Shell evolution of exotic nuclei around and beyond N=28 described by the universal monopole picture

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Acknowledgment

- NuShellX code V4.0R2 by W. D. M. Rae (http://knollhouse.org/)
- MSHELL by T. Mizusaki

Outline of the talk

- General property of the monopole interaction causing shell evolution and its application to sd-pf shell
- Shell and nuclear structure evolution from N=20 to 28
  - Clear evidence of reduction of the LS splitting by tensor force
- Structure beyond N=28 and shell turning
  - Probed by first forbidden β decay from K isotopes
- Summary

Conventional picture about shell evolution

- Question
  - How does the shell evolve from light to heavy regions?
  - Is there any difference between stable and unstable regions?
- Woods-Saxon potential
  - gives overall agreement with experiment near stable nuclei.
  - Slow and monotonic evolution

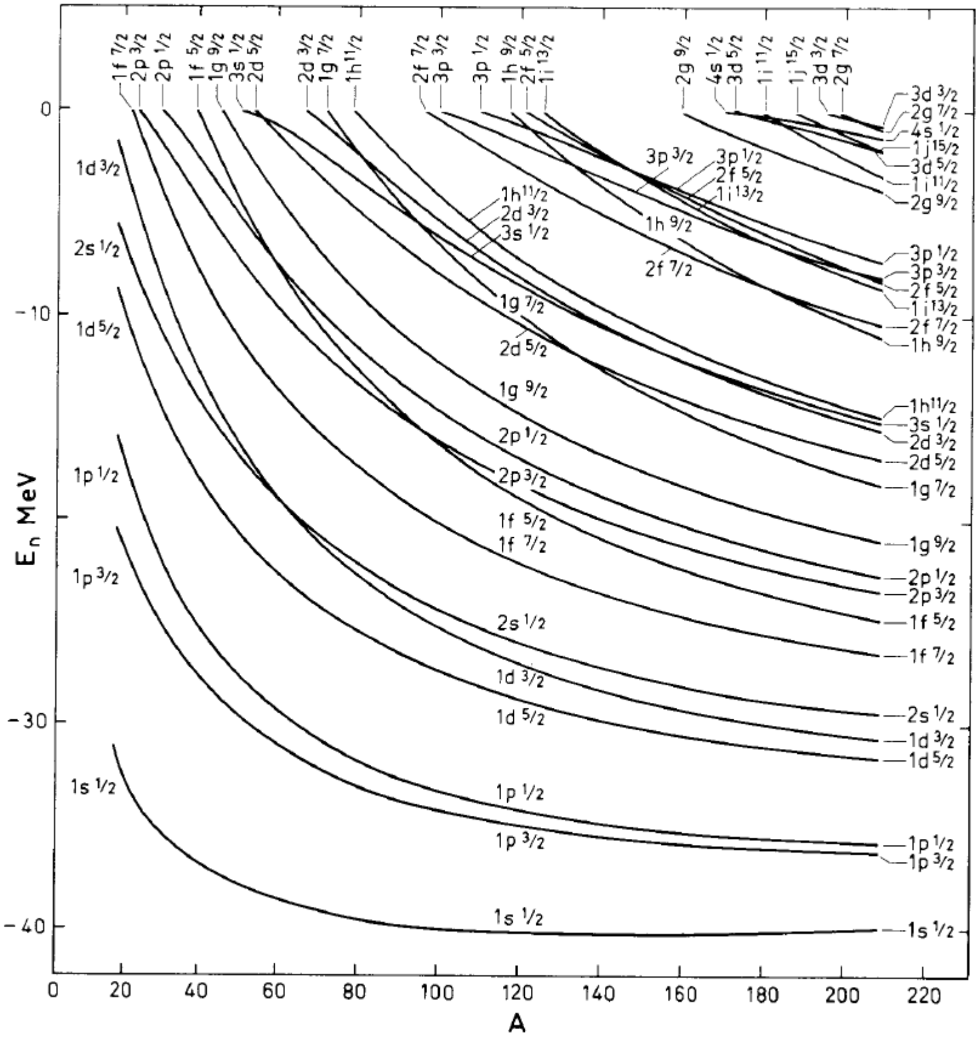
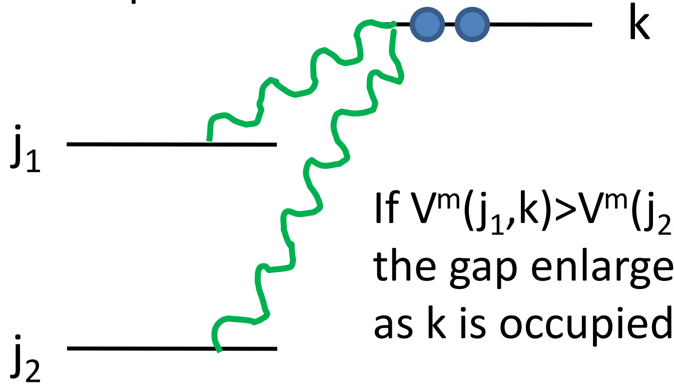


