CORTONA 2013

XIV CONVEGNO su PROBLEMI di FISICA NUCLEARE TEORICA

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# Realistic shell-model calculations and exotic nuclei

Angela Gargano, INFN Napoli

# Outline

- **Theoretical framework**
- **Results for different mass regions**

✓ **Oxygen isotopes**

✓ **Nuclei north-east $^{48}$Ca**

✓ **$^{132}$Sn neighbors**

- **Outlook**



# The "Realistic" Shell Model

- **Eigenvalue problem**

$$H_{eff}\psi_{\alpha} = E_{\alpha}\psi_{\alpha}$$

$$H_{eff} = U + V_{eff} = \sum_i \varepsilon_i a_i^+ a_i + \frac{1}{4}\sum_{ijkl} \langle ij \mid V_{eff} \mid kl \rangle a_i^+ a_j^+ a_l a_k$$

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$$\langle ij | H_{eff} | kl \rangle$$

from the free potential

$$V_{NN} + (V_{NNN})$$

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$$\langle ij \mid H_{eff} \mid kl\rangle \quad \Longleftrightarrow \quad \text{from the free potential } V_{NN} + (V_{NNN})$$

◆ **Understand the properties of nuclei starting from the forces between nucleons**

◆ **Understand limits of the theory, because of the absence of free parameters**

# The "Realistic" Shell Model

## Schrödinger equation for A nucleons

$$\boxed{H\psi_\alpha = (H_0 + H_1)\psi_\alpha = E_\alpha \psi_\alpha}$$

$$\begin{cases} H_0 = T + U \\ H_1 = V_{NN} - U \end{cases}$$

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## Shell-model equation for N-valence nucleons in a reduced space

$$PH_{eff}P\psi_\alpha = P(H_0 + V_{eff})P\psi_\alpha = E_\alpha P\psi_\alpha$$

$$P = \sum_{i=1}^{d} |\phi_i\rangle\langle\phi_i|$$

$$\phi_i = [a_1^+ a_2^+ \dots a_N^+]|c\rangle$$

# Derivation of $H_{eff}$

## Two main ingredients

- Nucleon-nucleon potential

- Many-body theory

L. Coraggio et *al*, Prog. Part. Nucl. Phys. 62, 135 (2009)
L. Coraggio et *al*, Annals of Phys. 327, 2061 (2012)



# Nucleon-Nucleon potential

Potentials which reproduce the two-body data with

$\chi^2/N_{data} \sim 1$

- **CD-Bonn**

- **Chiral potentials**

✓ long-range components ruled by the symmetries of the low-energy QCD

✓ two- and many-body forces generated on the same footing

calculations: 2 body at next-to-next-to-next-to-leading order – $N^3LO$
3 body at next-to-next-to-leading order - NNLO

# Optimitazion of the NN chiral potential

namely of the short-range components included as contact terms and parametrized in terms of constants

PRL 110, 192502 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

## Optimized Chiral Nucleon-Nucleon Interaction at Next-to-Next-to-Leading Order

A. Ekström,[1,2] G. Baardsen,[1] C. Forssén,[3] G. Hagen,[4,5] M. Hjorth-Jensen,[1,2,6] G. R. Jansen,[4,5] R. Machleidt,[7] W. Nazarewicz,[5,4,8] T. Papenbrock,[5,4] J. Sarich,[9] and S. M. Wild[9]

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[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Fundamental Physics, Chalmers University of Technology, SE 412 96 Göteborg, Sweden*
[4]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
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[6]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
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[8]*Faculty of Physics, University of Warsaw, ul. Hoża 69, 00-681 Warsaw, Poland*
[9]*Mathematics and Computer Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

(Received 19 March 2013; published 7 May 2013)

We optimize the nucleon-nucleon interaction from chiral effective field theory at next-to-next-to-leading order (NNLO). The resulting new chiral force $\mathrm{NNLO}_{\mathrm{opt}}$ yields $\chi^2 \approx 1$ per degree of freedom for laboratory energies below approximately 125 MeV. In the $A = 3$, 4 nucleon systems, the contributions of three-nucleon forces are smaller than for previous parametrizations of chiral interactions. We use $\mathrm{NNLO}_{\mathrm{opt}}$ to study properties of key nuclei and neutron matter, and we demonstrate that many aspects of nuclear structure can be understood in terms of this nucleon-nucleon interaction, without explicitly invoking three-nucleon forces.

# $V_{low-k}$ potential

**High-momentum repulsive components of $V_{NN}$ prevent its use in nuclear structure perturbative calculations**

$V_{low-k}$ **potential**

- is confined within a momentum-space cutoff $\Lambda$

high-momentum modes are integrated out down to $\Lambda$

- preserves the onshell properties of the original NN potential

# The perturbative approach to the shell-model $H_{eff}$

## $\hat{Q}$ - box folded-diagram method

- $H_{eff}$ is written as a series

in terms of the $\hat{Q}$ - box and its derivatives

$$\boxed{\hat{Q} = PH_1P + PH_1Q \frac{1}{\varepsilon - QHQ} QH_1P}$$

*Q=1-P*

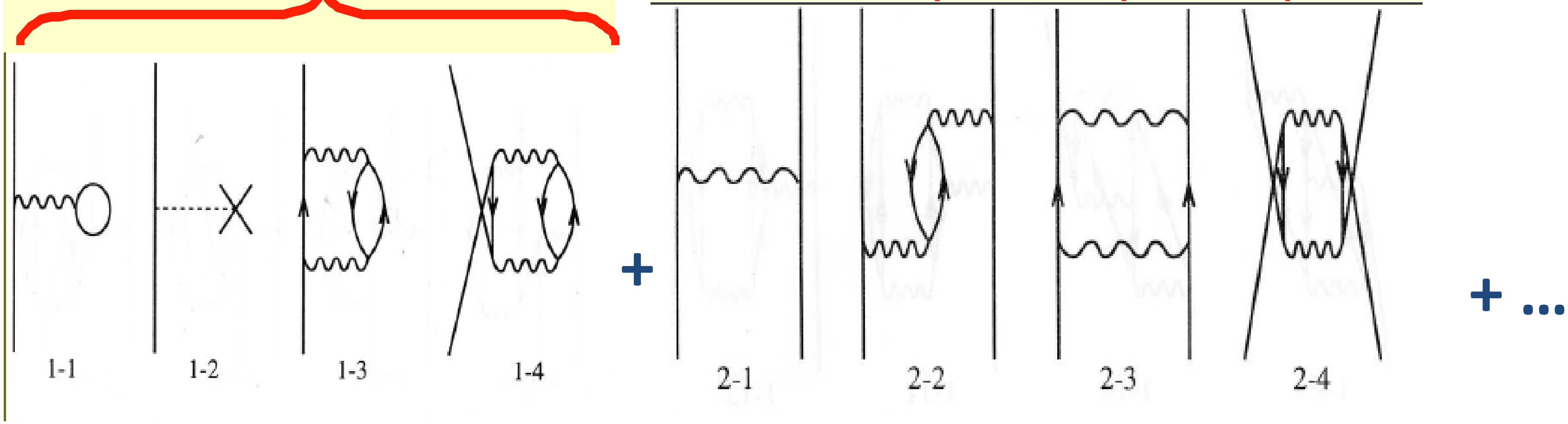
**ε = unperturbed energy for a degenerate model space (*$PH_0P=\varepsilon$*)**

- the series for $H_{eff}$ is summed up by iterative techniques (Krenciglowa-Kuo, Lee-Suzuki)

# Diagrammatic expansion of the $\hat{Q}$- box

1-body diagrams up to 2nd order S-box

2-body diagrams up to 2nd order: V $V_{1p1h}$ $V_{2p}$ $V_{2p2h}$




with $V_{low\text{-}k}$ in the interaction vertices

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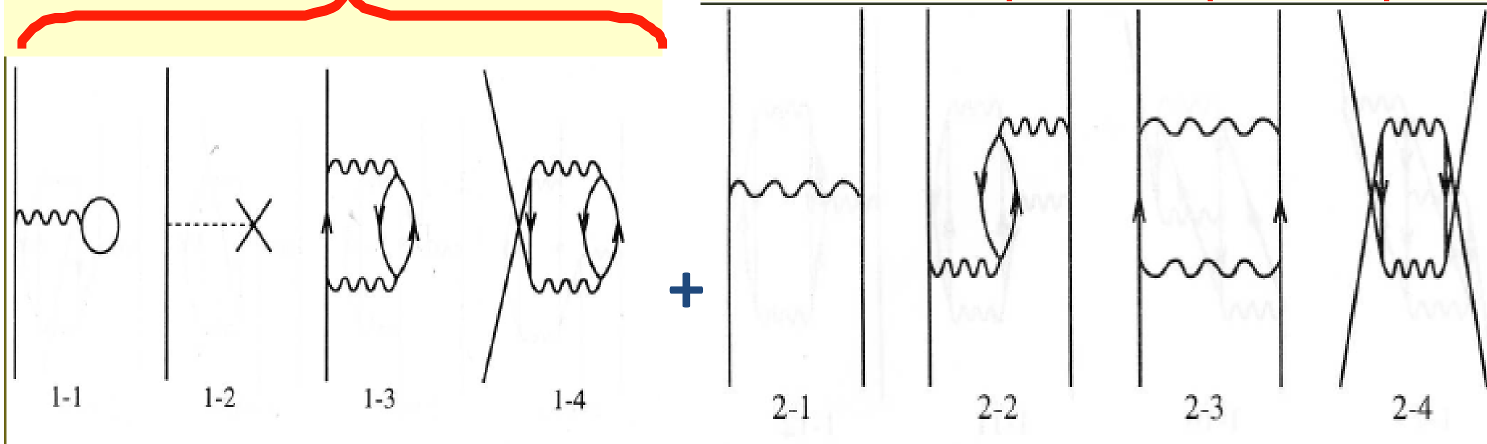


+ ...

with $V_{low\text{-}k}$ in the interaction vertices

**Note:** No (V-U)-insertion diagrams [1-1+1-2] are shown except for the 1-body 1st-order case. These arise from the presence of -U in $H_1$=V-U, and are zero only when U=HF potential



