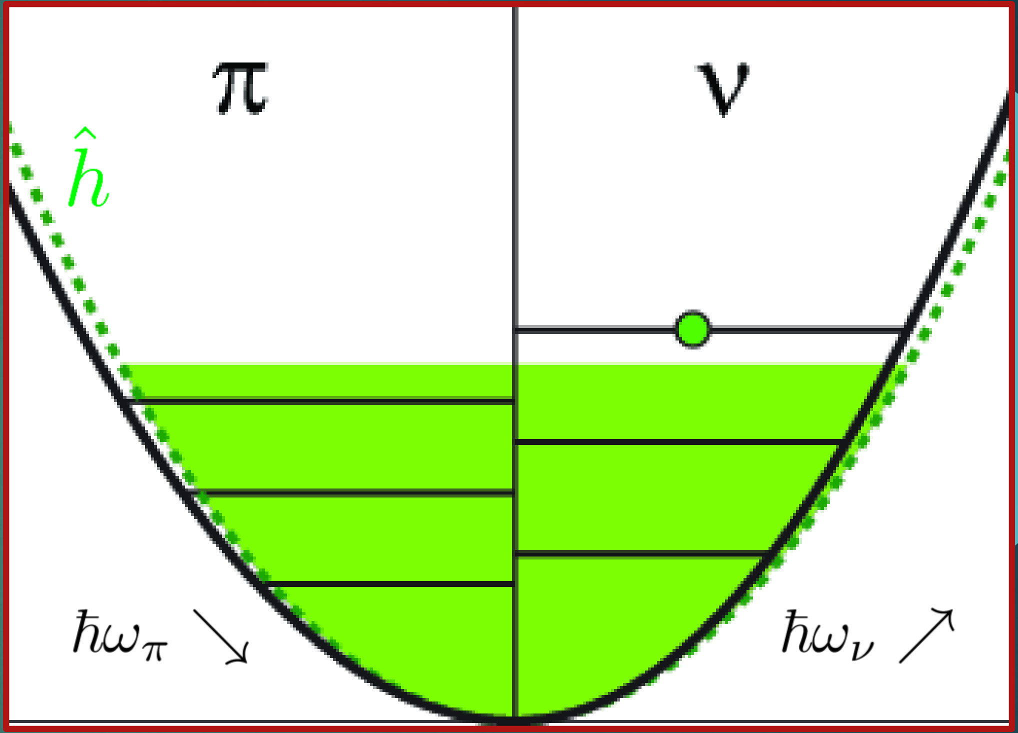
Toy model

Zuker, Czech. J. Phys. B 25, 311 (1975)

The extra particle polarizes the system by inducing particle-hole jumps from the core

$$\hat{H} = \hat{h} + \hat{H}_0 + \hat{H}_1$$

- $\hat{h}$ *unperturbed system*
- $\hat{H}_0$ *isoscalar: overall increase*
- $\hat{H}_1$ *isovector: differential contraction-dilation of the fluids*



Approximate solution:

