High-momentum Correlated Nucleons, Tensor Blocking and Nuclear the Shell Structure

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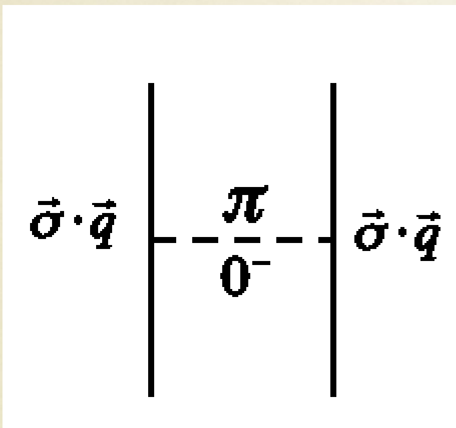
New Shell Structures observed in Neutron Rich Nuclei

- Why "doubly magic" ^{10}He and ^{28}O are not bound yet ^{48}Ca is doubly mogic?
- How are new magic numbers N=6, 14, 16, 32, 34 made?
- Why magic numbers N=8 and N=20 disappear in neutron rich nuclei?
- Why the neutron dripline suddenly extend very much in F isotopes?
- Can we understand peculiar configurations of ^{11}Li, ^{11}Be, ^{12}Be consistently?

Pion exchange interactions

- **80% of attraction comes from pions.**
  - ***R. B. Wiringa: Ann. Rev. Nucl. Part. Sci.51(2001)***

Pion exchange interaction



pion is a pseudo-scaler (0^-) meson

$$S_{12}(\hat{q}) = \sqrt{\frac{24\pi}{5}}\left[Y_2(\hat{q})[\sigma_1\sigma_2]_2\right]_0$$

$$\vec{\sigma}_1\cdot\vec{q}\,\frac{1}{m_\pi^2+q^2}\,\vec{\sigma}_2\cdot\vec{q}$$

$$= \frac{1}{3}\frac{q^2}{m_\pi^2+q^2}S_{12}(\hat{q}) + \frac{1}{3}\left(\cancel{1} - \frac{m_\pi^2}{m_\pi^2+q^2}\right)\vec{\sigma}_1\cdot\vec{\sigma}_2$$