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

A. Bohr and B.R. Mottelson, Nuclear Structure, vol. 1

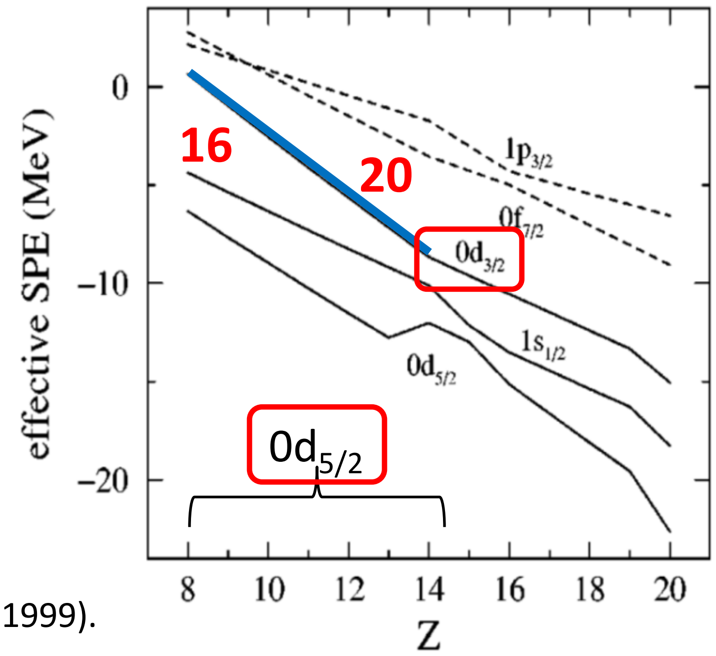
Two-body picture about shell evolution

- What causes the change of shell gap: difference in mean force between orbits
  - Sometimes gives a sharp evolution
  - Sensitive to the Fermi surface and can be non-monotonic.
- What we want:
  - To detect those features
  - To account for and predict the shell evolution from more basic point of view



Monopole interaction

If $V^m(j_1,k)>V^m(j_2,k)$, the gap enlarges as k is occupied.



Y. Utsuno et al., Phys. Rev. C 60, 054315 (1999).

Spin dependence and the tensor force

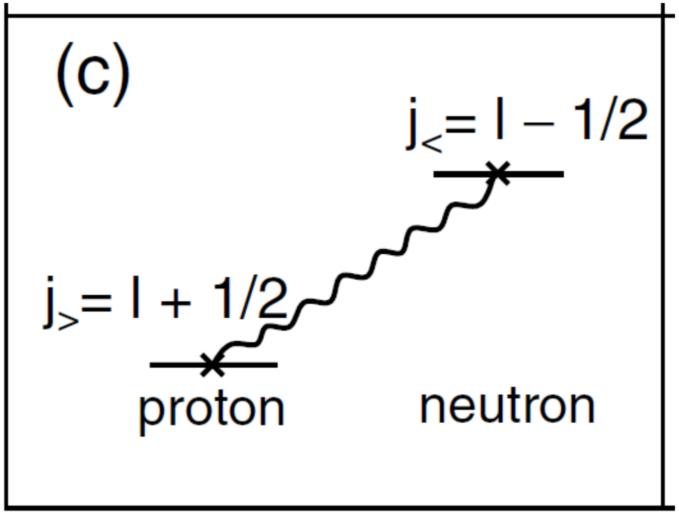
- Origin of the drastic change
  - Spin dependence (T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001).)
- Tensor force