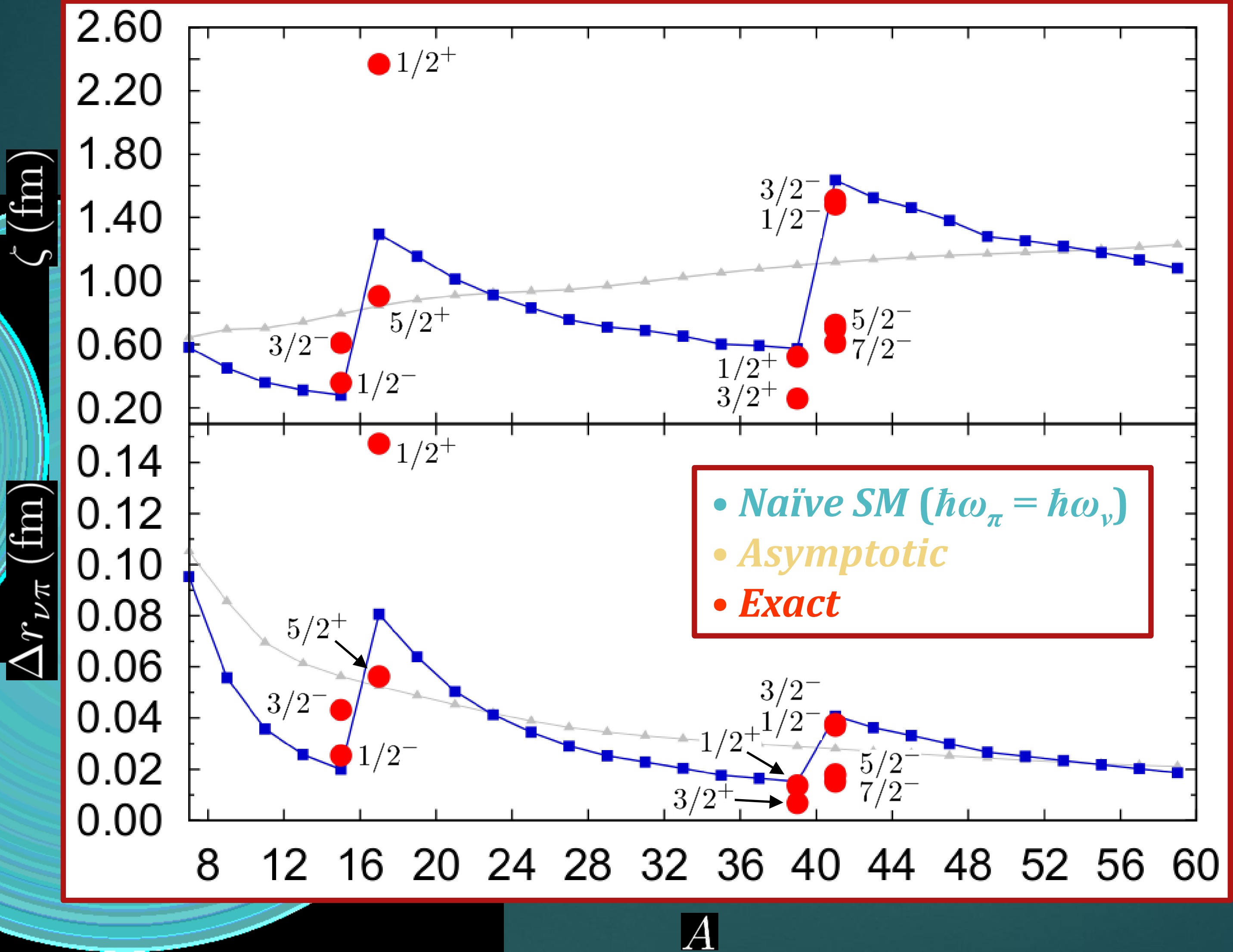
The NSA disappears as the ***proton and neutron radii tends to equalize***

$$\hbar\omega_\nu > \hbar\omega_\pi$$

$0\hbar\omega$ *no-core shell model with* $V_{\mathrm{low}-k}$ *potentials from* ***chiral N3LO interaction*** *that* ***incorporates all isospin-breaking effects***

Results for binding energies

Single-particle/hole states built on ^{16}O and ^{40}Ca



$s_{1/2}$ and $p_{3/2,1/2}$ orbits in the ^{17}O and ^{41}Ca respectively are **huge**

Bonnard, Lenzi, Zuker, PRL 113, 212501 (2016)