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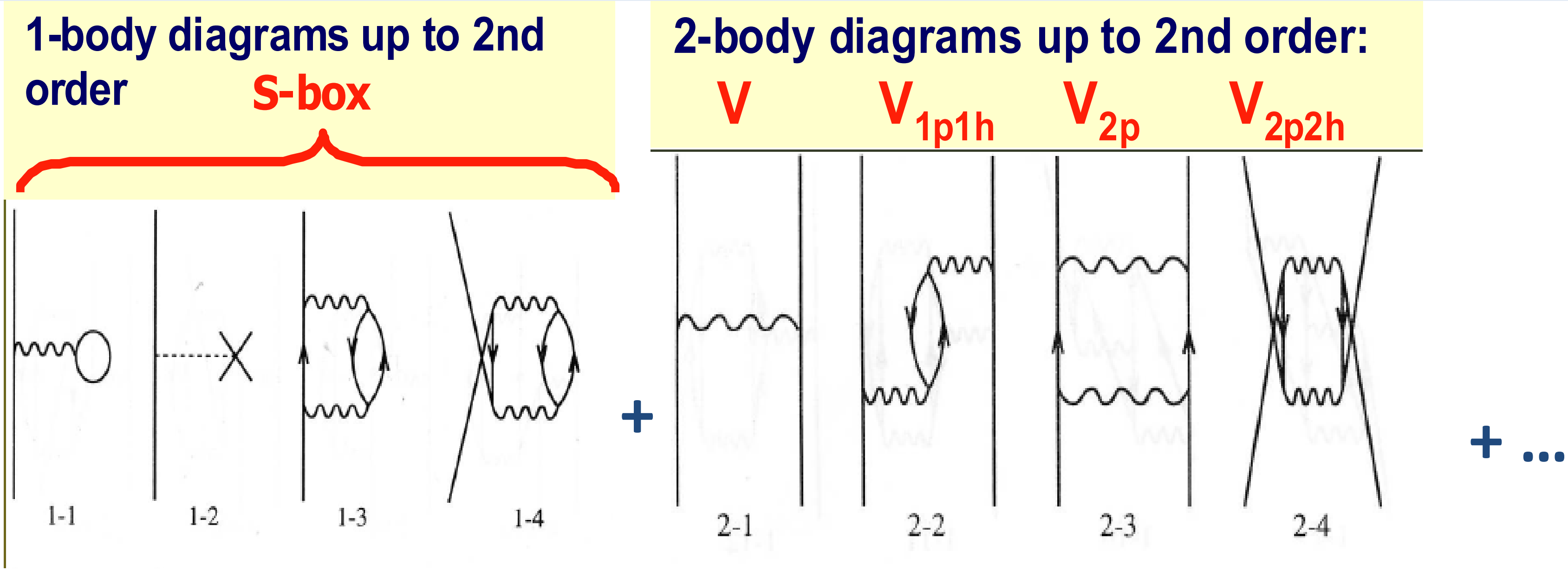


**with $V_{low-k}$ in the interaction vertices**

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**Modern calculations do not go beyond third order**

# Convergence properties

- order-by-order convergence

inclusion of diagrams up to finite order in the interaction

- intermediate-state space convergence

truncation of the Q space

L. Coraggio et *al*, Annals of Phys. 327, 2061 (2012)

# Remarks on the calculation of $H_{eff}$

◆ $\mathbf{H_{eff}}$ is constructed for a **two-valence-particle nucleus** and used for more complex systems ➔ **three- or higher-body forces arising for these systems** *(even if the original potential contains only two-body terms)* **are not taken into account**

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◆ **Single particle energies**

**two-body component**

$$H_{eff} = U + V_{eff} = U + V^{(1)}_{eff} + V^{(2)}_{eff}$$

**one-body component**

**from theory – S-Box**

**from experiment**

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# Oxygen isotopes

L. Coraggio et *al*, J.Phys, Conf. Ser. 312, 092021 (2011)

- **$V_{eff}$ @ third order from $N^3LOW$+ Coulomb interaction**

  $N^3LOW=N^3LO$ with a sharp cutoff (2.1 $fm^{-1}$)
  ➔no need of $V_{low-k}$

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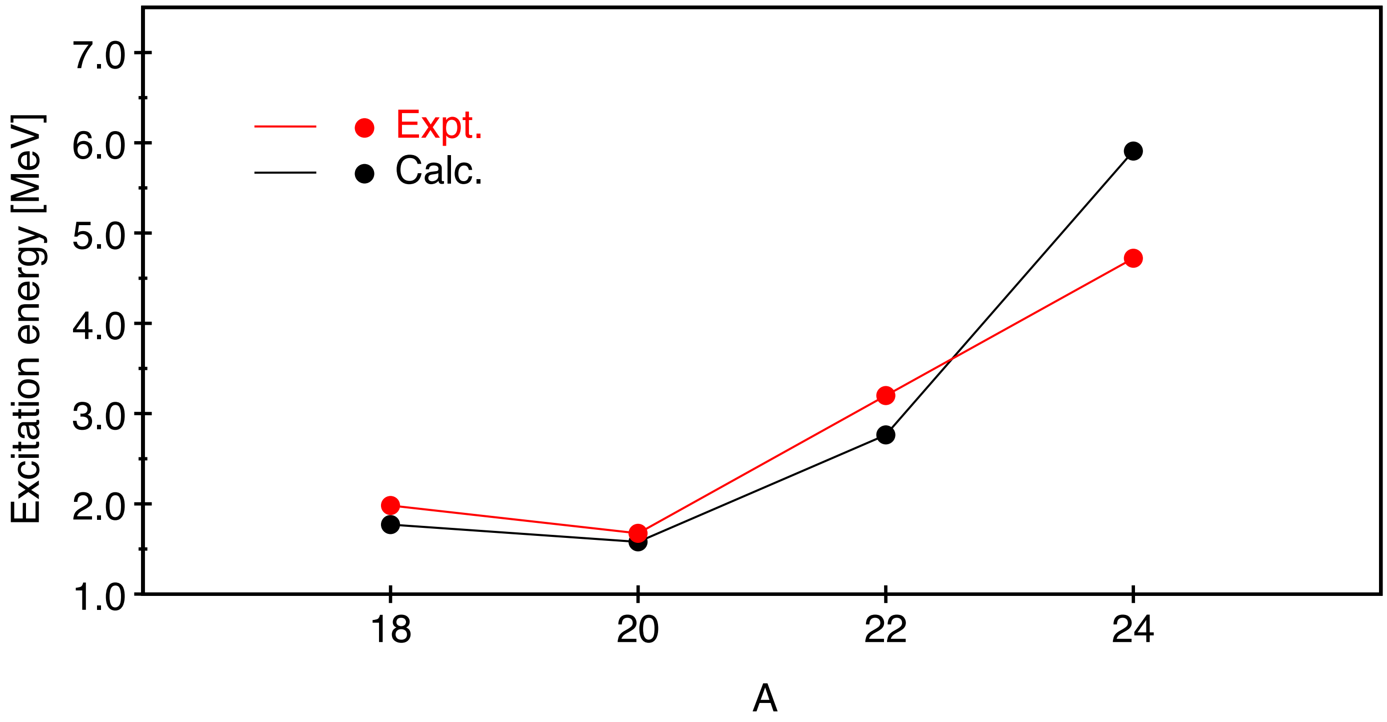
magicity @ N= 14 & 16

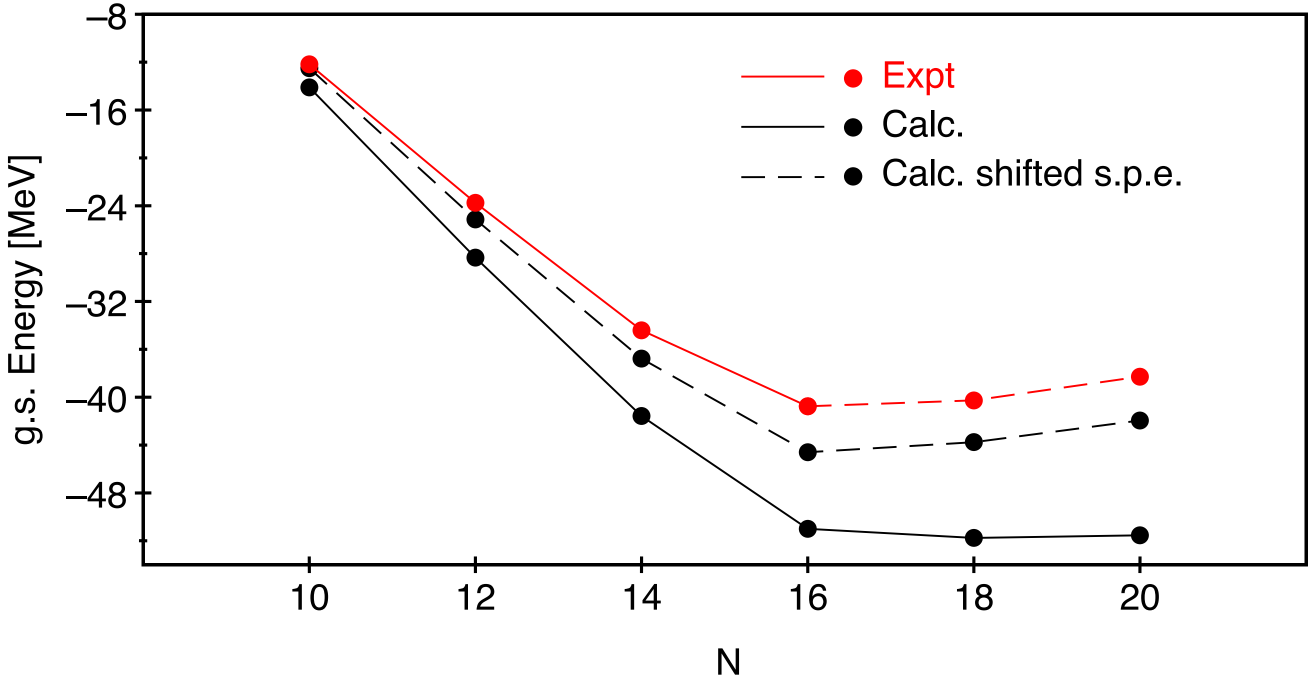
location of the neutron drip line and 3-body forces

T. Otsuka et al, PRL 105, 032501 (2010)
G. Hagen et al, PRL 108, 242501 (2012)
H. Hergert et al, PRL, 110, 242501 (2013)…

# Yrast $2^+$ states in Oxygen isotopes



# Ground-state energies for Oxygen isotopes

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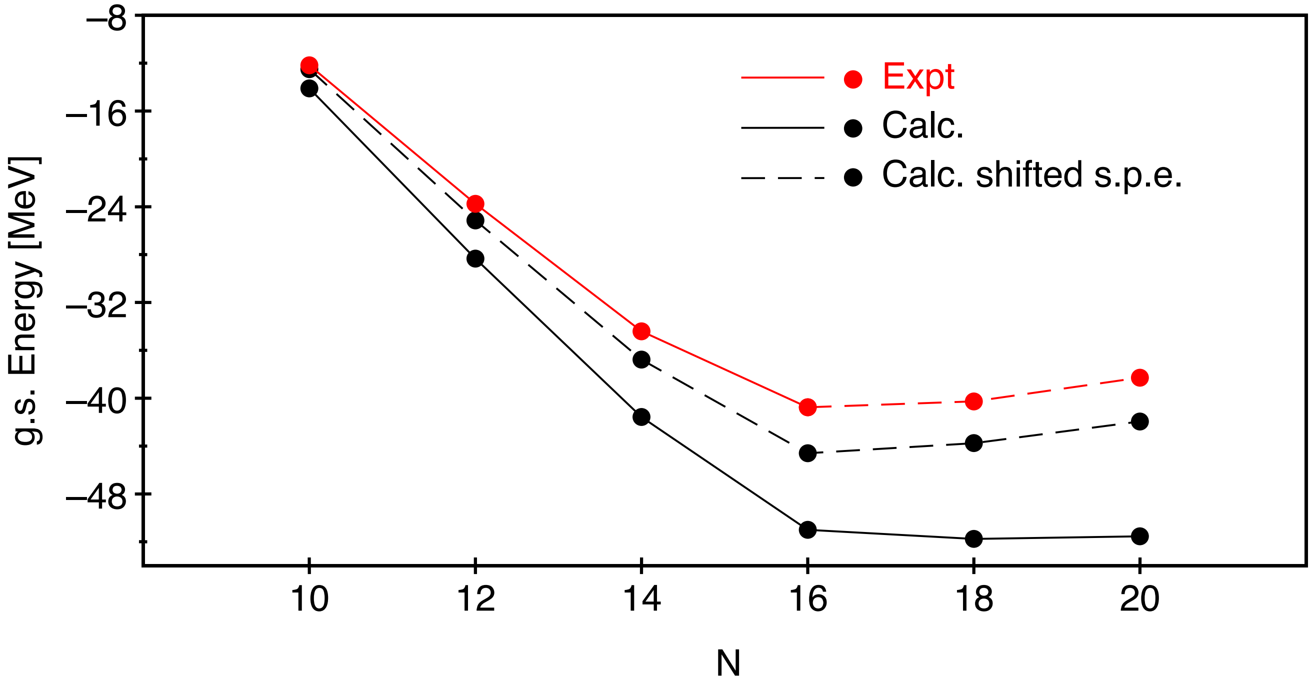