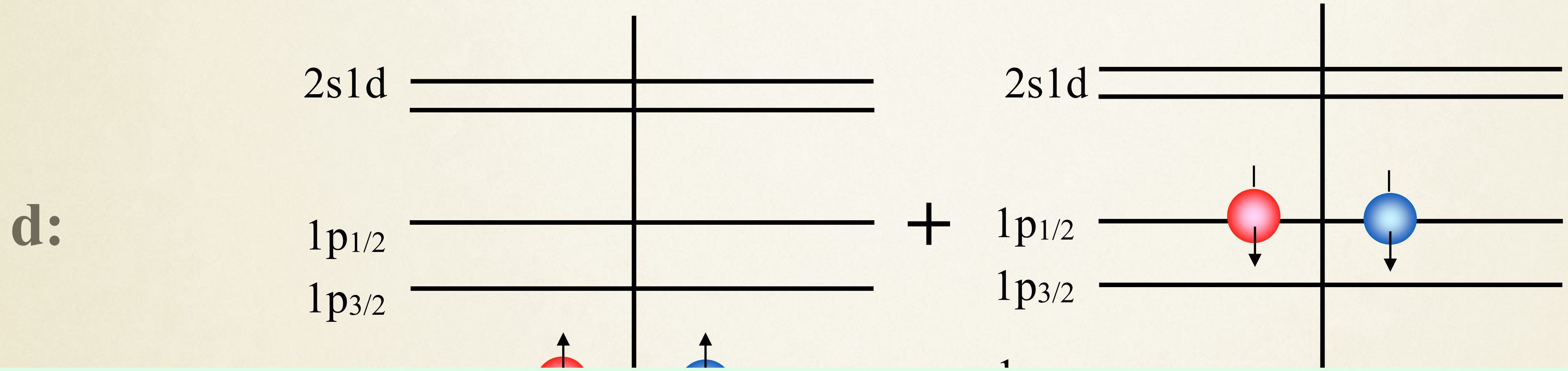
Tensor

Spin-spin

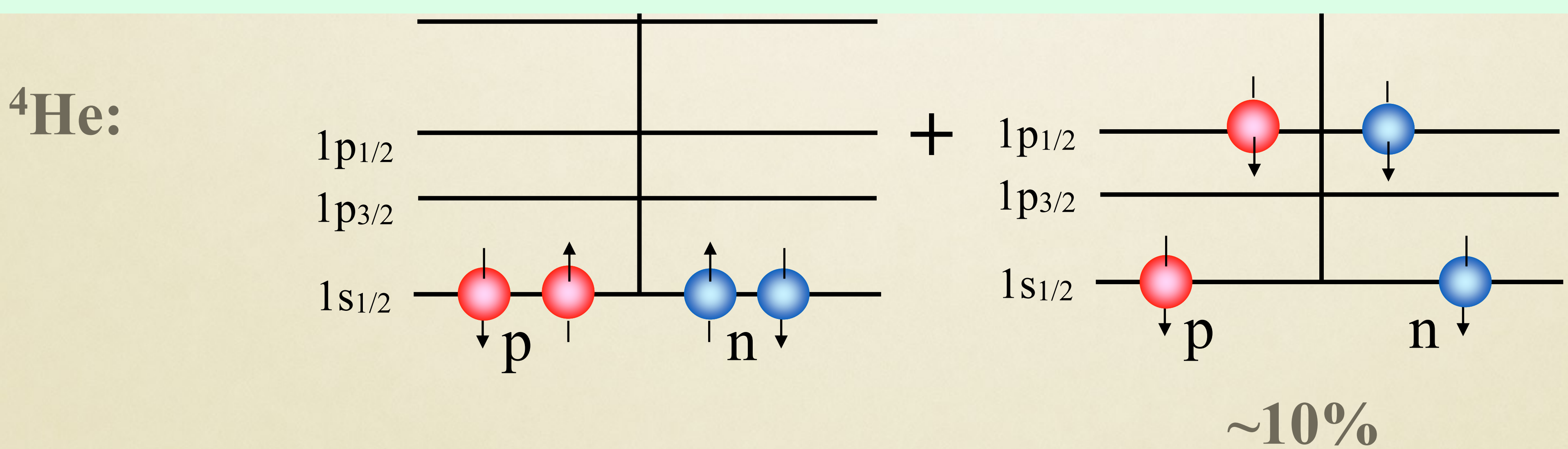
gain energy from
high momentum nucleons

gain energy from
low momentum nucleons

The most important configuration for tensor interaction

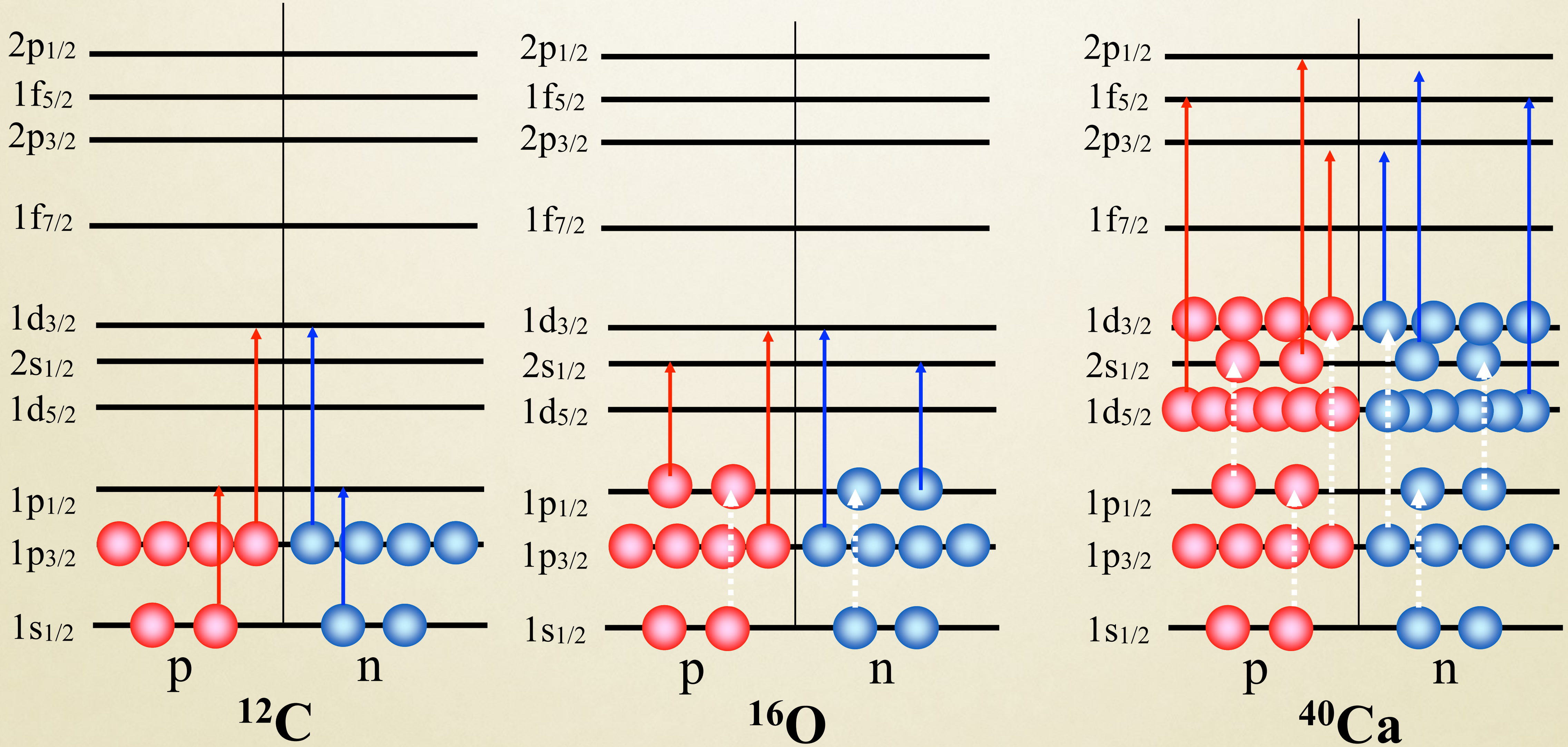


Highest spin orbital ($j_>$) in a major shell is not used for the tensor interaction.
An example is $1p_{3/2}$ orbital in ^{4}He and deuteron.



Nuclear Saturation by Tensor Blocking

Blocking and Opening occurs simultaneously and keep the binding per nucleon to be almost constant.



^{12}C do not suffer blocking o

^{16}O suffer blocking from $1s_{1/2}$ to $1p_{1/2}$.
But open new excitation from $1p_{1/2}$ to $2s_{1/2}$.

High-momentum nucleons?

- Those are observed in the ground state of ^{16}O by (p,n) and (p,pd) reactions at RCNP.

see

- H.-J. Ong et al., Phys. Lett. B 725, 277-281 (2013)
- S. Terashima et. al., Phys. Rev. Lett. 121, 242501 (2018)

High momentum nucleons (~2 fm^{-1}) are observed in the ground state of ^{16}O. High-momentum nucleons comes from (T=0, S=1) correlated pairs.

Tensor Optimized Shell Model (TOSM)

NO core!

