NEW PHENOMENON IN EXOTIC NEUTRON-RICH Sn ISOTOPES : ROLE OF 3-BODY FORCE

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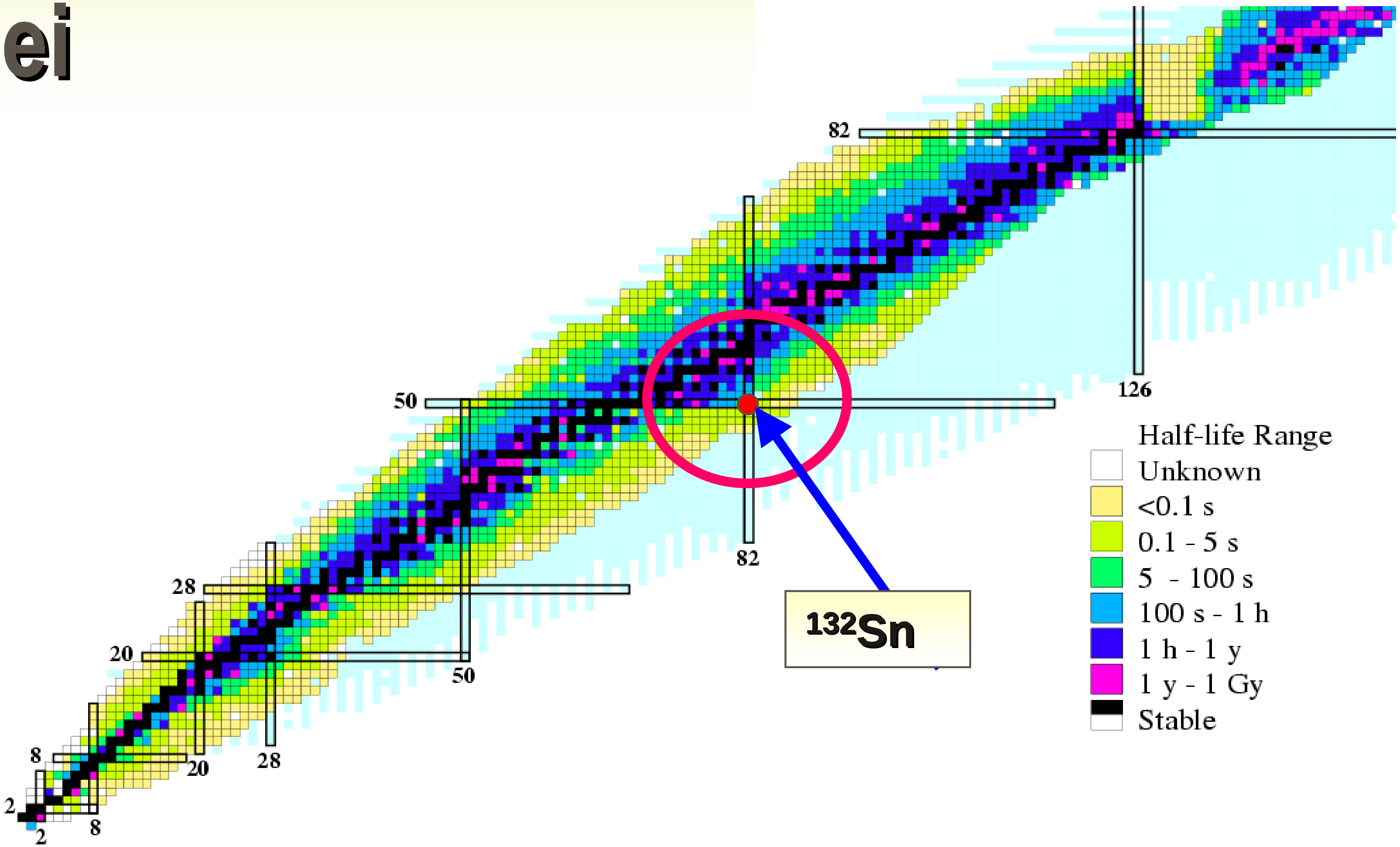
Experimental Chart of Nuclei