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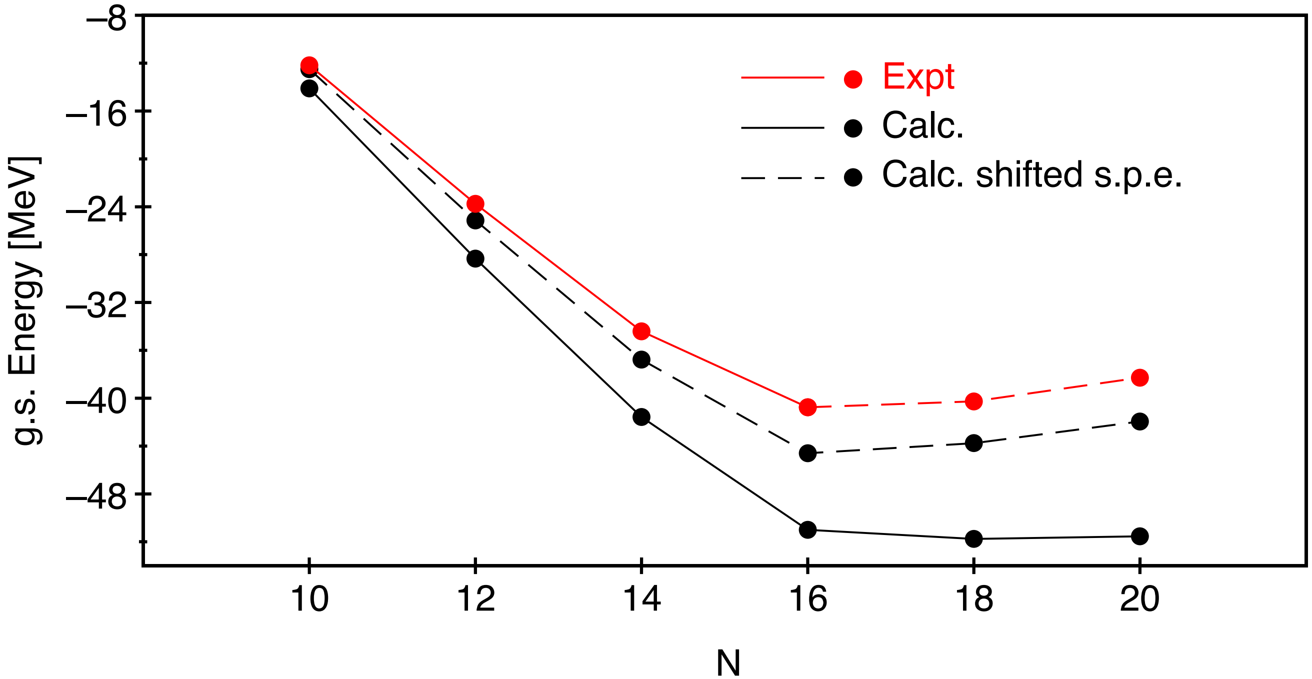


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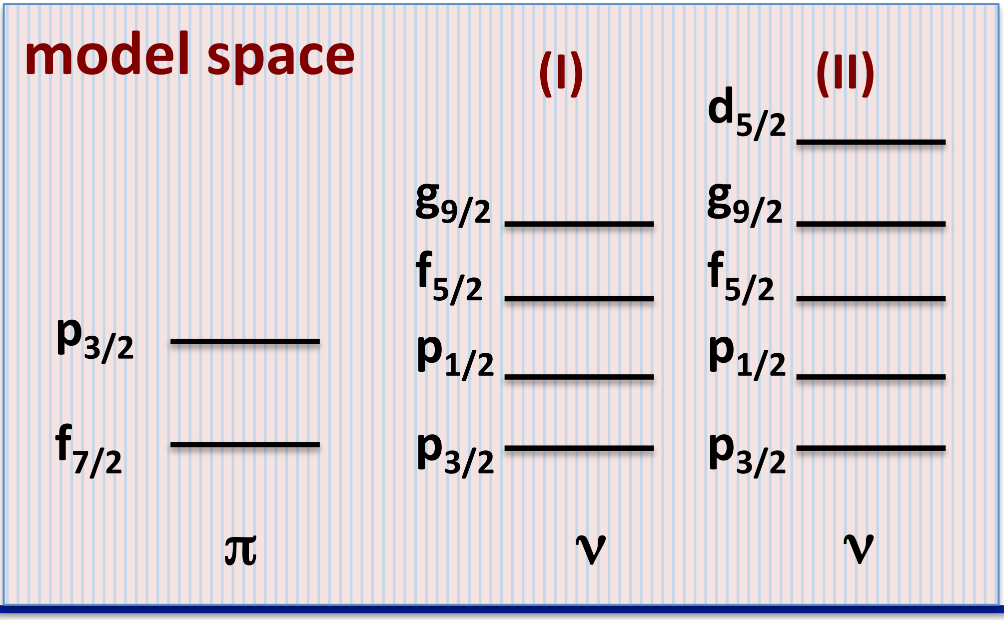
Three-body forces???

# Nuclei north-east $^{48}$Ca
## $_{22}$Ti, $_{24}$Cr, $_{26}$Fe, and $_{28}$Ni

- **$V_{eff}$ @ third order from $V_{low-k}$ of CD-Bonn ($\Lambda$=2.6 fm$^{-1}$) + Coulomb interaction**
- **SP energies from experiment**
- **effective $e_\pi$ & $e_\nu$ derived consistently with $H_{eff}$**




L. Coraggio et *al*, submitted to Phys. Rev. C

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✓ N/Z value of 1.79 for $^{78}Ni$

✓ the shell structure evolves through three different subshell closures at N = 28, 40, 50

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- **Disappearance of the N=40 shell closure and onset of a collective behavior** when removing protons from the $f_{7/2}$ orbital

**"island of inversion" as @ N=20 ($^{32}Mg$)**

S.M. Lenzi et al, PRC **82**, 054301 (2010)
A. Gade et al, PRC **81**, 051304(R) (2010)
K. Sieja et al, PRC **85**,051301(R) (2012)…

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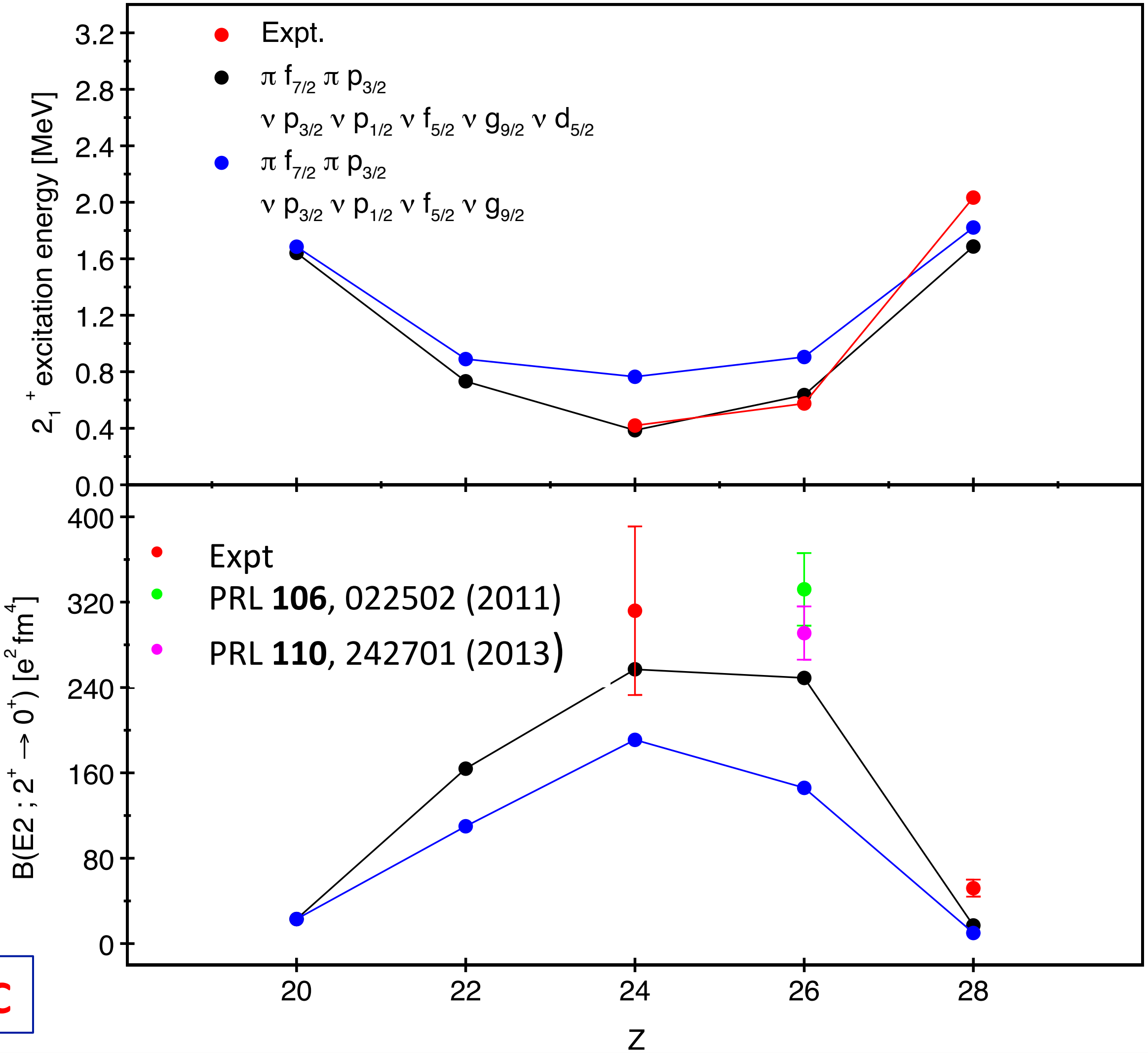
**"island of inversion" as @ N=20 ($^{32}Mg$)**