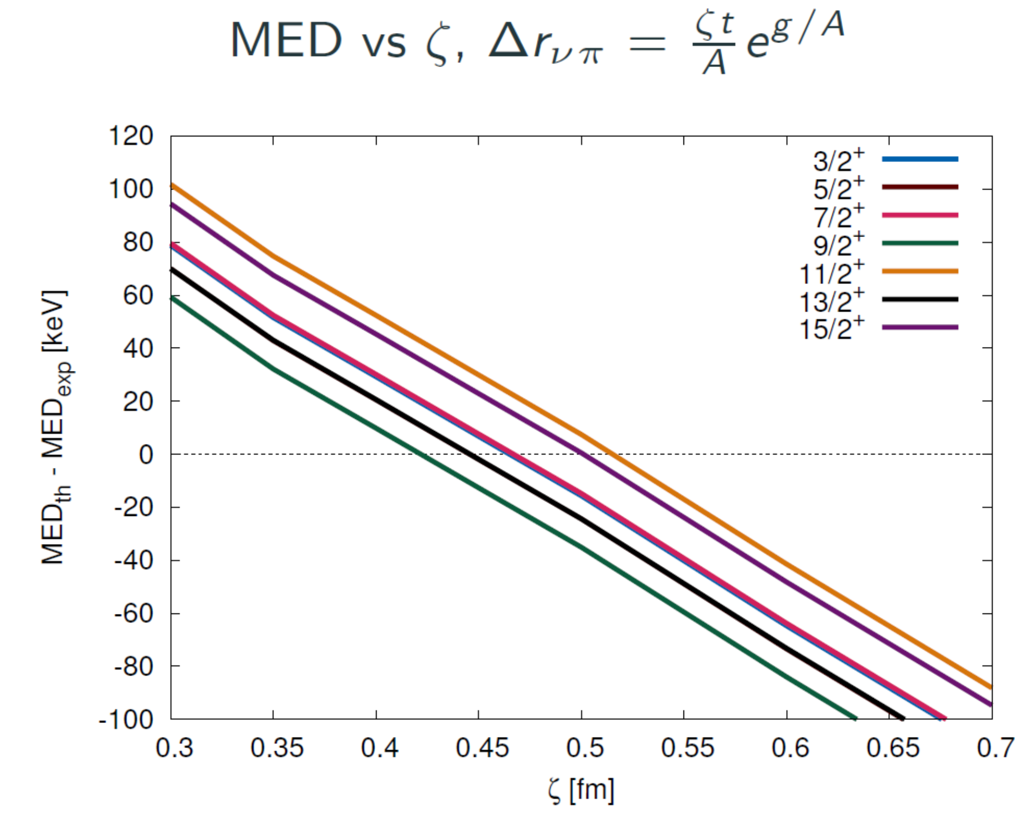
ζ - Isovector polarizability from MED

How to get $\hbar\omega_{\nu,\pi}$ for both nuclei??

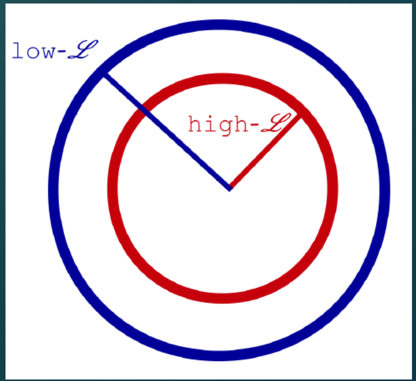
- $\hbar\omega_{\pi,\nu} \propto \frac{1}{\langle r^2_{\pi,\nu} \rangle}$
- 4 radii to determine
- IS: $r_\pi(N > Z) = r_\nu(N < Z)$
- $r_\pi(N > Z)$ is **measured**
- $r_\nu(N > Z)$ from **MED** ?