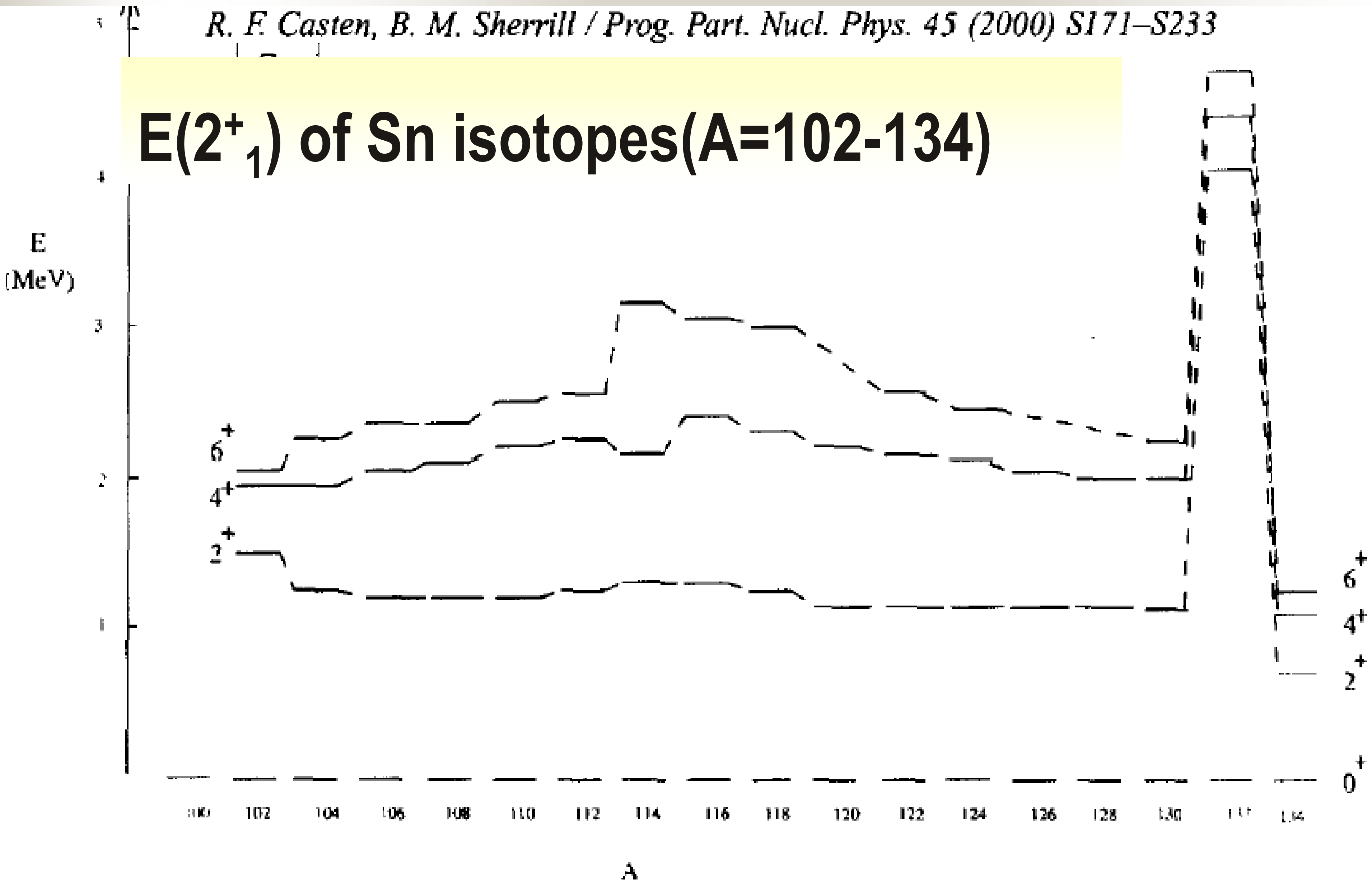
Introduction: ^{132}Sn region

- Nuclei with $50 \leq Z \leq 56$ and $82 \leq N \leq 88$ in the π(gdsh) ν(hfpi) valence space above the ^{132}Sn core lie on or close to the path of astrophysical r-process flow.
- Their structure,particularly the binding energy (BE), low-lying excited states and beta decay rates at finite temperatures are important ingredients for nucleosynthesis calculations.
- Sn isotopes are of particular importance.
- Even Sn isotopes, say ^{136}Sn, is known to be the classical "waiting point" nucleus in A=130 solar system abundance peak under typical r-process condition.

Experimental Status

- Spectroscopic information, such as BE and low lying spectrum, is known experimentally only for ^{134}Sn.
- Recently half-lives of $^{135-137}Sn$ have been measured through $\beta^{-}n$ decay process. No other information exists.Lifetimes of these nuclei are very small and production rates are also very low presenting challenges to spectroscopic studies.
- Reliable theoretical results are therefore necessary and useful.

E(2^+_1) of Sn isotopes(A=102-134)



Theoretical Endeavours

Shell Model Calculations:

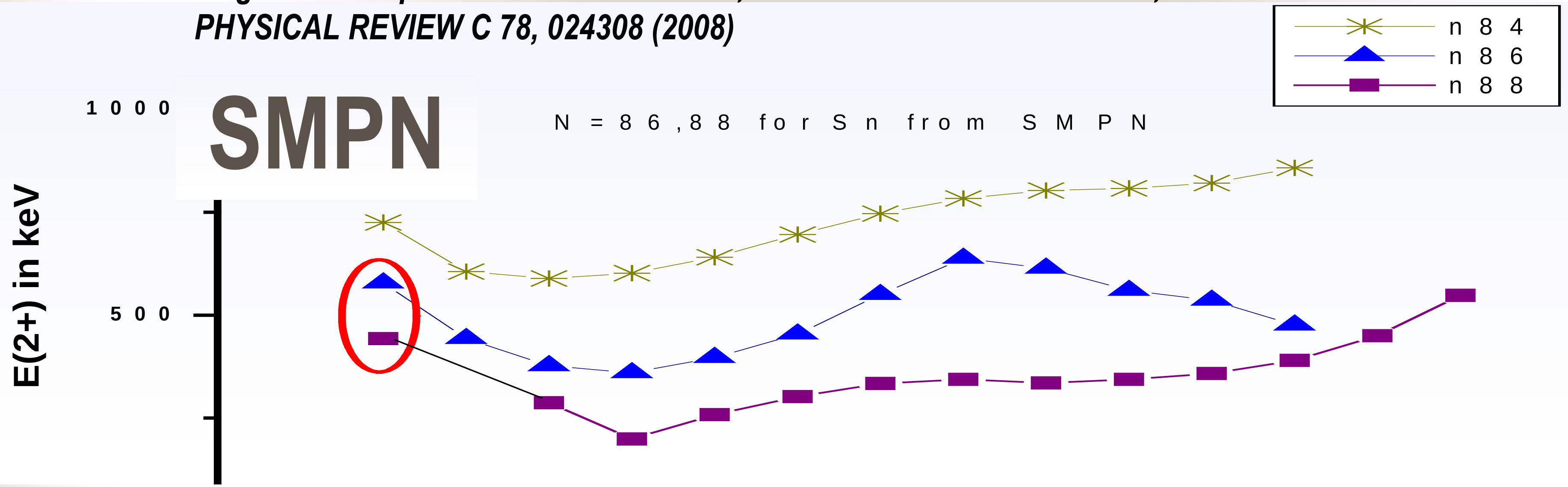
- Few valence particle nuclei above the doubly closed magic ^{132}Sn core are generally described in the valence space consisting of
  - Proton ($1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$ and $1h_{11/2}$) and
  - Neutron ($1h_{9/2}$, $2f_{7/2}$, $2f_{5/2}$, $3p_{3/2}$, $3p_{1/2}$ and $1i_{13/2}$) orbitals.

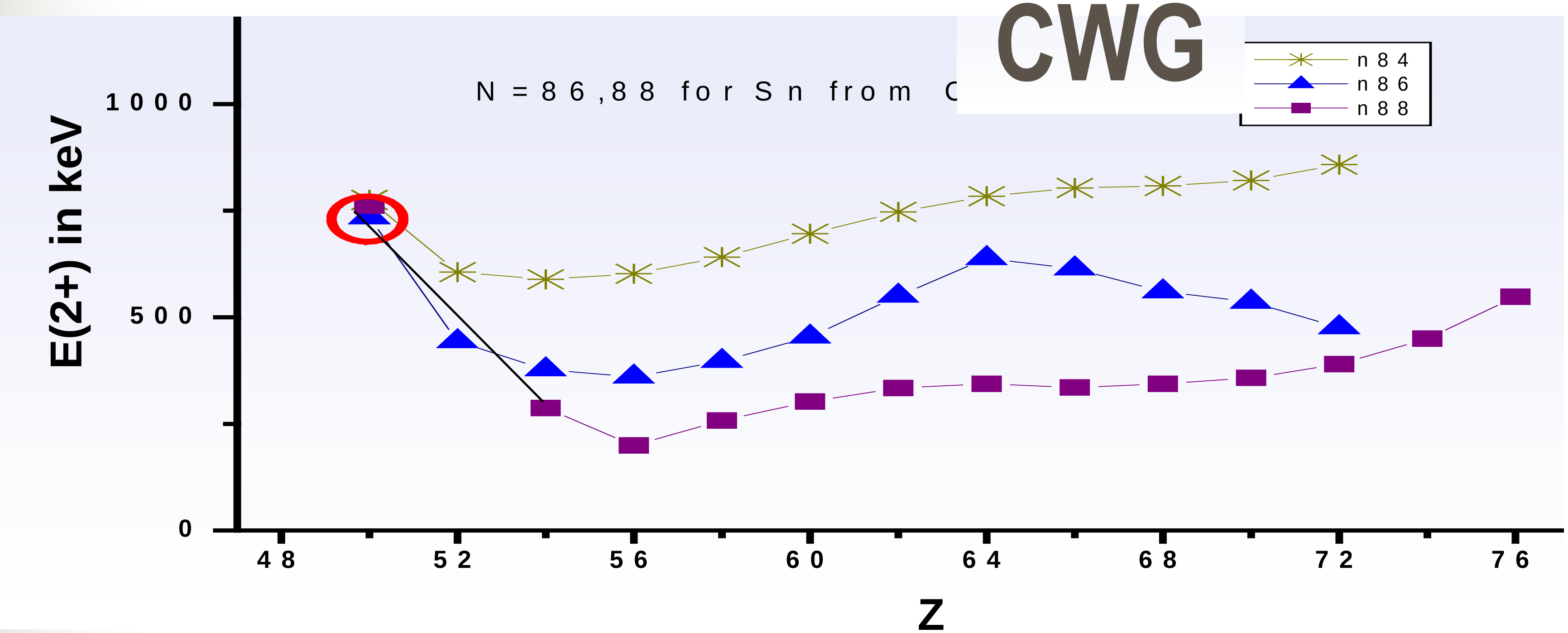
- Remarkably good results for isotopes of Sn, Sb, Te, I, Xe, Cs with different interactions for $134 \leq A \leq 138$ and $50 \leq Z \leq 56$.