**This may be explained as due to the interplay of**

✓ reduction in the neutron $g_{9/2}$ - $f_{5/2}$ gap induced by proton holes in the $f_{7/2}$ orbital

✓ quadrupole-quadrupole component of the effective interaction between the neutron $g_{9/2}$ and $d_{5/2}$ orbitals

# Energy of the yrast $2^+$ state and B(E2; $2^+ \rightarrow 0^+$) for Ca, Ti, Cr, Fe, and Ni @ N=40



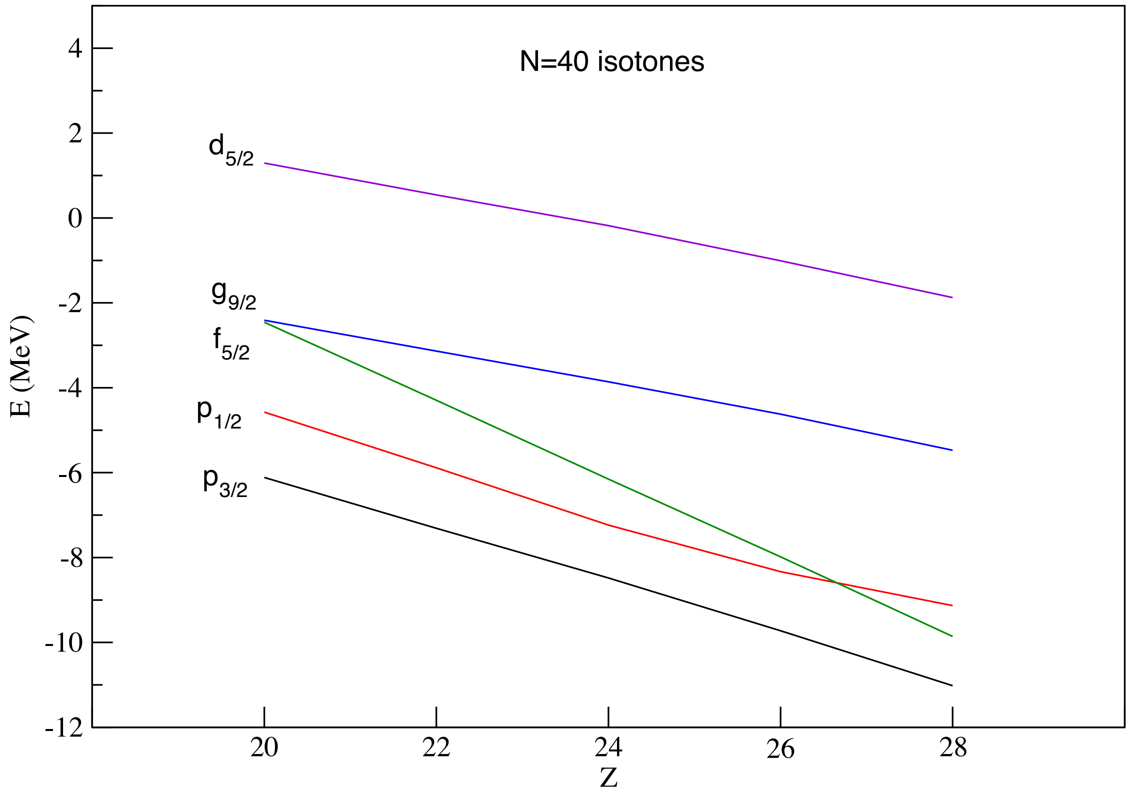

Expt= NNDC

# ESPE @ N=40

$$\overline{\varepsilon}_{j_\nu} = \varepsilon_{j_\nu} + \sum_{j'_\pi} V^M(j_\nu j'_\pi) N_{j'_\pi}$$

$V^M$ monopole interaction

$N_j$ number of nucleons in orbit j



# Neutron ESPE @ N=40

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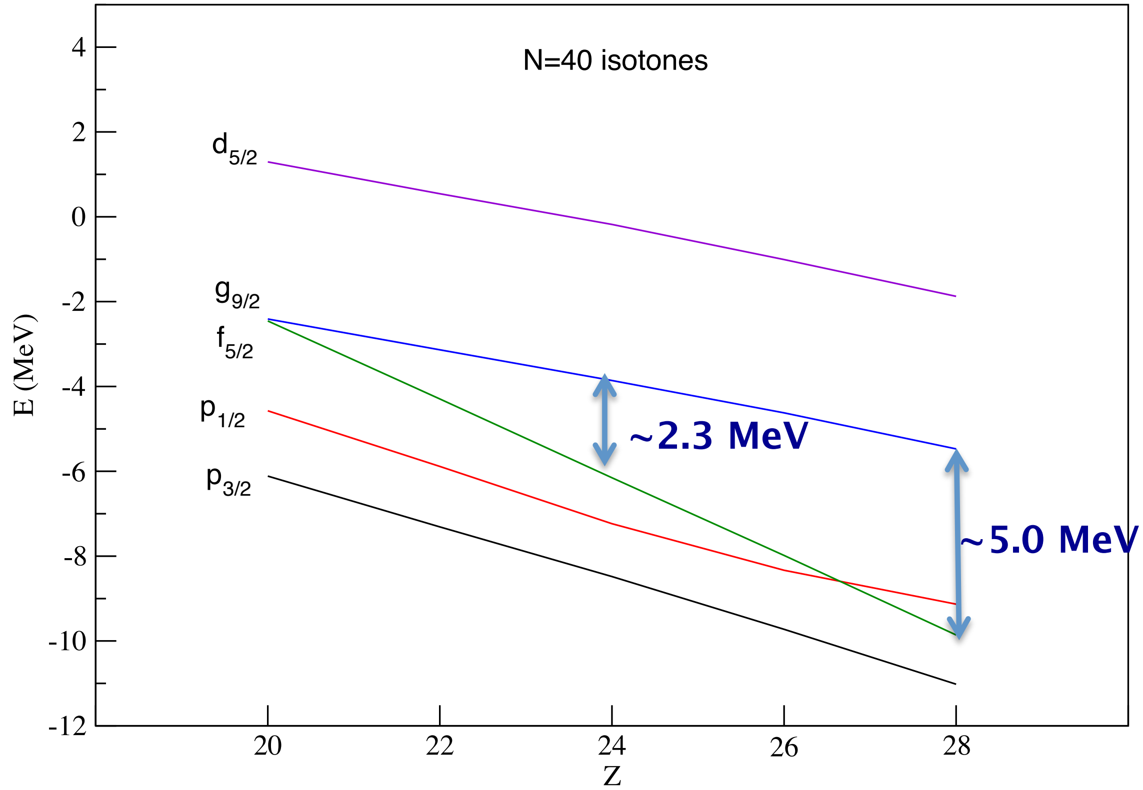

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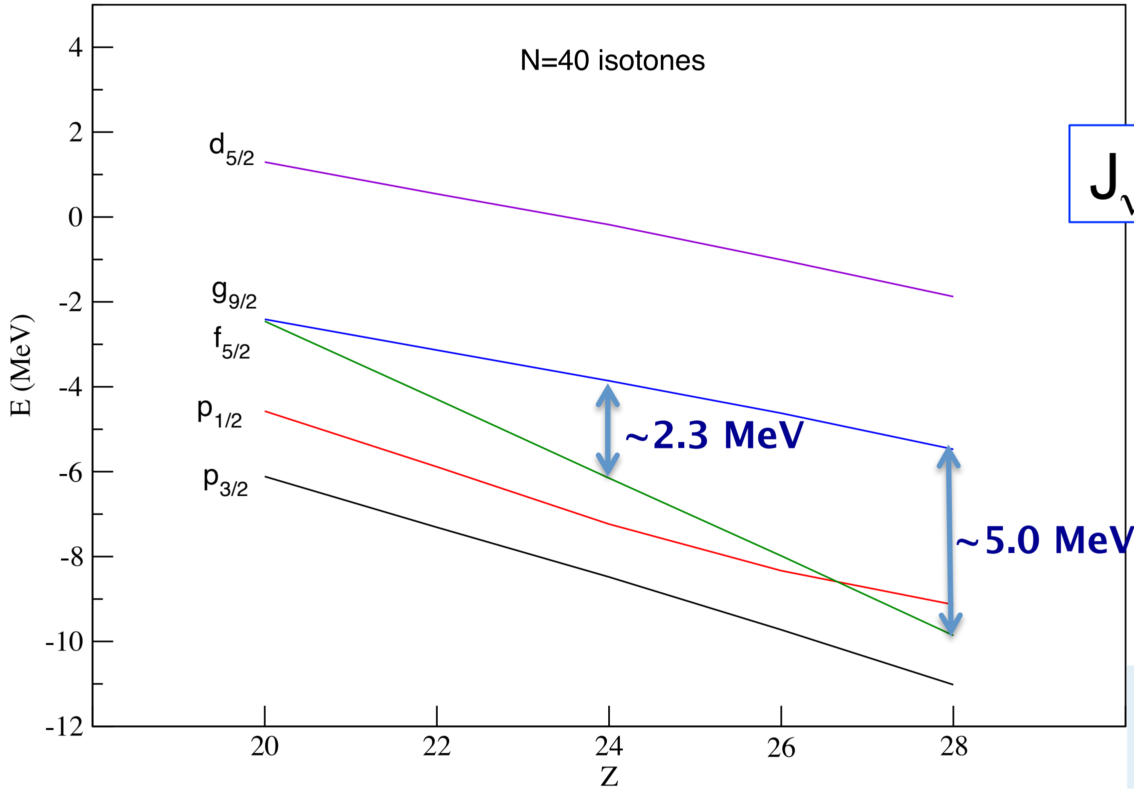
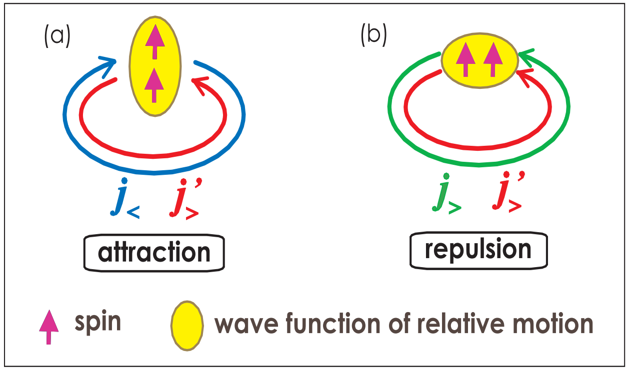



tensor force

$J_\pi(f_{7/2})=l+1/2$

$J_\nu(f_{5/2})=l-1/2$ $J_\nu(g_{9/2})=l+1/2$




[T. Otsuka et al, PRL **95**, 232502 (2005)]