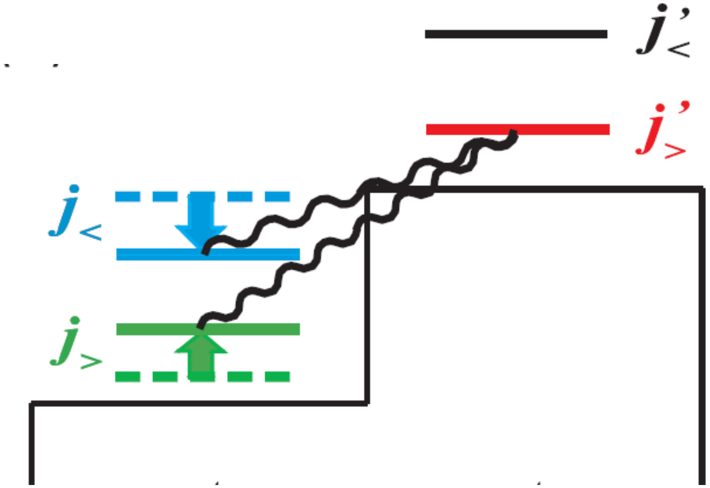
$$(2j_> + 1)V^T_{j_>,j'} + (2j_< + 1)V^T_{j_<,j'} = 0,$$

Attraction between $j_>$ and $j'_<$

Repulsion between $j_>$ and $j'_>$

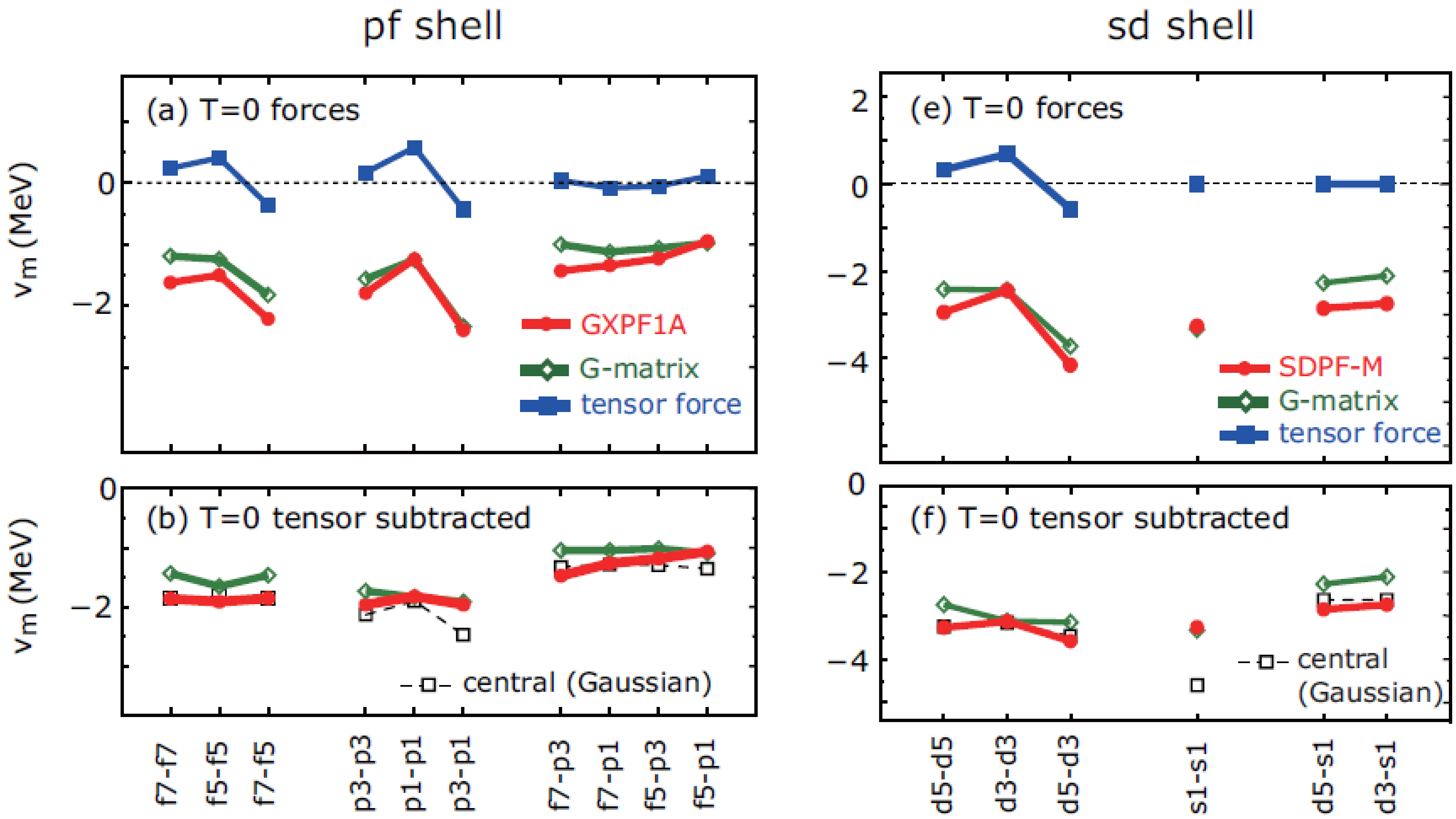
Large effect on the LS splitting





T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).