Myo, Toki, Ikeda, Kato, Sugimoto, PTP 117 (2006)

0p-0h + 2p-2h

$$\Phi(^4\mathrm{He}) = \Sigma_i C_i \psi_i(\{b_\alpha\}) = C_1 (0s)^4 + C_2 (0s)^2 (\overline{0p}_{1/2})^2 + \cdots$$

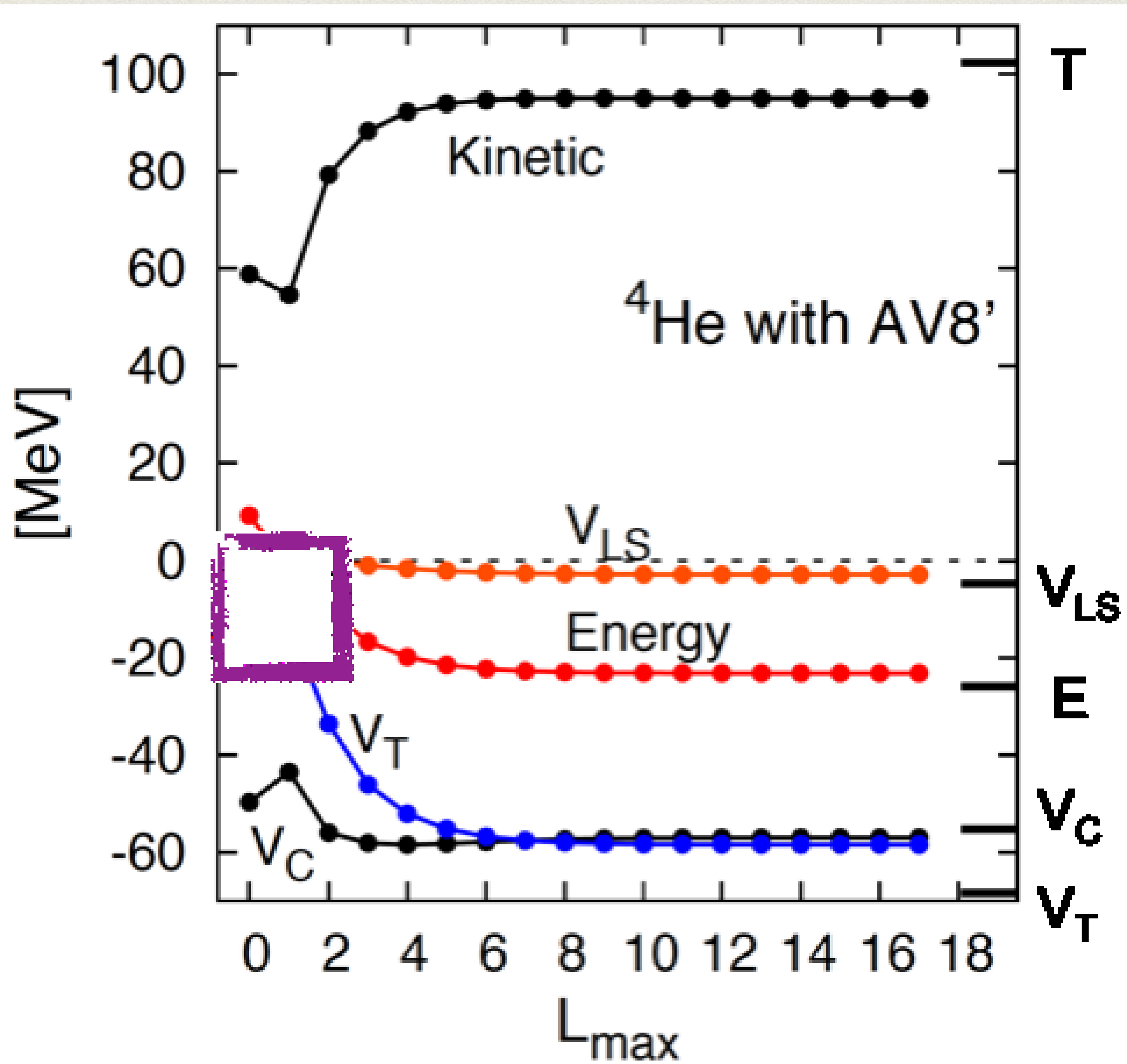
size parameter: $b_{0s} \neq b_{\overline{0p}}$