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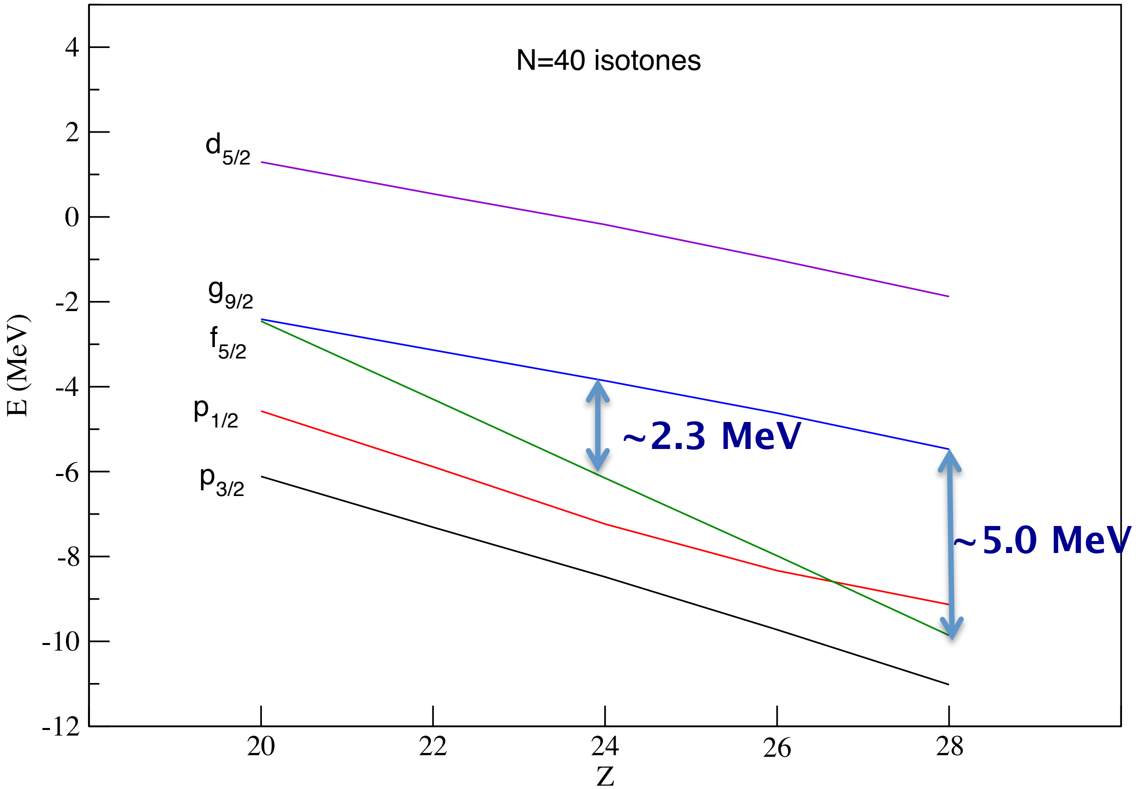


## Occupation numbers

| | | I | II |
|---|---|---|---|
| Ti | πf7/2 | 1.87 | 1.69 |
| | νg9/2 | 3.23 | 3.72 |
| | νd5/2 | | 0.36 |
| Cr | πf7/2 | 3.64 | 3.31 |
| | νg9/2 | 2.88 | 3.73 |
| | νd5/2 | | 0.57 |
| Fe | πf7/2 | 5.61 | 5.31 |
| | νg9/2 | 1.75 | 2.81 |
| | νd5/2 | | 0.33 |
| Ni | πf7/2 | 7.89 | 7.85 |
| | νg9/2 | 0.42 | 0.47 |
| | νd5/2 | | 0.05 |

# $^{132}$Sn region

A. Covello et *al*, J. Phys. Conf. Ser. **267**, 012019 (2011), and refs therein
L. Coraggio et *al*, Phys. Rev. C **87**, 034309 (2013), and refs therein

- **$V_{eff}$ @ second order from $V_{low\text{-}k}$ of CD-Bonn ($\Lambda$=2.2 fm$^{-1}$) + Coulomb interaction**

- **SP energies from experiment**

proton particles and neutron holes in $0g_{7/2}$,1d,2s,$0h_{11/2}$
neutron particles in $0h_{9/2}$,1f,2p,$0i_{13/2}$

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Possible changes of shell structure across the N=82 shell closure



## Peculiar properties of $^{134}$Sn and $^{136}$Te;

*very low excitation energy of the yrast $2^+$ state*

| $\Delta = E_{exc}(2^+_1)$ in MeV | $^{134}$Sn | $^{130}$Sn | $^{134}$Te | $^{136}$Te |
|---|---|---|---|---|
| | 0.73 | 1.22 | 1.28 | 0.61 |



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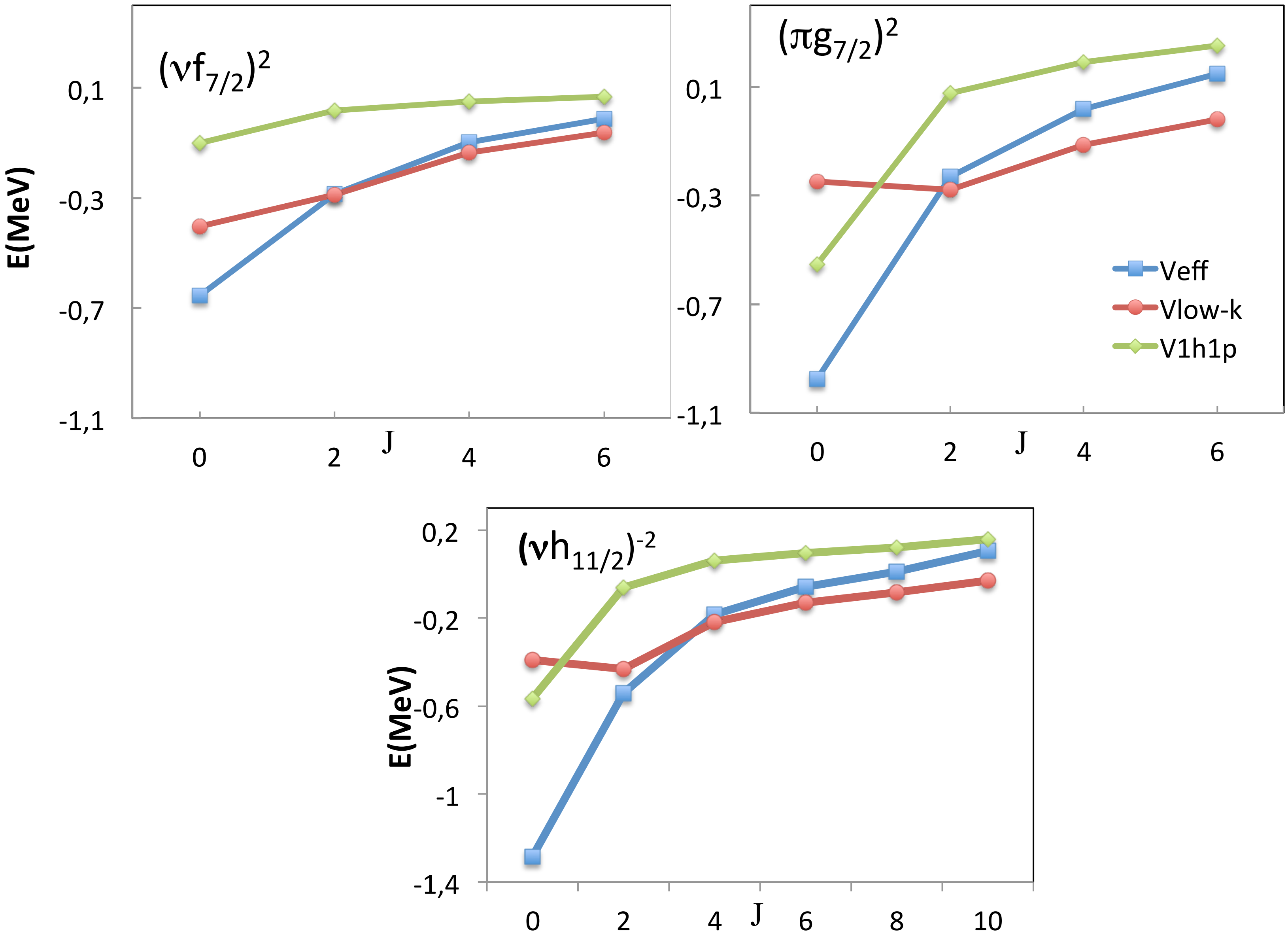
**evidence for a quenching of the N=82 shell closure ?**

**or "neutron pairing reduction for N>82" ?**

**➔the pairing force for 2 neutron particles in the 82-126 shell is *significantly weaker* than that for 2 neutron holes or 2 proton particles in the 50-82 shell**



# Diagonal matrix elements of interaction for the $(\nu f_{7/2})^2$ , $(\pi g_{7/2})^2$ and $(\nu h_{11/2})^{-2}$ configurations



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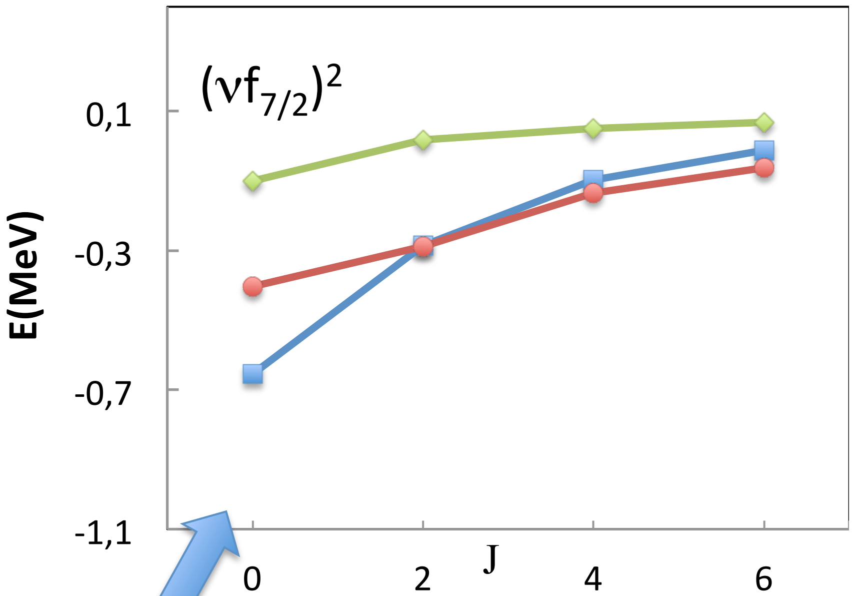
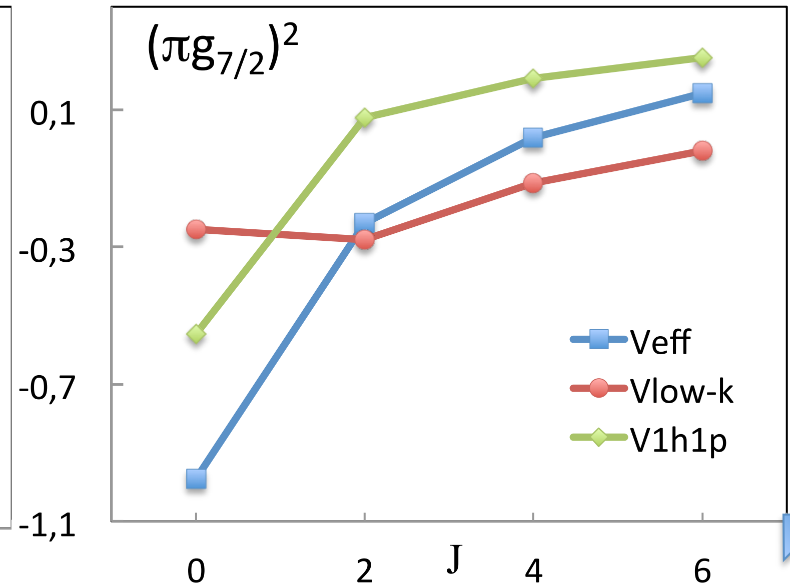
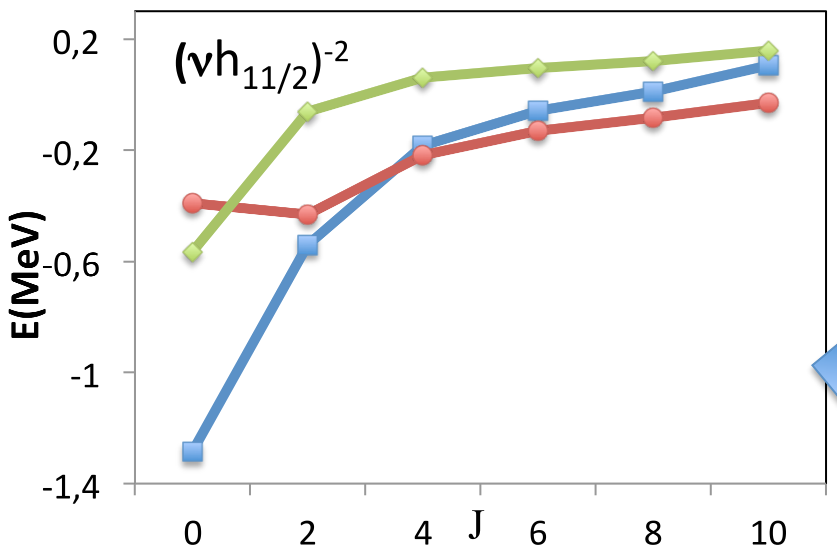