Interactions used

- Primarily two types of interactions used: realistic and empirical
  - Empirical interactions : the interaction derived from ^{208}Pb region (Chou & Warburton) which fails for N > 84: specific matrix elements are tuned to reproduce known experimental levels (S. Sarkar and M. Saha Sarkar)
  - Realistic interactions obtained starting with a *G* matrix derived from the CD-Bonn nucleon-nucleon interaction using the *Q*-box method (B.A. Brown, M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, + F. Andreozzi, L. Coraggio, A. Covello, A. Gargano)

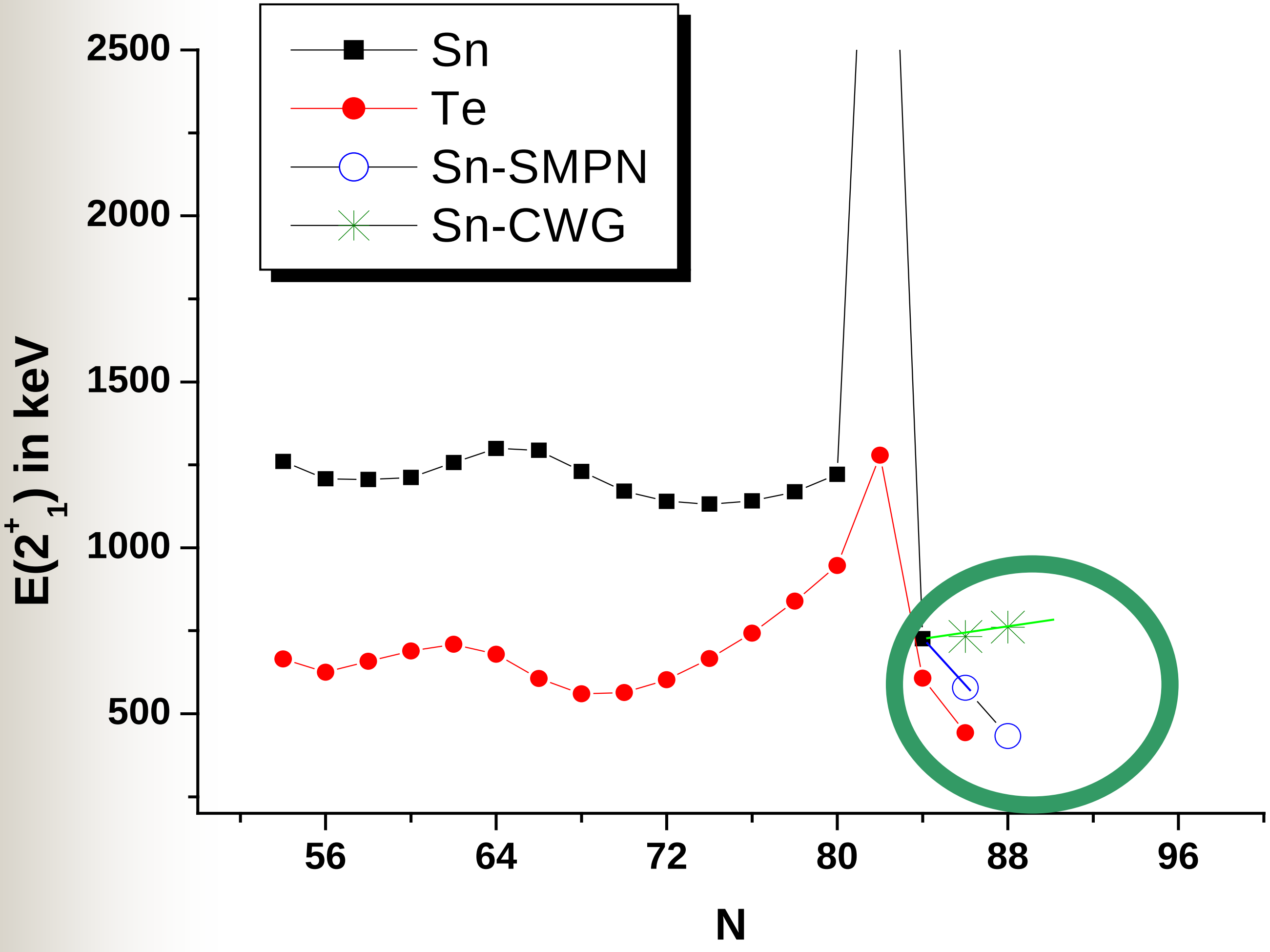
Structure of even-even A = 138 isobars and the yrast spectra of semi-magic Sn isotopes above the ^{132}Sn core, S. Sarkar and M. Saha Sarkar, PHYSICAL REVIEW C 78, 024308 (2008)