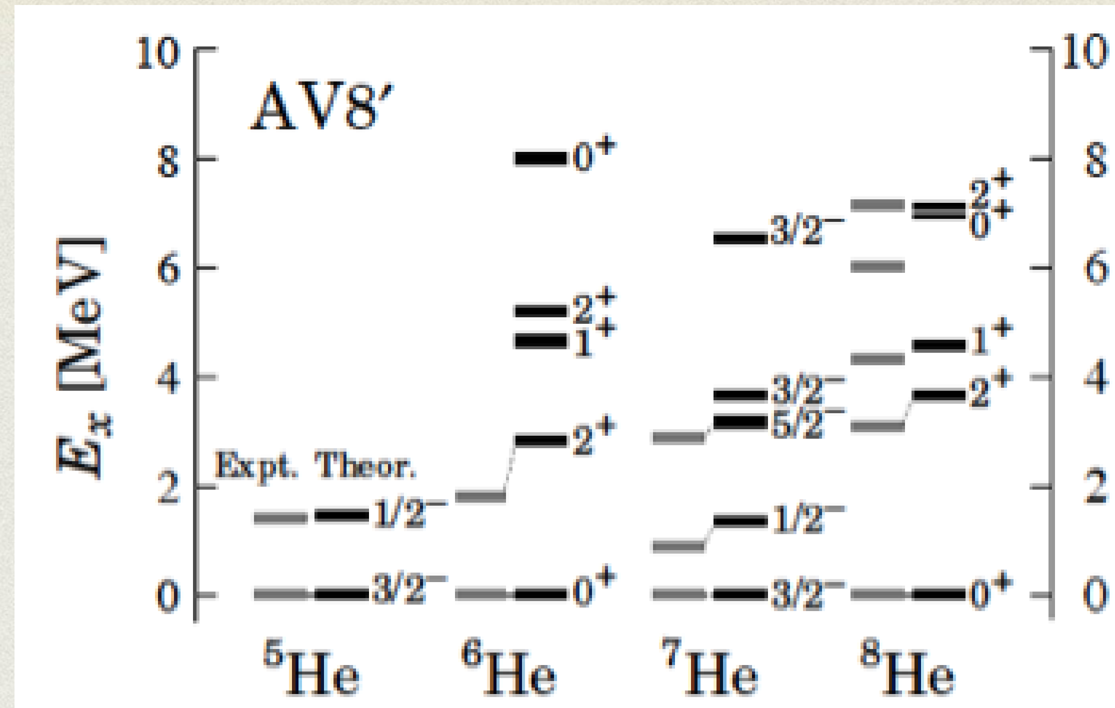
Energy variation

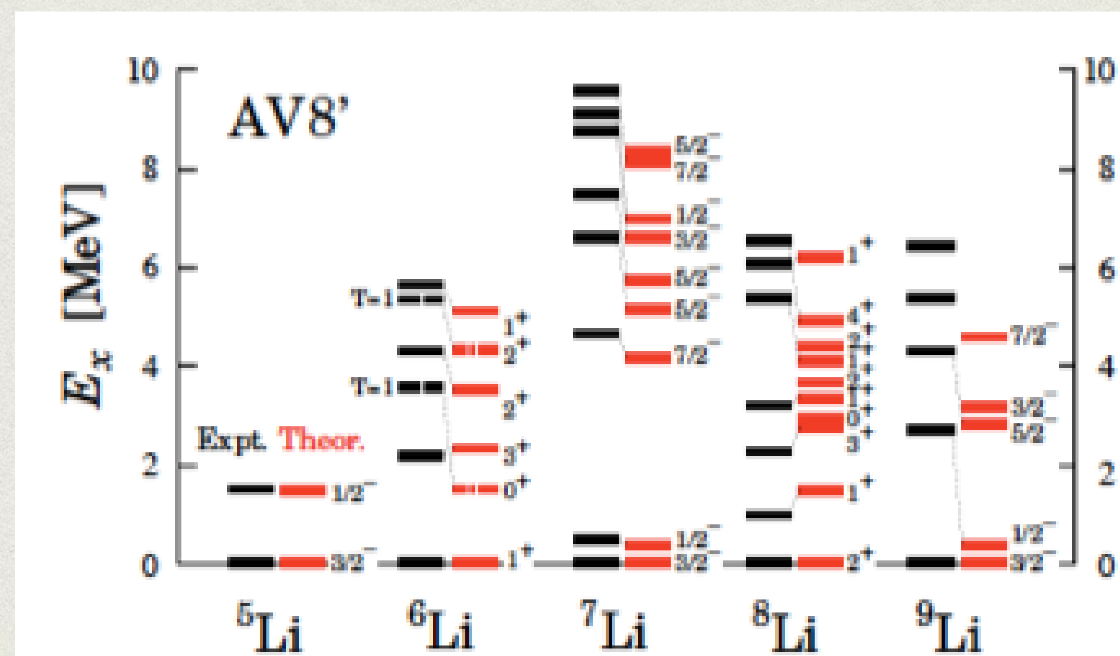
$$H = \sum_{i=1}^{A} t_i - T_G + \sum_{i<j}^{A} v_{ij}, \qquad v_{ij} = v_{ij}^{C} + v_{ij}^{T} + v_{ij}^{LS} + v_{ij}^{Clmb},$$

$$\delta \frac{\langle\Phi|\,H\,|\Phi\rangle}{\langle\Phi|\Phi\rangle} = 0 \quad \Rightarrow \quad \frac{\partial\langle H-E\rangle}{\partial b_\alpha} = 0\,, \quad \frac{\partial\langle H-E\rangle}{\partial C_i} = 0.$$