G= -0.16 MeV

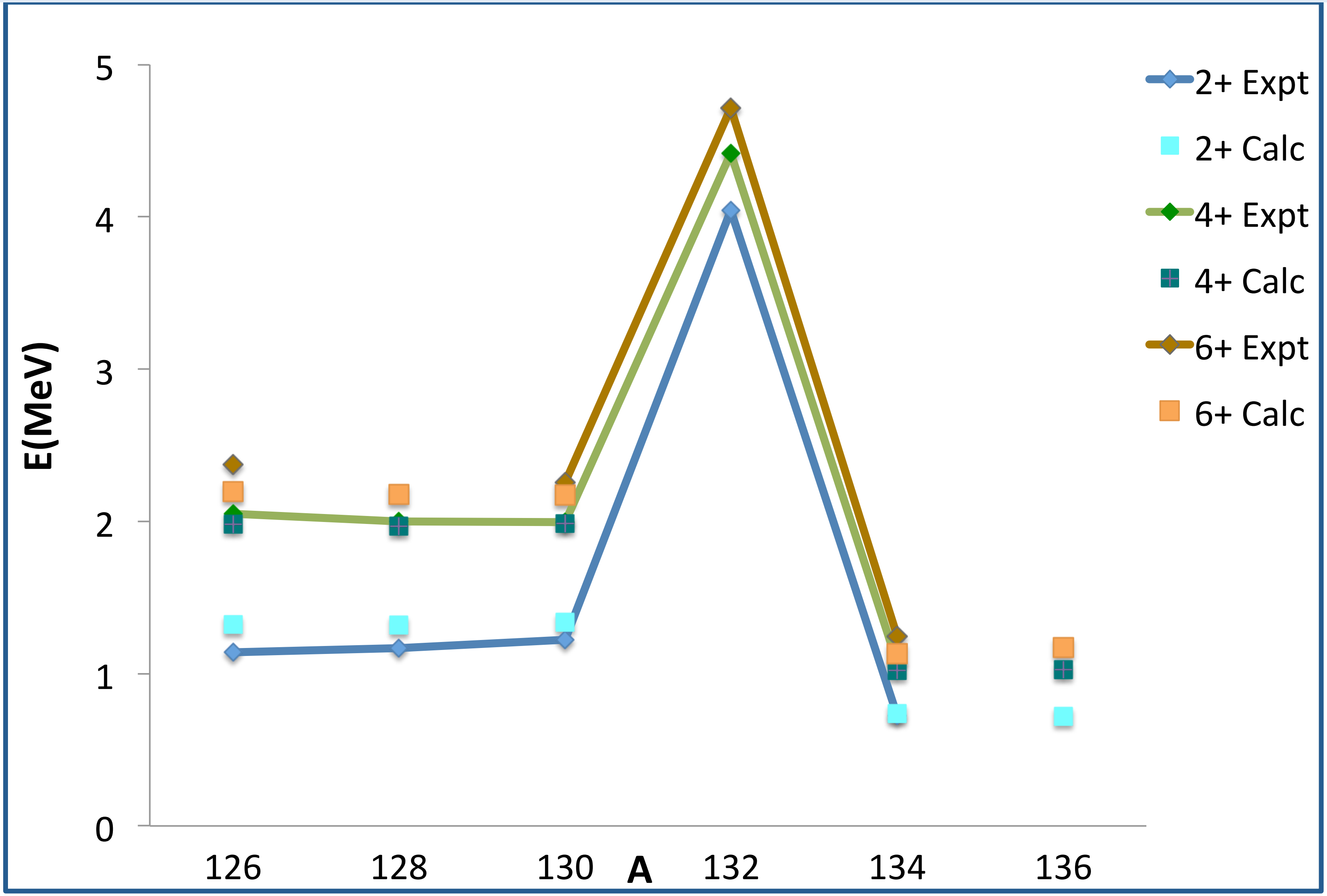



G= -0.24 MeV

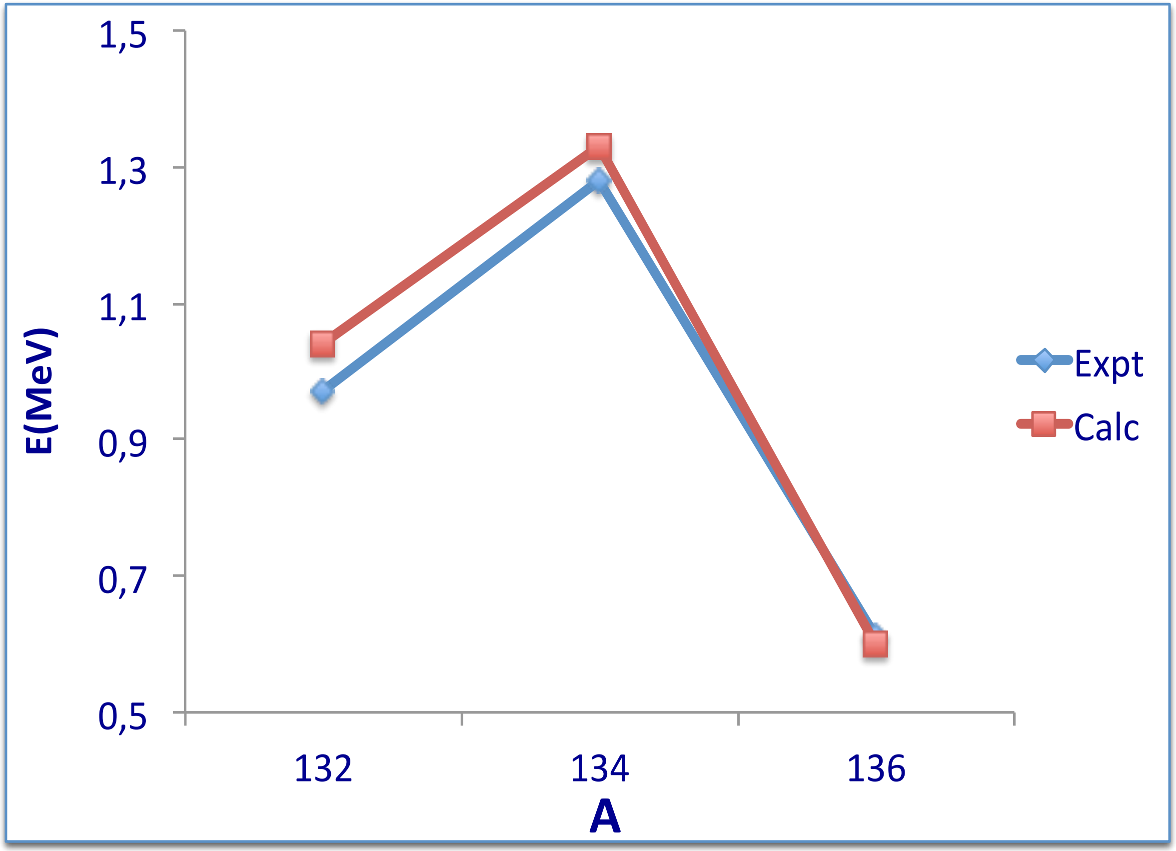



G= -0.21 MeV

# Energy of the $2^+,4^+,6^+$ states for Sn isotopes



# Energy of the $2^+$ state in Te isotopes



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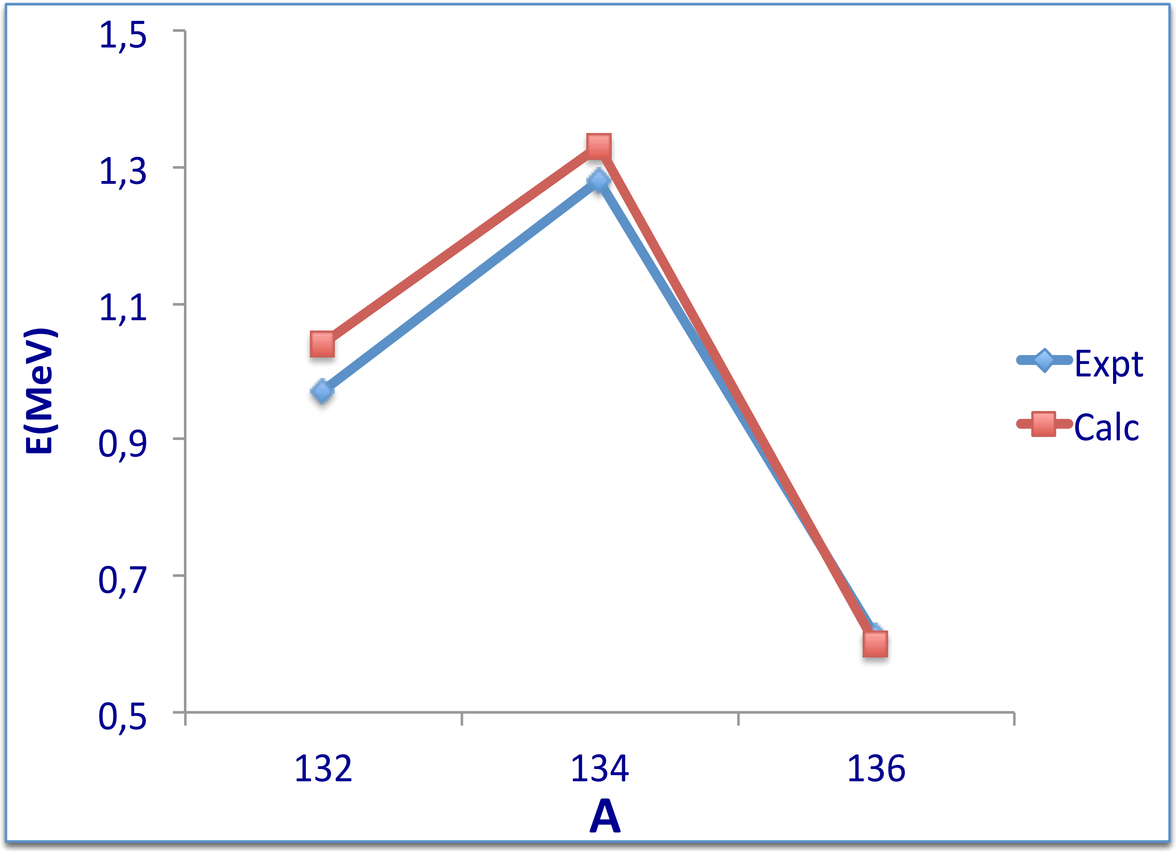