Casten-Sherill Systematics

R. F. Casten and B. M. Sherill, Prog. Part. Nucl. Phys. 45, S171 (2000).



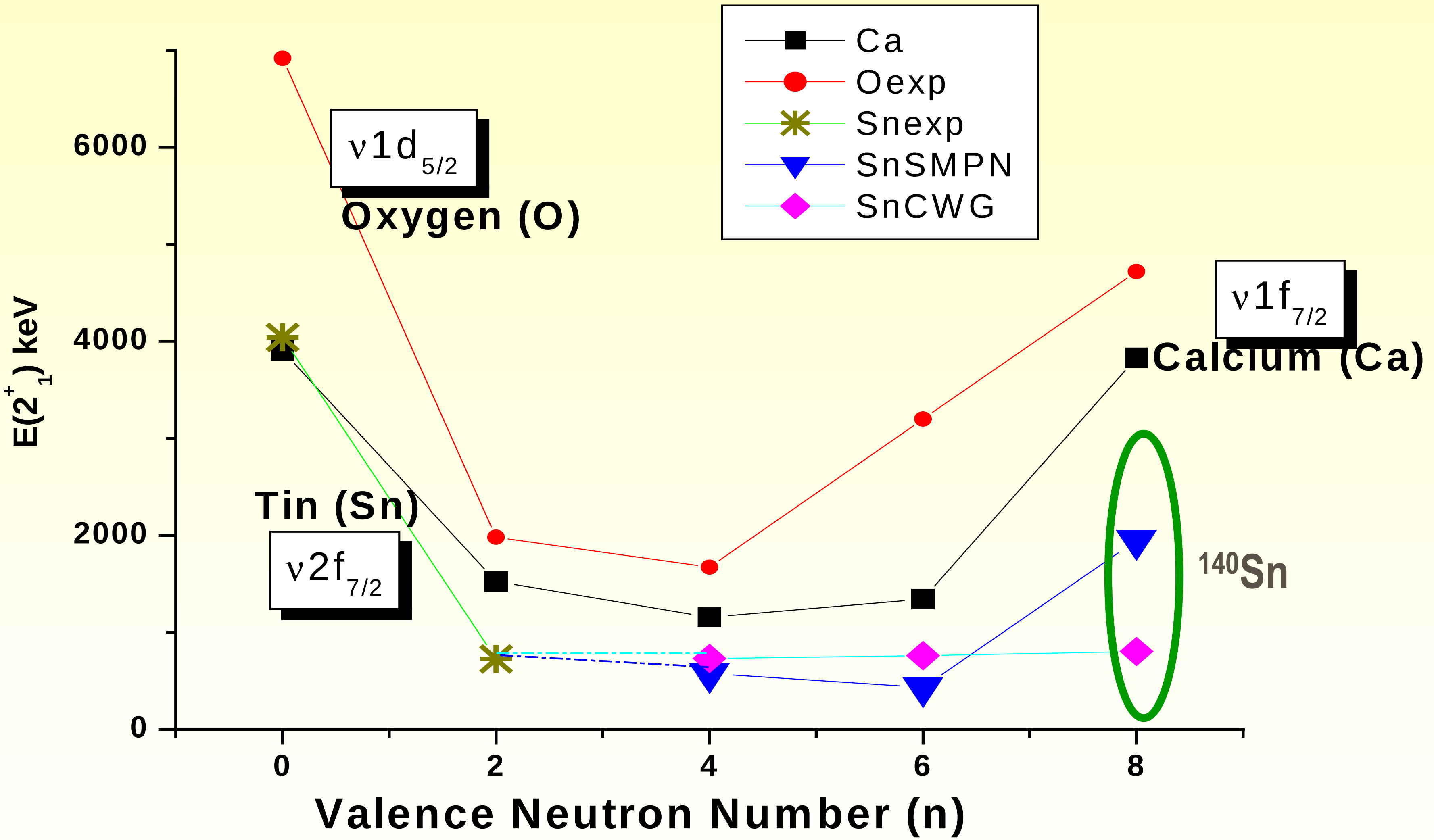
- Casten and Sherill have pointed out that, although [$E(2^+_1)$Sn − $E(2^+_1)$Te] 400 keV for a given neutron number over most of the N = 50–82 shell, the difference is only 119 keV for N = 84
- The difference for N = 86 is 108 keV with SMPN. It is consistent with the trend discussed by Casten and Sherill. (Casten-Sherill Systematics)
- For CWG, this difference is 733 − 356 = 377 keV for N = 86, which deviates from the trend.

Present Work

- We have used
  - extended the calculations for more neutron rich ^{140}Sn
  - The shell model codes OXBASH and NUSHELL@MSU have been used

- The results are
  - The $E(2^+_1)$ for ^{140}Sn is 1949 keV showing a sudden increase for N=90, indicating a shell closure
  - With CWG interaction, the 0^+_1 - 2^+_1 spacing remains nearly constant at around 750 keV for $^{136-142}Sn$, except for a small increase at ^{140}Sn
  - To understand the implication of these completely different trends in the results using these two interactions, the theoretical results for these experimentally unobserved nuclei have been compared with the $E(2^+_1)$ values of neutron rich nuclei in other mass regions for which experimental data are available.

Comparison with neutron-rich isotopes

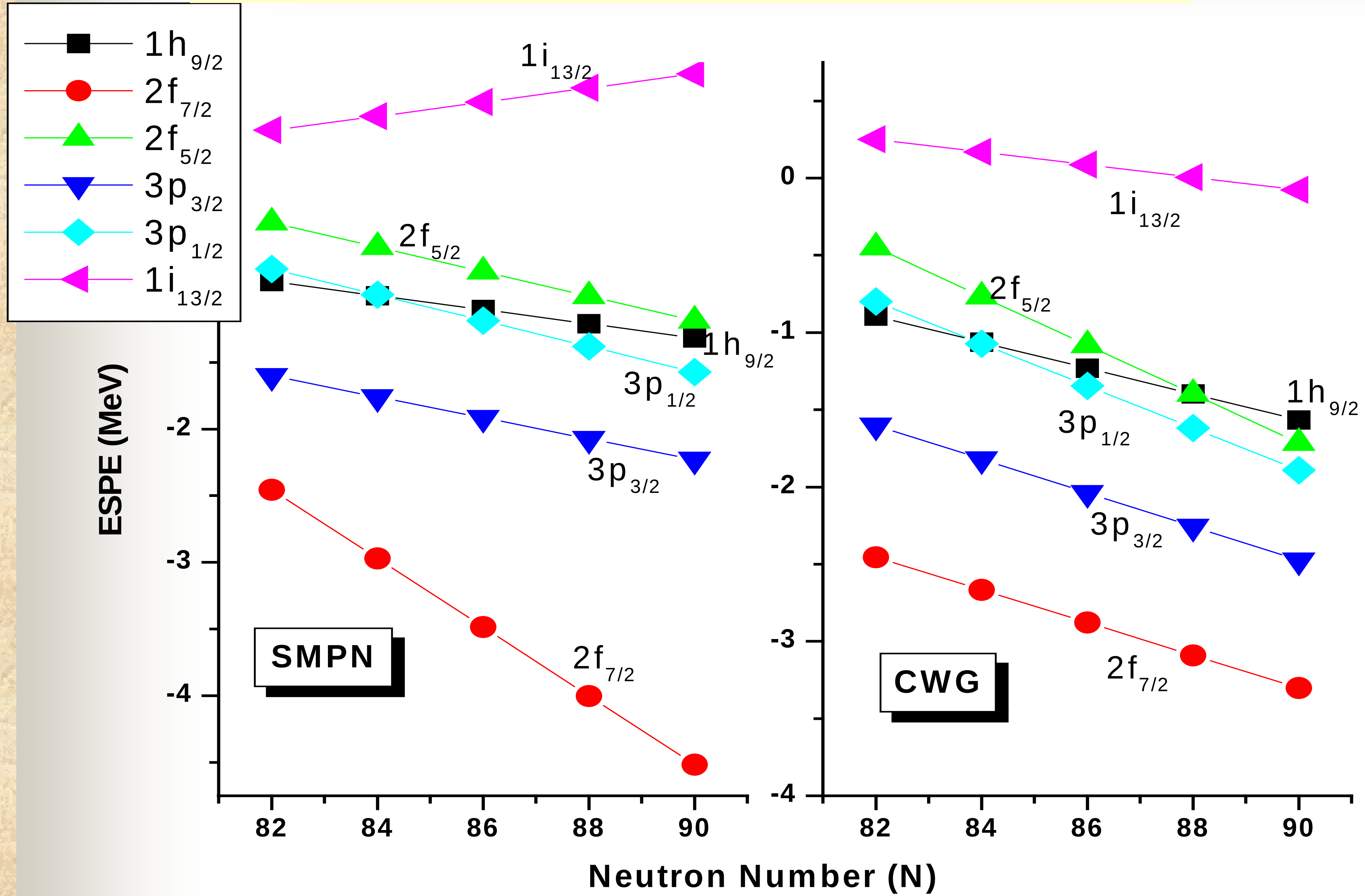


The shell closure at N=90

- In order to put forward further evidence and to understand the shell closure at ^{140}Sn more precisely, the effective single-particle energies (ESPE) for the neutron orbitals for the two Hamiltonians have been compared.
- **The ESPE is defined as bare single particle energy (spe) added with the monopole part of the diagonal two body matrix elements (tbme).**