TOSM results for light nuclei

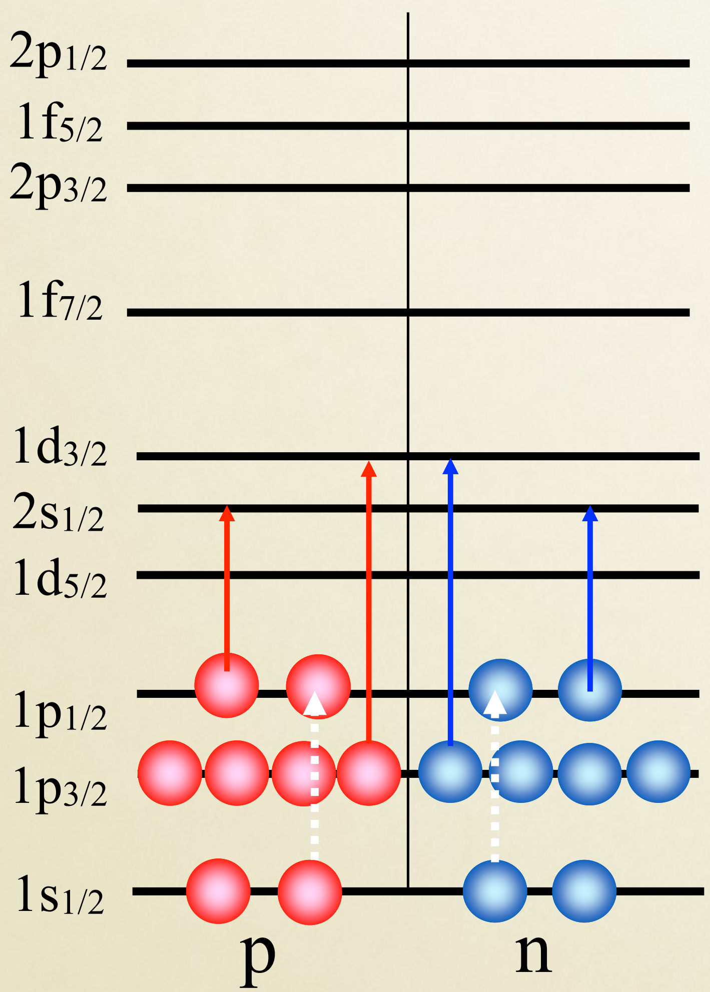






What is the difference between stable and neutron rich nuclei?

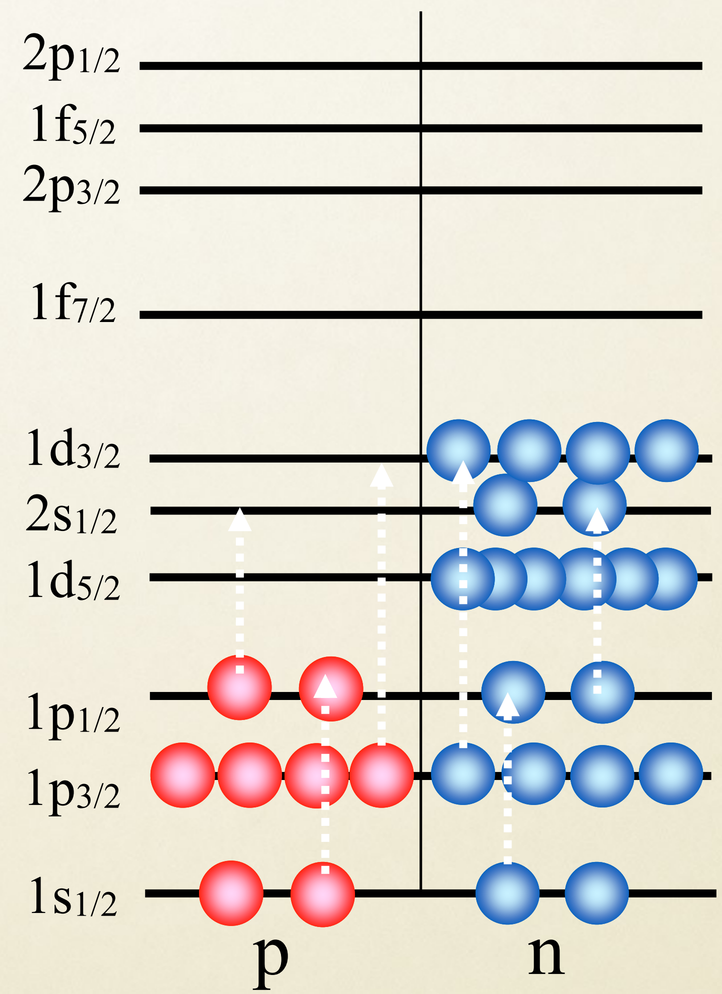
Symmetric nuclei



^{16}O

Blocking and Opening occur simultaneously.

Neutron rich nuclei



^{28}O

Only tensor blocking occurs.

Tensor Blocking Shell Model

- Use spirit of TOSM (include 2p-2h configurations as base wave function so that tensor force is treated properly).
- Treat only Δl=1 orbital separately. All light nuclei so far fills only up to Δl=1 orbitals.
- Higher excitations $\Delta l \geq 2$ is treated in Q-space and consider only to give mean field potential.

Tensor Blocking in Shell Model

$H = T + V_C + V_T$ $\qquad$ $\Psi = \psi_{sh} + \psi_{2p\text{-}2h}$

ψ_{sh} only low momentum
$\psi_{2p\text{-}2h}$ includes high-momentum

Otsuka's monopole term

Potential energy

$$\langle \Psi | V_C + V_T | \Psi \rangle = \langle \psi_{Sh} | V_C | \psi_{Sh} \rangle + \langle \psi_{Sh} | V_T | \psi_{Sh} \rangle + \boxed{\qquad\qquad} + \langle \psi_{2p-2h} | V | \psi_{2p-2h} \rangle$$

Δl=1 gives 5~8 MeV additional energy in the binding.

Usual shell model

$$H_{sh} = \sum_{i,j} v_{ij}$$
$$= V_{mf} + \sum_{i,j} \bar{v}_{ij}$$

mean field potential
and
residual interactions

V_{mf}: includes tensor
$\bar{v}_{ij}$: does not!

Treatment of Tensor Blocking

$$V = H - \Box\, T^{i} = V_C + V_T + \Box\, v_c^{ij} + \Box\, v_T^{ij}$$

$$V_{sh} = V_C + V_T$$

$$V_T = V_{T1} - V_{T1}^{0} + (V_{T1}^{0} + \underset{l=2\ldots}{\Box}\, V_{Tl})$$

$$= \boxed{\phantom{V_{T1} - V_{T1}^{0}}} + V_T^{0}$$

V_T^{0} **: is the tensor potential energy for a closed shell.**

$V_{T1} - V_{T1}^{0}$ **: is the the tensor blocking energy for the Δl=1 shell**

Δl=1 blocking energy is 5~8 MeV for an orbit.