$$\left|{}^{132}\mathrm{Te};2^+_1\right\rangle = 0.66\left|{}^{134}\mathrm{Te};\ 2^+_1\right\rangle\left|{}^{130}\mathrm{Sn};\ 0^+_{gs}\right\rangle + 0.62\left|{}^{134}\mathrm{Te};\ 0^+_{gs}\right\rangle\left|{}^{130}\mathrm{Sn};\ 2^+_1\right\rangle + \cdots$$

$$\left|{}^{136}\mathrm{Te};2^+_1\right\rangle = 0.72\left|{}^{134}\mathrm{Te};\ 0^+_{gs}\right\rangle\left|{}^{134}\mathrm{Sn};\ 2^+_1\right\rangle + 0.36\left|{}^{134}\mathrm{Te};\ 2^+_1\right\rangle\left|{}^{134}\mathrm{Sn};\ 0^+_{gs}\right\rangle + \cdots$$

| $e_\nu$=0.7 e <br> $e_\pi$=1.55 e | B(E2; $2^+ \rightarrow 0^+$) in W.u. | |
|---|---|---|
| | Expt | Calc |
| $^{130}$Sn | 1.2(3) | 1.4 |
| $^{134}$Sn | 1.4(2) | 1.6 |
| $^{130}$Te | 10(1) | 7.8 |
| $^{134}$Te | 5.6(6) | 4.9 |
| $^{136}$Te | 5.9(9) | 9.9 |

Expt from NP A 746, 83c (2004); NP A 752, 264c (2005); PRC 84, 061306(R) (2011)

| $e_\nu$=0.7 e<br>$e_\pi$=1.55 e | B(E2; $2^+ \rightarrow 0^+$) in W.u. | |
|---|---|---|
| | Expt | Calc |
| $^{130}$Sn | 1.2(3) | 1.4 |
| $^{134}$Sn | 1.4(2) | 1.6 |
| $^{130}$Te | 10(1) | 7.8 |
| $^{134}$Te | 5.6(6) | 4.9 |
| $^{136}$Te | 5.9(9) | 9.9 |

Expt from NP A 746, 83c (2004); NP A 752, 264c (2005); PRC 84, 061306(R) (2011)

# Evolution of the single-particle states around $^{132}$Sn

**How proton and neutron SP states change when adding pairs of neutrons and protons to $^{133}$Sb and $^{133}$Sn**

➔ One-particle spectroscopic factors which give direct information on single-particle excitations

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➔ One-particle spectroscopic factors which give direct information on single-particle excitations

- **Z=51 isotopes**
- **N=83 isotones**

$^{137}_{51}\mathrm{Sb}_{86}$

$^{137}_{54}\mathrm{Xe}_{83}$

$^{136}$Xe(*d*,*p*) tranfer reaction
B. P. Kay et al, PRC 84, 024325 (2011)

## single-proton states

| $^{137}$Sb | E Calc |
|---|---|
| 7/2+ | 0.0 |
| 5/2+ | 0.18 |
| 3/2+ | 0.33 |
| 1/2+ | 0.40 |
| 11/2- | 2.59 |

## single-neutron states

| $^{137}$Xe | E Calc | $C^2S$ Calc | E Expt | $C^2S$ Expt |
|---|---|---|---|---|
| 7/2- | 0.0 | 0.86 | 0.0 | 0.94 |
| 3/2- | 0.73 | 0.57 | 0.60 | 0.52 |
| 1/2- | 1.13 | 0.43 | 0.98 | 0.35 |
| 9/2- | 1.33 | 0.72 | 1.22 | 0.43 |
| 5/2- | 1.35 | 0.17 | 1.30 | 0.22 |
| 13/2+ | 2.08 | 0.75 | 1.75 | 0.84 |

number of states

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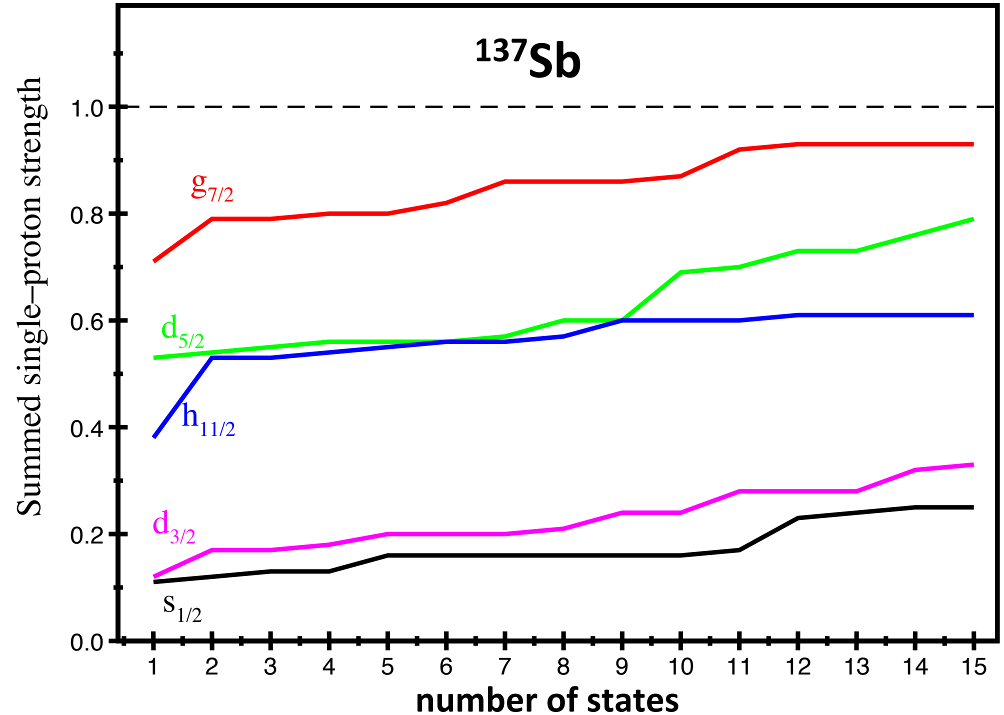


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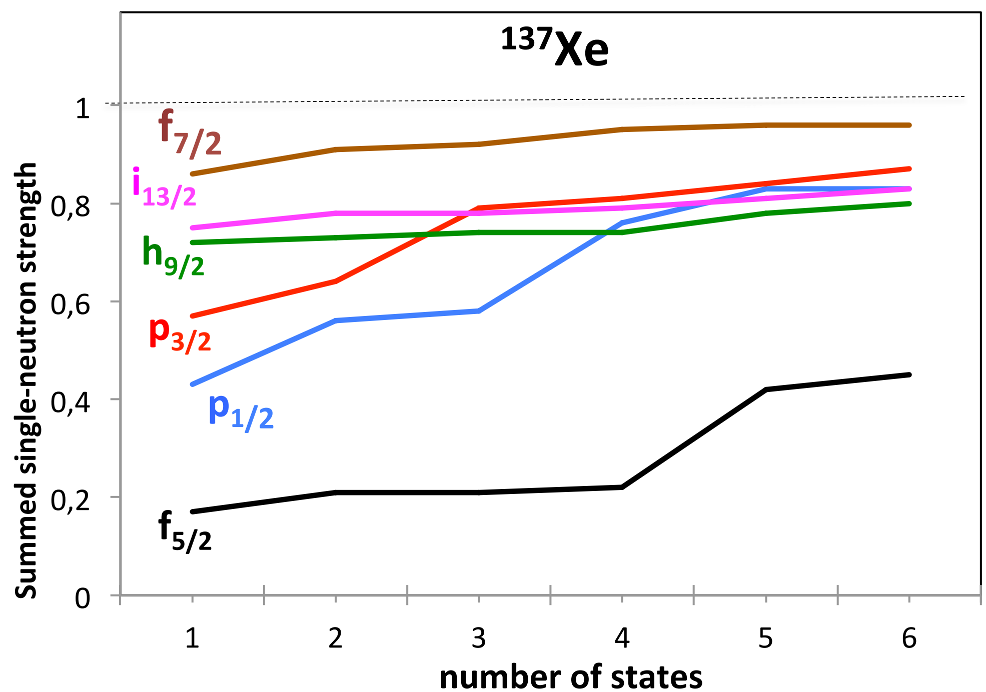


PRL **100,** 072501 (2008) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2008

**Restoration of the $N = 82$ Shell Gap from Direct Mass Measurements of $^{132,134}$Sn**

M. Dworschak,[1,*] G. Audi,[2] K. Blaum,[1,3,4] P. Delahaye,[5] S. George,[1,3] U. Hager,[6] F. Herfurth,[1] A. Herlert,[5] A. Kellerbauer,[4] H.-J. Kluge,[1,7] D. Lunney,[2] L. Schweikhard,[8] and C. Yazidjian[1]

## 0.5 MeV deviation from the accepted value

➔ **restores the neutron shell gap at N=82 considered to be a case of "shell quenching"**

PRL **109,** 032501 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

**Precision Mass Measurements beyond $^{132}$Sn: Anomalous Behavior of Odd-Even Staggering of Binding Energies**

J. Hakala,* J. Dobaczewski, D. Gorelov, T. Eronen,† A. Jokinen, A. Kankainen, V. S. Kolhinen, M. Kortelainen, I. D. Moore, H. Penttilä, S. Rinta-Antila, J. Rissanen, A. Saastamoinen, V. Sonnenschein, and J. Äystö‡