$$V^T_{j,j'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)},$$

Neutron ESPEs with CWG and SMPN interactions for increasing neutron numbers



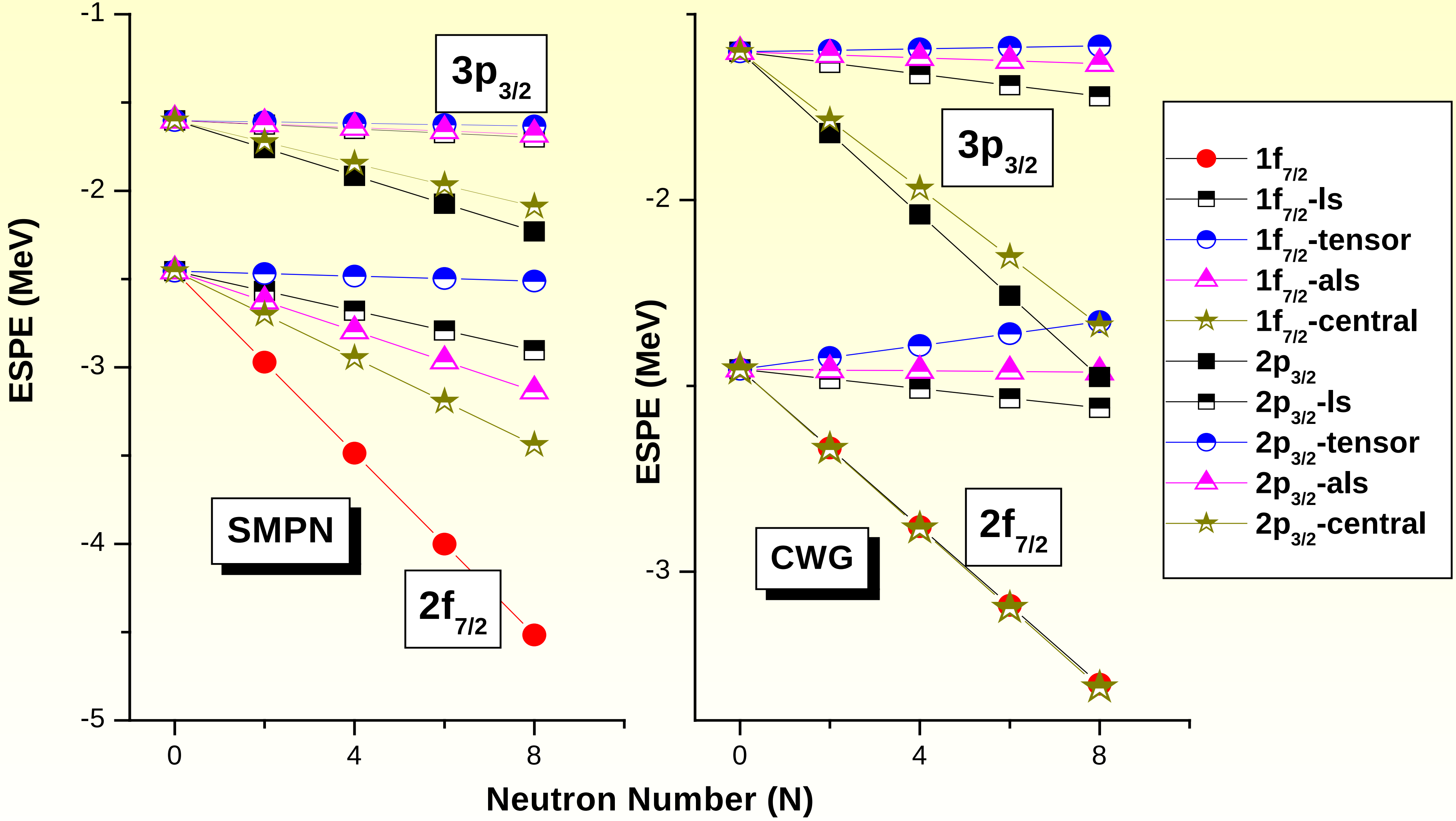
Origin of this new shell closure

Spin-tensor decomposition of the two body matrix elements (tbmes). - central, antisymmetric spin-orbit (ALS), spin-orbit (LS) and tensor parts of tbmes identified

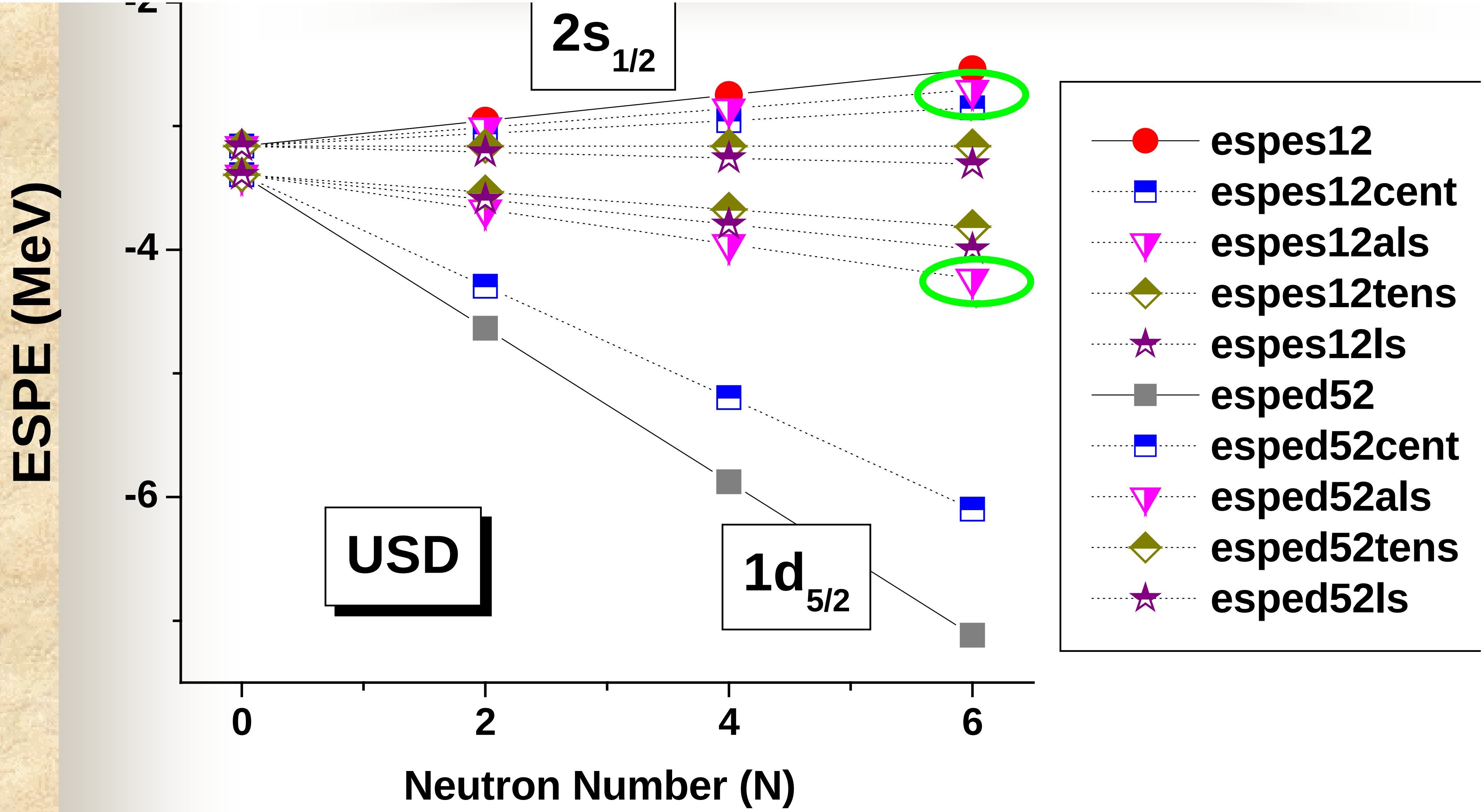
For SMPN,

- the **central and ALS** part for **$2f_{7/2}$- $2f_{7/2}$ tbmes** account for **majority of the downward shift** of the ESPE of $2f_{7/2}$with increasing valence neutron number (n).
- tbmes involving $3p_{3/2}$ - **dominant contribution from the central part**.
- The central parts of $2f_{7/2}$ and $3p_{3/2}$ vary with similar slopes for increase in n.
- **Variation in ALS part is primarily responsible for this observed shell gap at N=90.**

Decomposition



Decomposition of USD tbmes for oxygen isotopes



The implication of ALS term?