Now it's become very simple

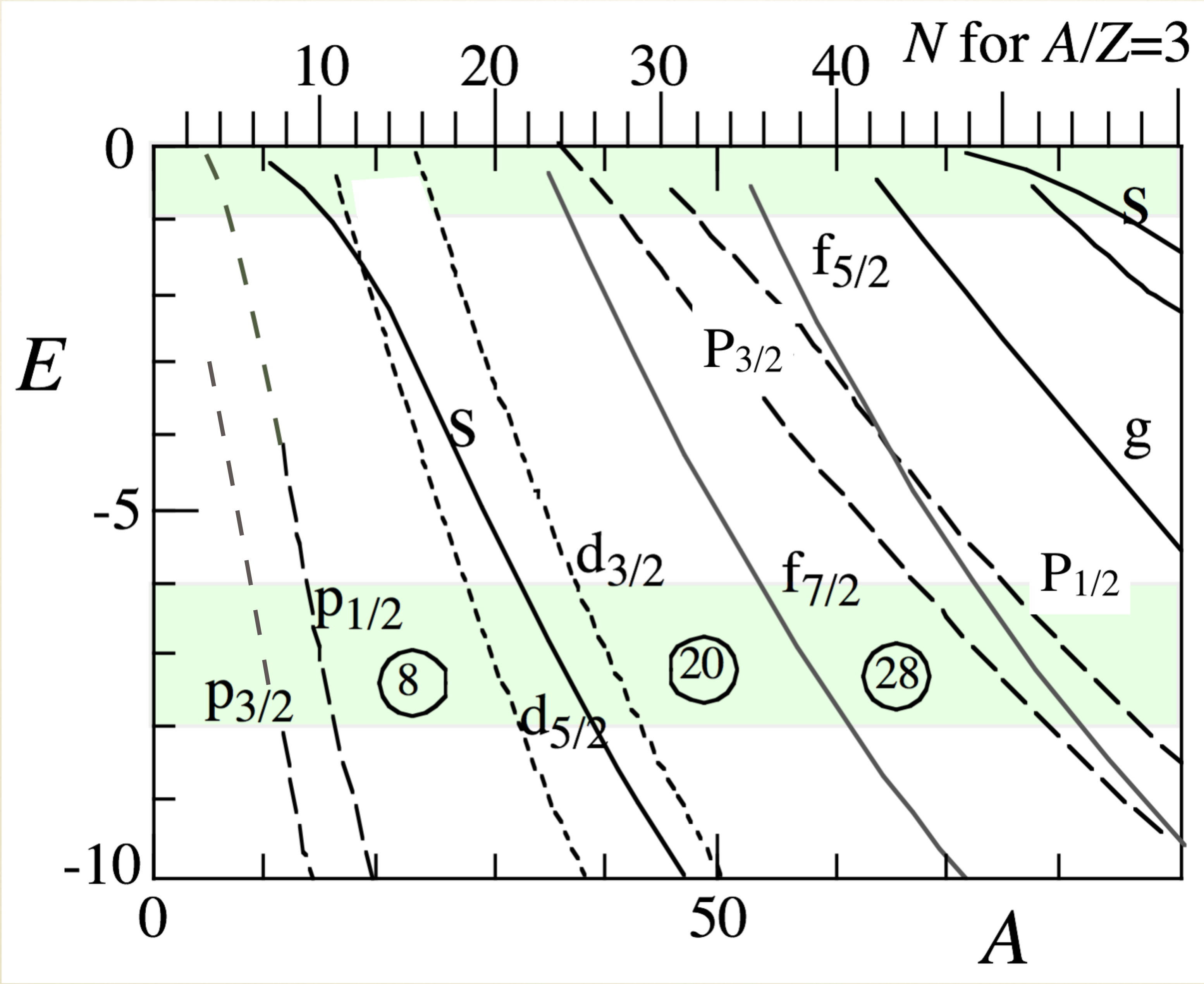
- **Only two ingredients,**

mean filed

and

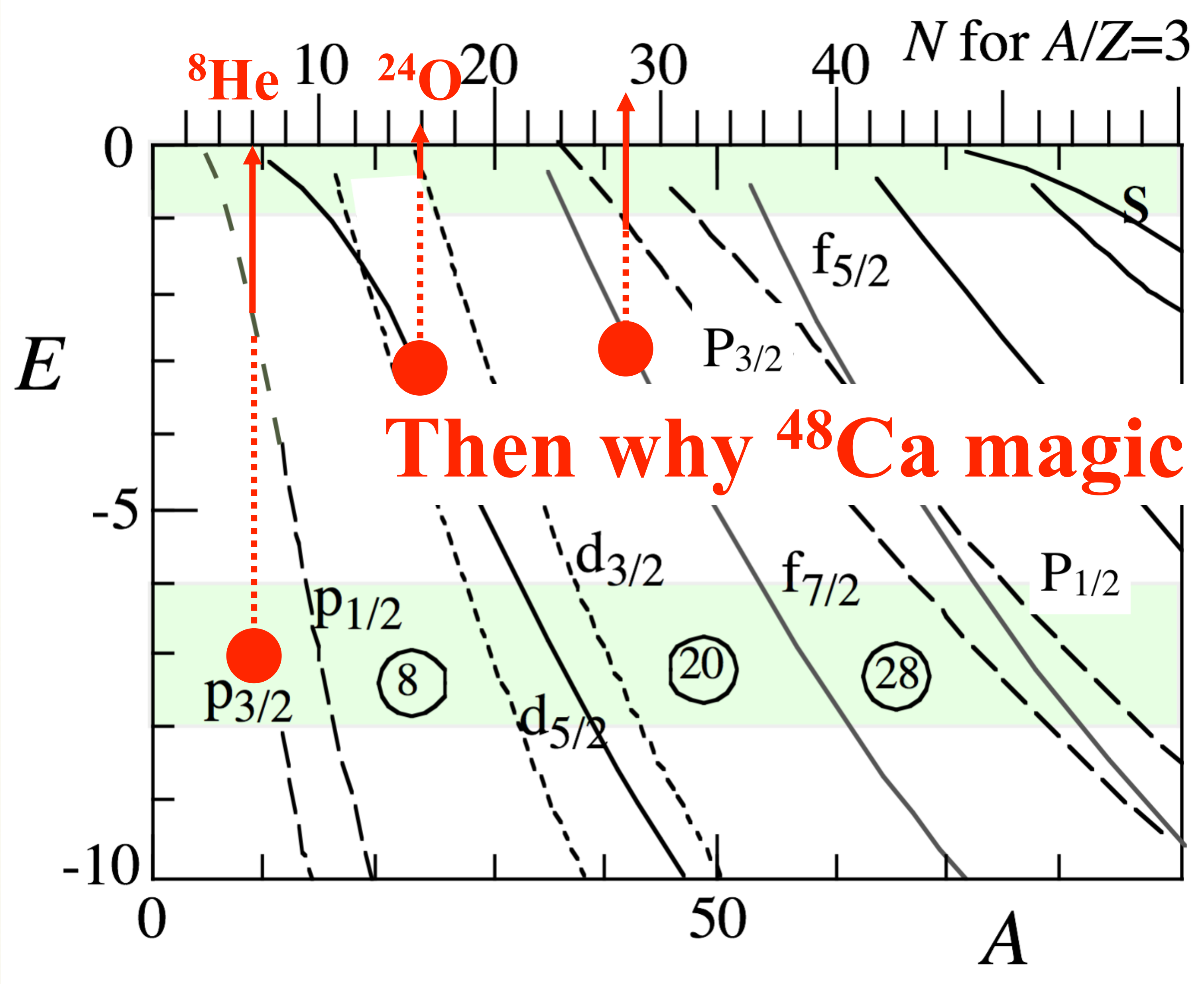
***Δl*=1 tensor.