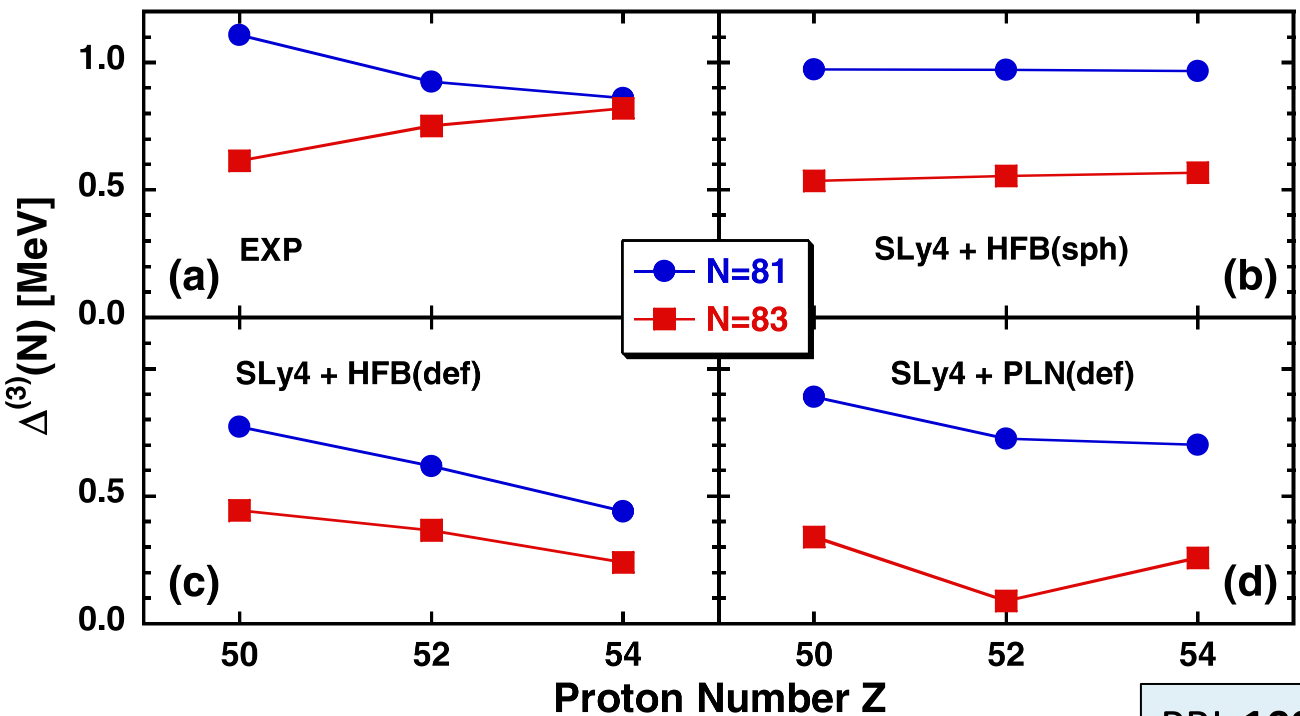
*Department of Physics, P.O. Box 35 (YFL), FI-40014 University of Jyväskylä, Finland*

(Received 5 March 2012; published 16 July 2012)

Atomic masses of the neutron-rich isotopes $^{121-128}$Cd, $^{129,131}$In, $^{130-135}$Sn, $^{131-136}$Sb, and $^{132-140}$Te have been measured with high precision (10 ppb) using the Penning-trap mass spectrometer JYFLTRAP. Among these, the masses of four *r*-process nuclei $^{135}$Sn, $^{136}$Sb, and $^{139,140}$Te were measured for the first time. An empirical neutron pairing gap expressed as the odd-even staggering of isotopic masses shows a strong quenching across $N = 82$ for Sn, with a $Z$ dependence that is unexplainable by the current theoretical models.

$$\Delta^{(3)}(N,Z) = \frac{1}{2}[B(N+1,Z) + B(N-1,Z) - 2B(N,Z)]$$

self-consistent calculations with
SLy4 Skyrme energy density functional
+ contact pairing force




PRL **109**,032501 (2012)

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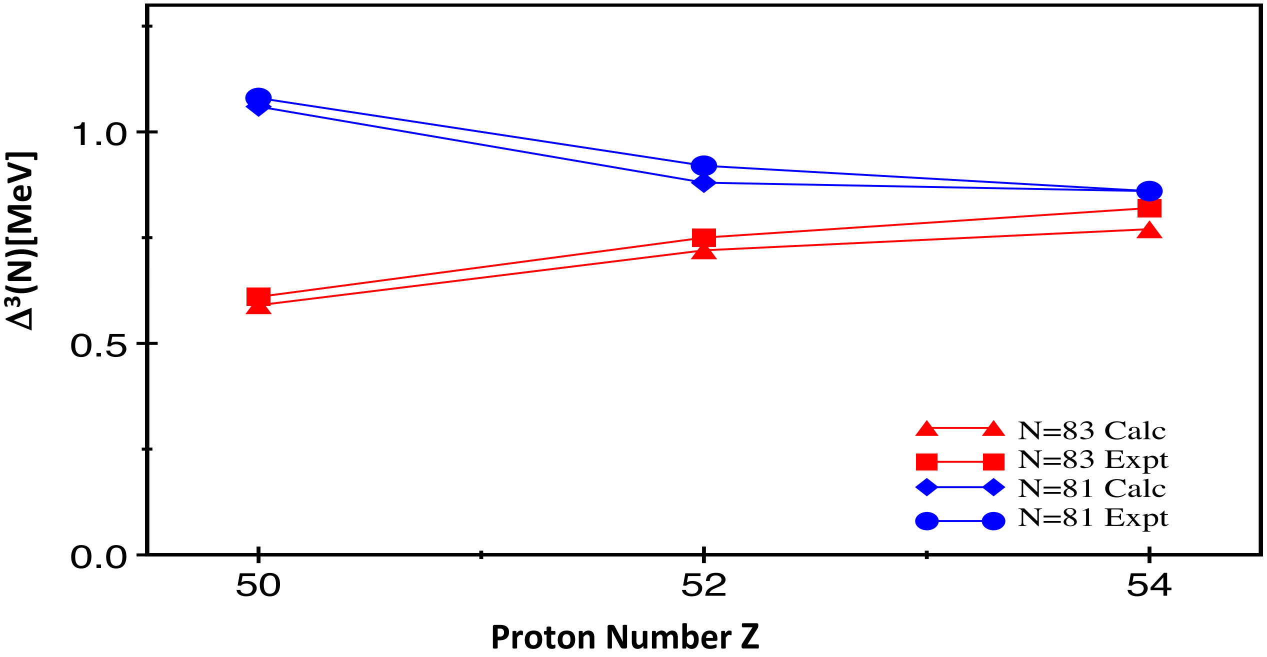


SM calculations

L. Coraggio et al, PRC 88, 041301(R) 2013)

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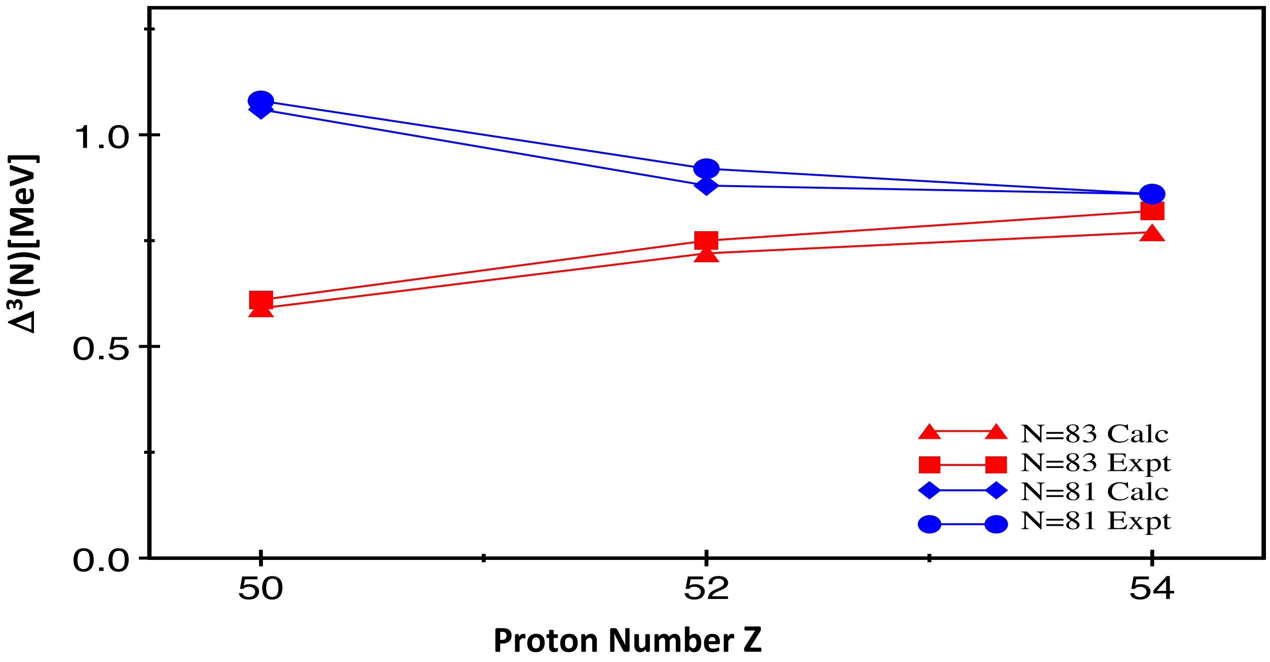


SM calculations

- The drop of 0.5 MeV in the observed OES for Sn when crossing N = 82 is accounted for by the **different pairing properties of $V_{eff}$ for neutron particles and neutron holes**
- When going to Te and Xe, the N = 81 and 83 lines **come closer to each other as a result of the *p-n* $V_{eff}$. (*repulsive in the particle-hole channel, attractive in the particle-particle channel*)**. The two lines would be parallel should one ignore this interaction.

**L. Coraggio et al, PRC 88, 041301(R) 2013)**

# Binding energies relative to $^{132}$Sn of Sn, Sb,Te, Xe

| Nucleus | $B_{\mathrm{calc}}$ (MeV) | $B_{\mathrm{expt}}$ (MeV) |
|---|---|---|
| $^{134}$Sn | 5.98 | 6.03 |
| $^{135}$Sn | 8.37 | 8.30 |
| $^{134}$Sb | 12.74 | 12.84 |
| $^{135}$Sb | 16.32 | 16.58 |
| $^{136}$Sb | 18.81 | 19.47 |
| $^{134}$Te | 20.81 | 20.57 |
| $^{135}$Te | 23.82 | 23.83 |
| $^{136}$Te | 28.26 | 28.60 |
| $^{137}$Te | 31.15 | 31.55 |
| $^{136}$Xe | 40.32 | 39.04 |
| $^{137}$Xe | 43.83 | 43.06 |
| $^{138}$Xe | 48.89 | 48.73 |

**Expt from PRL 109,032501 (2012)**

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| $^{138}$Xe | 48.89 | 48.73 |

**Expt from PRL 109,032501 (2012)**

# Outlook

- Test of the optimized chiral potential
- Role of genuine and effective three-body forces
- Microscopic origin of the properties of the shell-model interaction
- Further studies of nuclei far from stability



# Naples group

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**Grazie per l'attenzione**