- **ALS component in the tbmes** corresponds to those
- **LS-coupled matrix elements which have S≠S′**, i.e., terms non-diagonal in S (spin). **Do not conserve total spin** of the matrix elements.
- But the interactions which are parity conserving and isospin conserving must also conserve the total spin.
- **Bare nucleon- nucleon force contains no ALS term.**
- But effective interaction is not simply related to bare nucleon-nucleon force. **Core polarisation corrections to the G-matrix give rise to non-zero but small ALS** matrix elements.
- A characteristic feature common to many **empirical effective interactions is strong ALS components** in the tbmes.
  - It usually arises from **inadequate constraint by the data**.
  - It indicates the important contributions from **higher order renormalisation or many body forces** to the effective interactions.
  - In empirical SMPN such **many - body effects might have been included** in some way through the modification of important tbmes.

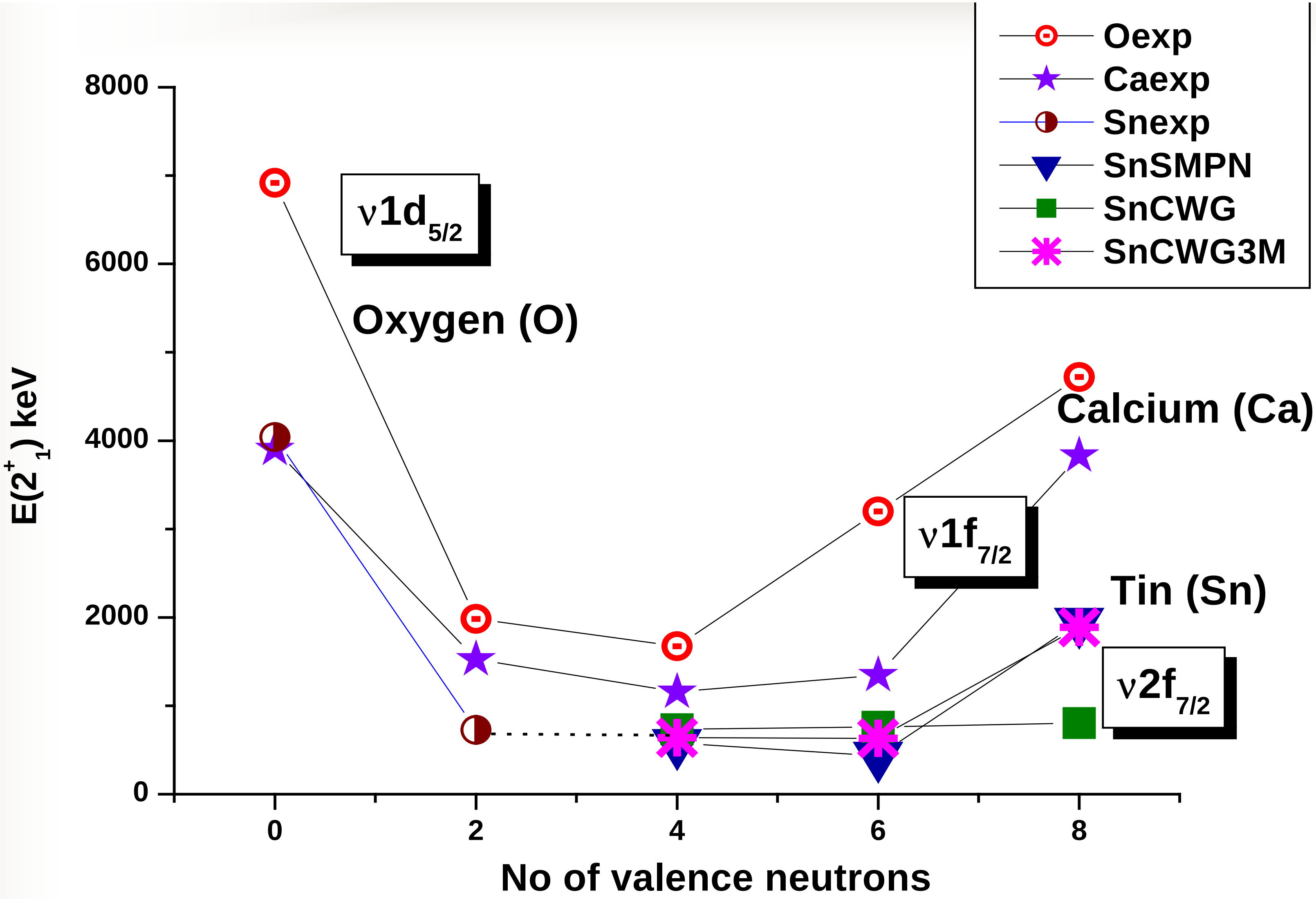
Features of Realistic Interaction

- **Two-body realistic interactions derived from the free nucleon-nucleon force fail to reproduce some shell closures**.
- **increase of** the $1d_{5/2}$ - $2s_{1/2}$ **gap** for Z=8 and $1f_{7/2}$ - $2p_{3/2}$ gap for Z=20 (as a function of neutron number), required to explain empirical data are not obtained in the calculations with these interactions.
- It has been shown that **the three-body forces** have to be taken into account **to reproduce** these shell gaps.
- **Otsuka et al.** have proposed a **three-body delta-hole mechanism** to explain these shell gaps and they have shown that three-body forces are necessary to explain why the doubly-magic ^{24}O nucleus is the heaviest oxygen isotope
- Zuker showed earlier that a **very simple three-body monopole** term can solve practically all the spectroscopic problems in the p, sd, and pf shells those were hitherto assumed to need drastic revisions of the realistic two-body potentials.