- MED **decrease** when skin increases
- **Linear** dependence
- For **each state** we can determine the value of the **skin**

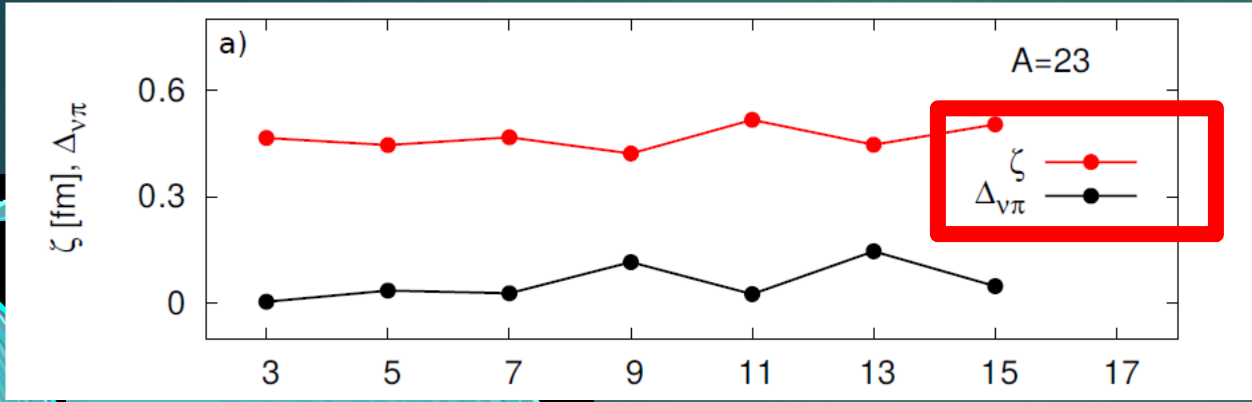
From **MED** we can determine the **neutron skin** value as a **function of J** (not measurable)



Can we relate the neutron skin with the difference of **occupation numbers of protons and neutrons in low-l orbitals??**