**

Orbitals in W-S potential and blocking of 2p-2h excitation (>5MeV)



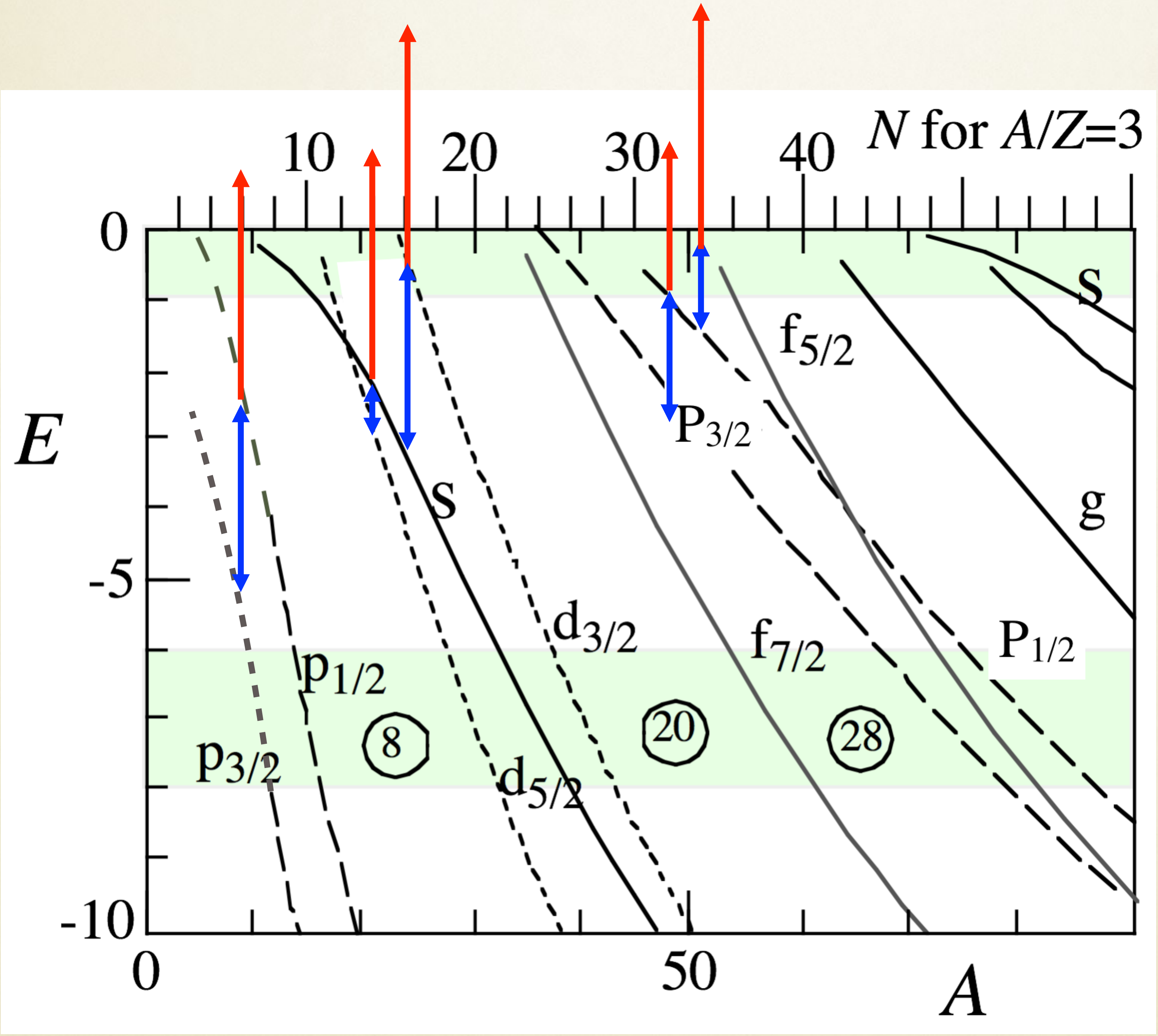
Woods-Saxon potential parameters are from the book of Bohr and Mottelson. Calculations are made for A/Z=3 nuclei.