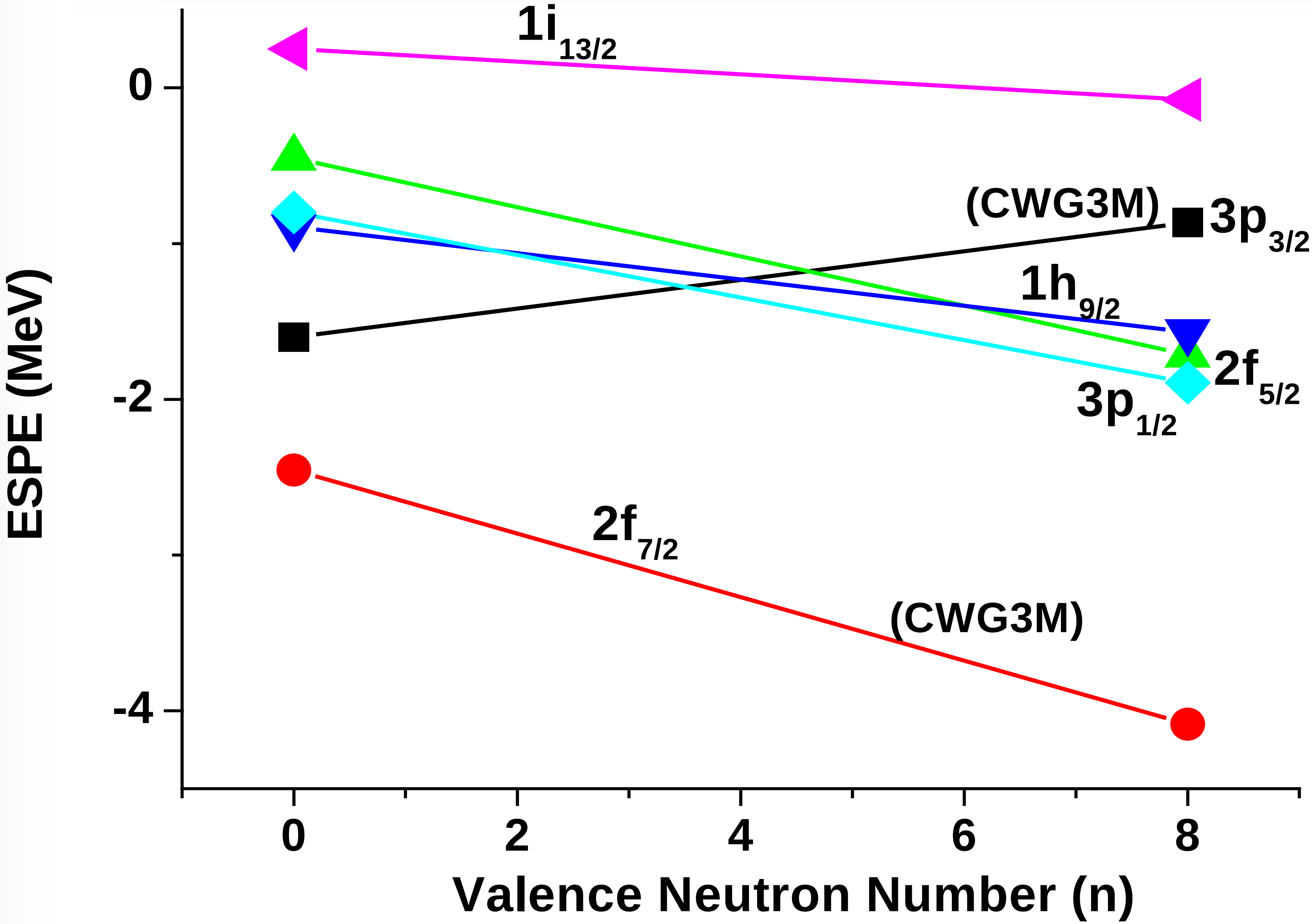
Three body forces and CWG interaction

- A simple three-body monopole term in CWG as prescribed by Zuker
- Corrections in $2f_{7/2}$-$2f_{7/2}$ and $2f_{7/2}$-$3p_{3/2}$ tbmes similar to those in KB3 for $1f_{7/2}$-$1f_{7/2}$ and $1f_{7/2}$-$2p_{3/2}$ tbmes.
- Included the effect of mass scaling. By $(40/132)^{(1/3)}$ factor.
- This factor reduces the effect of three - body correction on CWG compared to that in KB3.
- The correction terms included in the tbmes are
  - $V_{J,T=1}^{ffff}$ (CWG3M)= $V_{J,T=1}^{ffff}$ (CWG)−74 keV, for J=0,4and 6;
  - $V_{J=2,T=1}^{ffff}$ (CWG3M)= $V_{J=2,T=1}^{ffff}$ (CWG) − 208 keV and
  - $V_{J,T=1}^{frfr}$ (CWG3M)= $V_{J,T=1}^{frfr}$ (CWG)+201 keV for J=2, 3, 4 and 5.
- f stands for $2f_{7/2}$ and r stands for $3p_{3/2}$.
- The correction factor will be effective for nuclei for which the valence neutron number n≥ 3.
- A shell gap for N=90 now appears with CWG3M which is very close to that with SMPN.
- The $E(2^+_1)$ energies of $^{136,138}Sn$ are 0.639 and 0.633 MeV, respectively.
- The $E(2^+_1)$ energy of ^{140}Sn predicted by CWG3M (1.889 MeV) is close to that predicted by SMPN (1.949MeV).