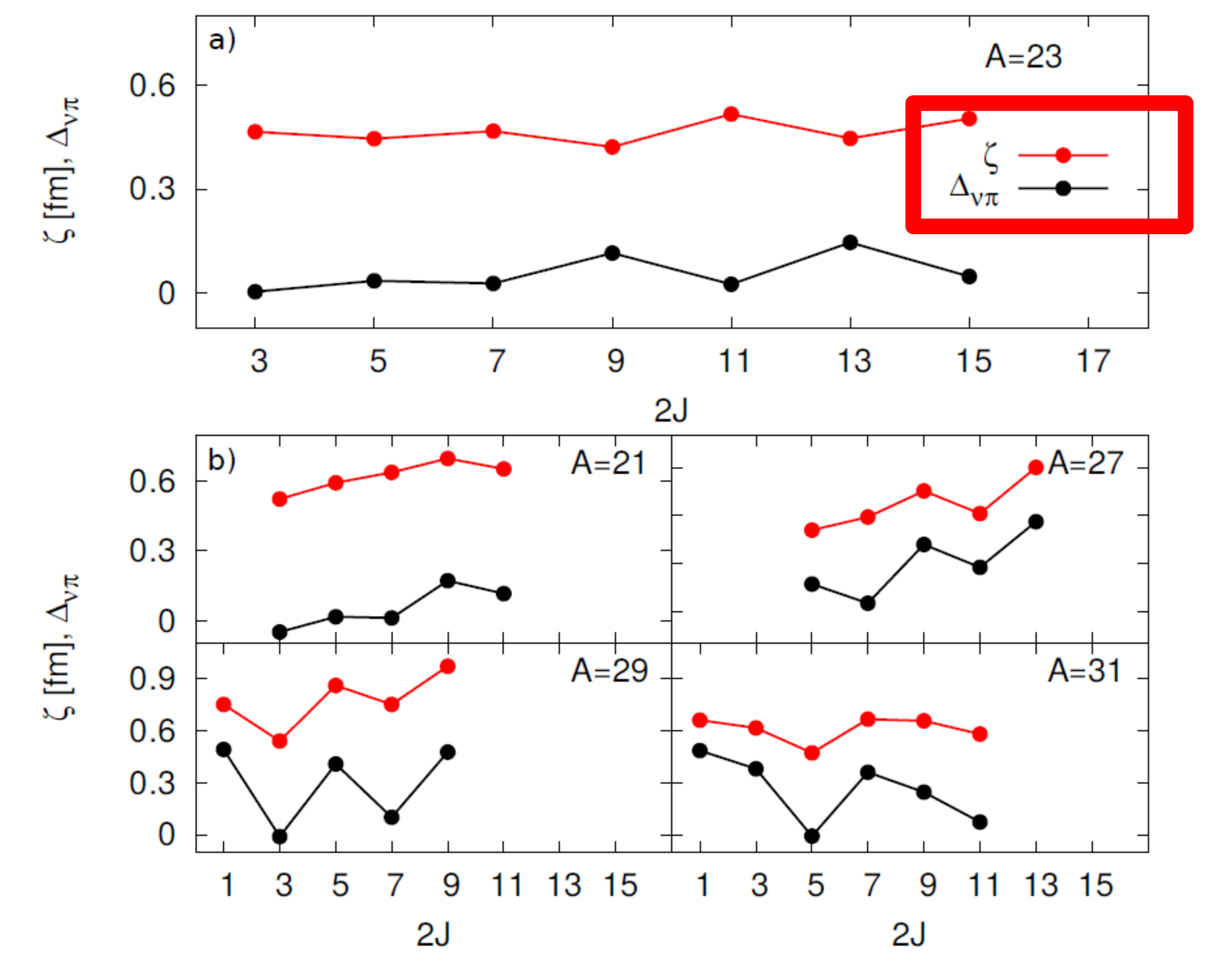


Neutron skin vs $s_{1/2}$ occupation numbers



- Clear correlation between the **difference in occupation numbers in the $s_{1/2}$ orbit** of protons and neutrons and the **neutron skin**

Neutron skin vs $s_{1/2}$ occupation numbers

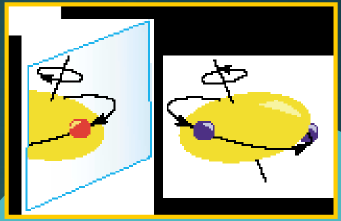


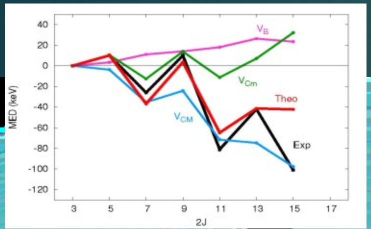
- Clear correlation between the **difference in occupation numbers in the $s_{1/2}$ orbit** of protons and neutrons and the **neutron skin**

Boso, Phys.Rev.Lett. 121, 032502 (2018)

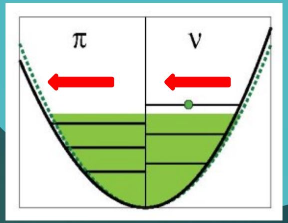
Conclusions

- Experimental Mirror Energy Differences in mirror nuclei **A=23** extended up to J = 15/2$^+$

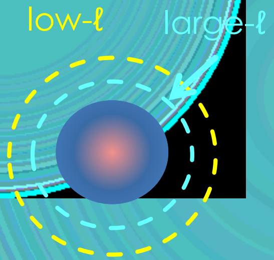




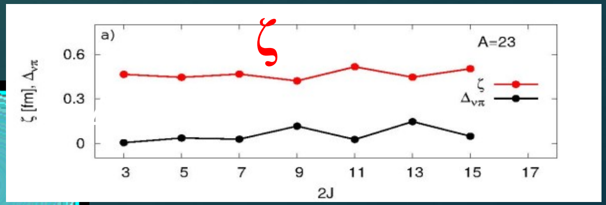
- Mirror Energy differences interpreted via the **USD interaction** and the procedure successfully adopted in the $f_{7/2}$ mirror nuclei



- Realistic chiral N3LO potential with different potential wells for π and ν adopted to reproduce MED



- Proved the possibility to determine the neutron skin for each excited state from the measured MED



- **Strong correlation between neutron skin and difference in occupation numbers of the $s_{1/2}$ orbit**