Why doubly magic ^{10}He and ^{28}O are not bound?



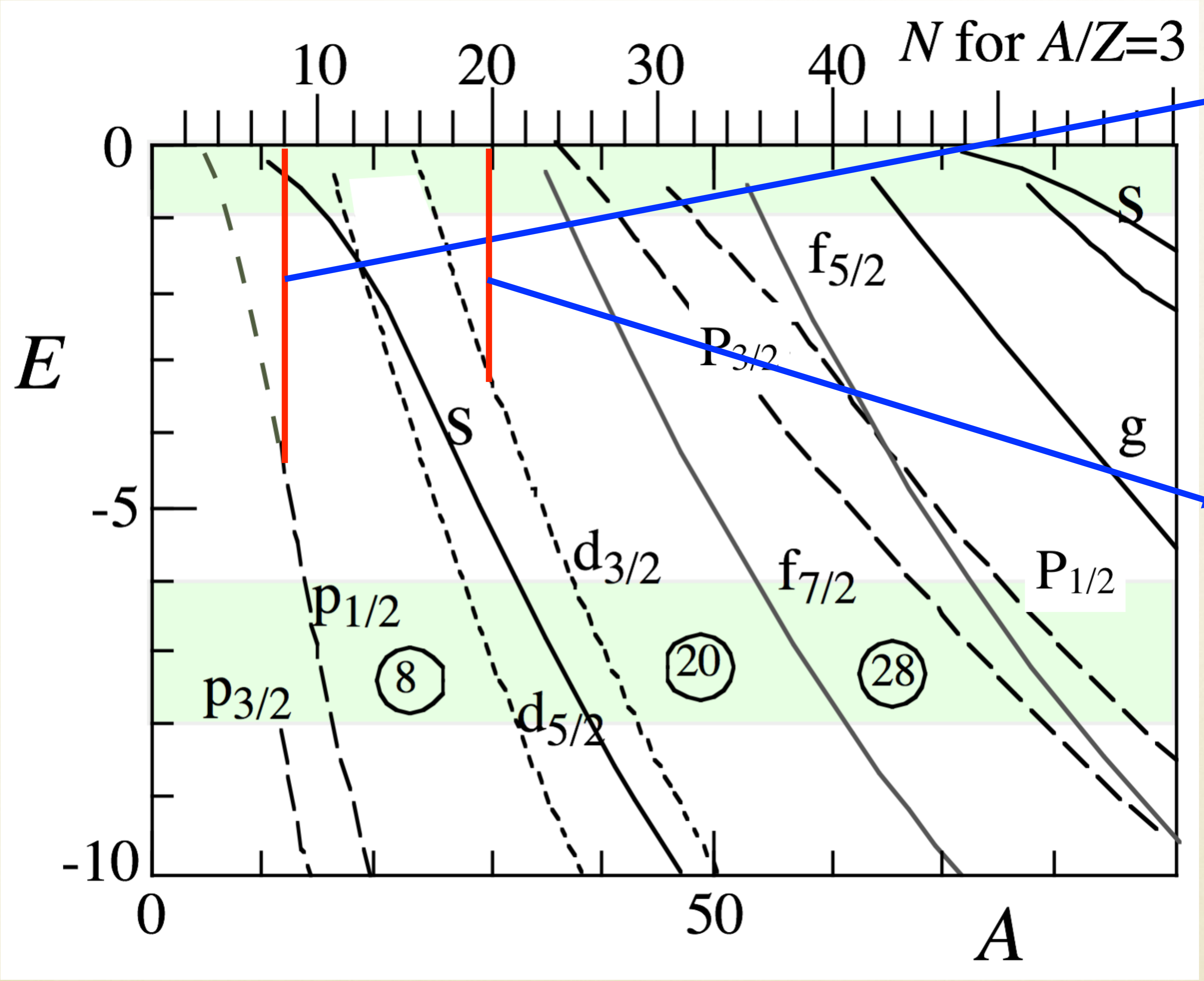
Then why ^{48}Ca magic and bound?

How are new magic numbers N=6,14,16,32,34 made?



energy gaps become more than factor of two larger due to the tensor blocking.

Why magic numbers *N*=8 and *N*=20 disappear in neutron-rich nuclei?



Originally a large gap but the tensor blocking effectively bring $p_{1/2}$ much loosely bound and mixes with sd-shell. Blocking occurs for $s_{1/2}$ until proton fills $p_{1/2}$.

Originally the energy gap is larger than ~4 MeV but the tensor blocking effectively bring $d_{3/2}$ much loosely bound and mixes with fp-shell. For loosely bound nuclei not only $f_{7/2}$ but also $p_{3/2}$ comes closer. $f_{7/2}$ has no blocking effect and $p_{3/2}$ does not until proton fills $d_{3/2}$.

Why the neutron drip line suddenly extend very much in F isotopes?

- Tensor opening occurs in F and binding energy is back to normal.

Summary

- Effects of recently observed high-momentum pn pair are considered in relation to the nuclear structures.
- Importance of the tensor blocking that is significant in neutron rich nuclei are discussed.
- A new model of nuclei "Tensor Blocking Shell Model" is introduced and used to examine new behaviors of neutron rich nuclei.

Conclusion

- All new magic numbers appeared in neutron rich nuclei are consistently explained.
- Disappearance of traditional magic numbers and non binding of ^{8}He and ^{28}O are explained.
- Sudden extension of dripline in F is understood.

Collaborators

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Thank you for your attention