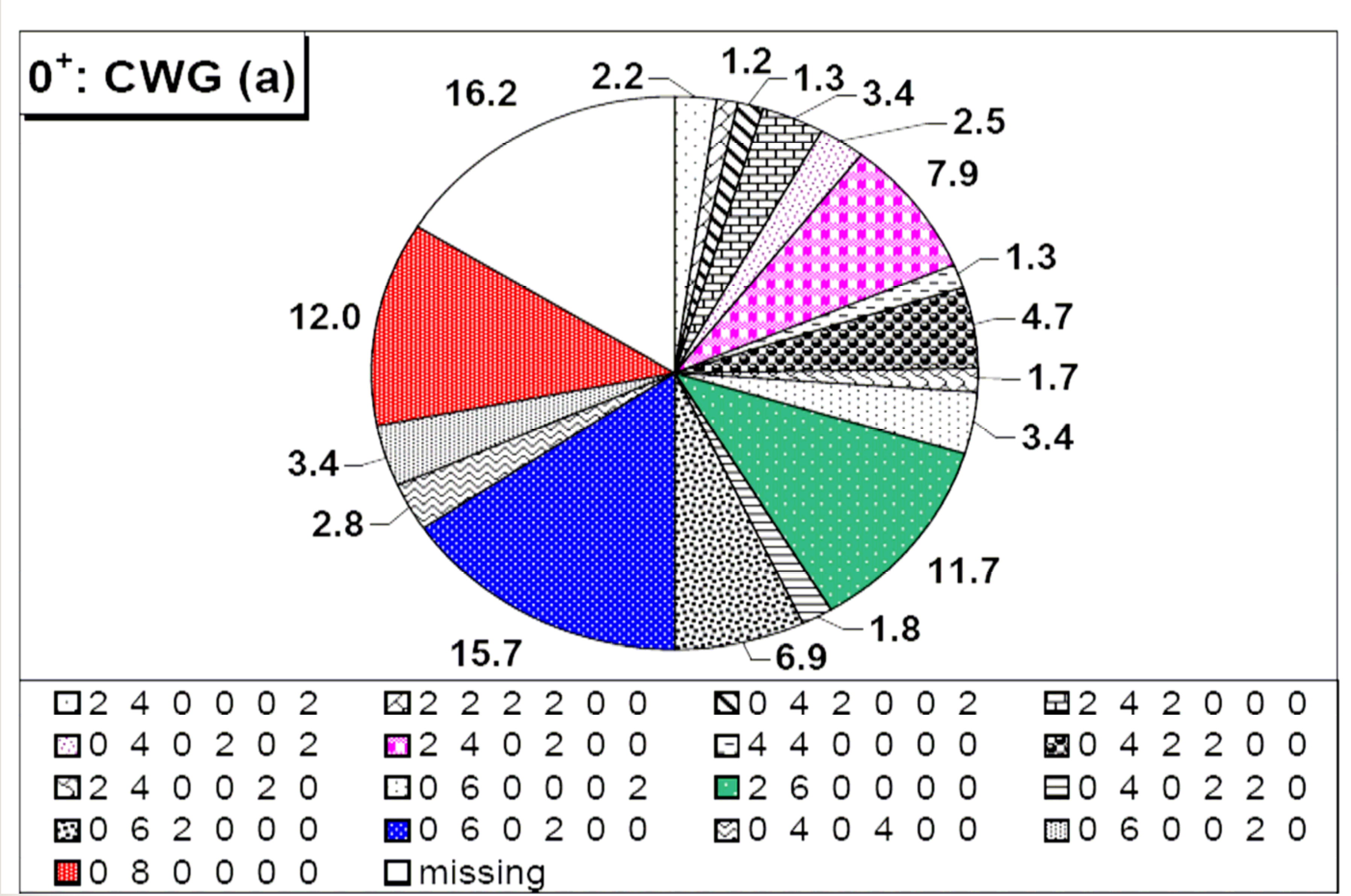
Comparison with neutron-rich isotopes



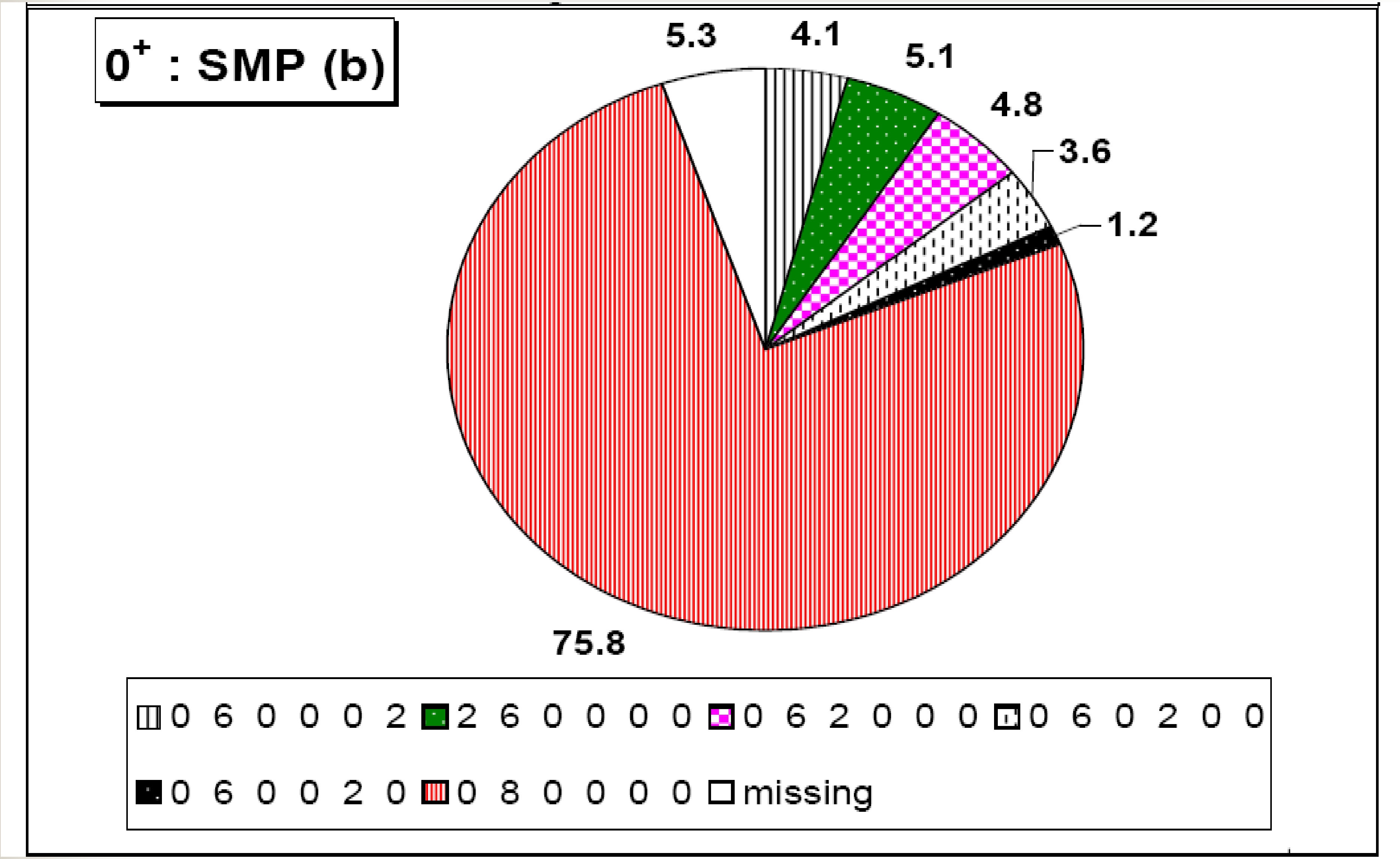
Neutron ESPEs with CWG interactions for increasing neutron numbers



Wavefunction structure for CWG



Wavefunction structure for SMPN



Wavefunction structure for CWG3M

For CWG3M, the wave function composition

- for the 0^+ *g.s* is (70.4%) from the $\nu(2f_{7/2})^8$ partition, similar to SMPN (75.8%)

•But due to overestimation of the up-sloping trend of $\nu(3p_{3/2})$ ESPE and for non-inclusion of corrections for other spes,

- •for 2^+_1 state, 29.0% originates from the $\nu(2f_{7/2})^6(1h_{9/2})^2$ and 9.6% from $\nu(2f_{7/2})^6(2f_{5/2})^2$.
- •The effective energy gap between $\nu(2f_{7/2})$ and $\nu(2f_{5/2})$ (the lowest orbital which contributes to the composition of 2^+ state) single particle orbitals is 2.370 MeV.

Conclusion

- ***A new shell closure at ^{140}Sn has been predicted.***
- ALS term in empirical interaction SMPN is found to be responsible for the gap observed in SMPN results.
- **A simple three-body monopole term** has been included in **CWG** to get CWG3M, which predicts a shell gap at N=90 for Sn isotopes as well as decreasing 2^+_1 energies for ^{136,138}*Sn*, similar to that from SMPN.
- This also indicates that three body effect plays an important role for shell evolution in neutron rich Sn isotopes above 132*Sn*, as also observed in *sd* and *fp* shells.
- The anomalously depressed 2^+_1 states in Sn isotopes having N=84-88, and the new magic number for N=90, might have interesting consequences for the r - process nucleosynthesis.

Construction of the new Hamiltonian

- **Modification of the CW5082 [W.T. Chou and E.K. Warburton, Phys. Rev. C 45, 1720 (1992)] Hamiltonian in the light of recently available information on binding energies, low-lying spectra of A=134 Sn,Sb and Te isotopes.**
- **The spes of the single particle orbitals of the valence space above the ^{132}Sn core have been replaced by the recently measured ones.**
- **The details of this modification procedure have been given in [Sukhendusekhar Sarkar, M. Saha Sarkar, Eur. Phys. Jour. A 21 (2004) 61].**
- **The new Hamiltonians work remarkably well in predicting binding energies, low-lying spectra and electromagnetic transition probabilities for N=82,83 and even for N >= 84 isotones of Sn,Sb,Te,I,Xe and Cs nuclei.**

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THANK YOU