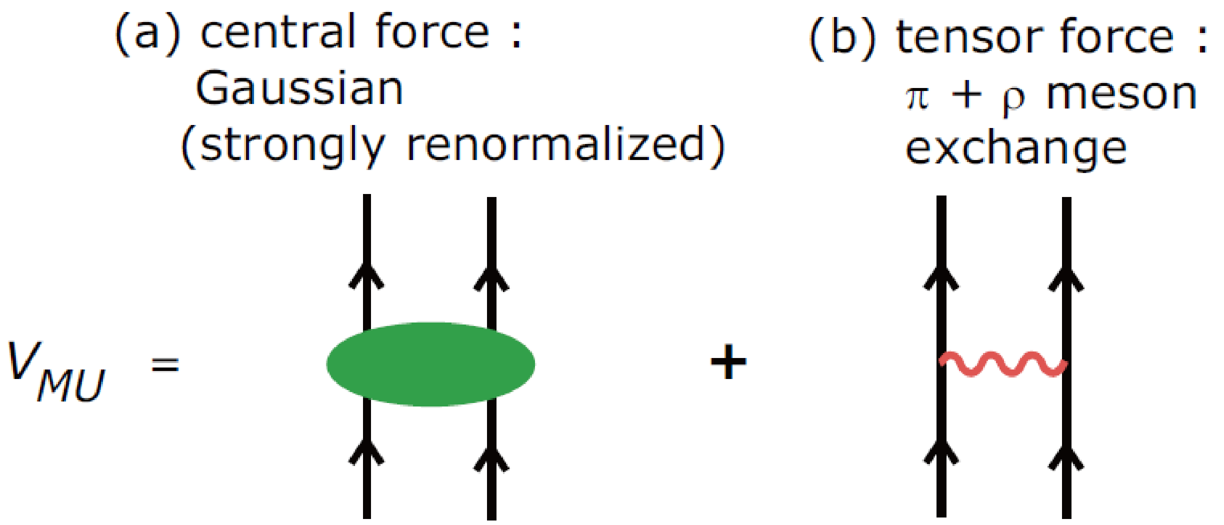
Simplicity of tensor-subtracted monopole



T. Otsuka, T. Suzuki, M. Honma, Y. Utsuno, N. Tsunoda, K. Tsukiyama, M. Hjorth-Jensen., Phys. Rev. Lett. 104, 012501 (2010).

- A simple Gaussian force fits excellently.

Monopole-based universal interaction



- Tensor force
  - Spin and node dependence
    - Spin dependence : direction of j and j' (different sign)
    - Node dependence: strength is larger between orbits with the same node
- Central force
  - Node dependence only

A new interaction for the sd-pf shell

- Components of the interaction
  - sd part + pf part + cross-shell part
  - USD as the sd part (with a slight modification as adopted in SDPF-M: changing magic number from N=16 to 20)
  - GXPF1B as the pf part (with a slight modification in the $f_{7/2}$ pairing and q-pairing matrix elements; improving the 2^+_1 of Si isotopes around N=22)
- **A newly constructed interaction** for the cross-shell interaction
  - Based on the monopole-based universal interaction picture
  - Consisting of central, LS (fixed to M3Y), and tensor ($\pi+\rho$) parts
  - Refined central force by including density dependence
  - Parameters of the central force are determined to fit the central monopole of GXPF1: a natural continuation of GXPF1 to the cross shell

Details of the Gaussian

Central force with density (or center-of-mass coordinate) dependence is

$$V_c(r,R) = \sum_{S,T} P^{S,T} D_c(R,S,T) d_c(r,S,T)$$

where R and r are center-of-mass and relative coordinates, respectively.

$$d_c(r,S,T) = f^{S,T} \exp\left(-(r/\mu)^2\right)$$

$$D_c(R,S,T) = D(R) = 1 + A_d F(R)^{B_d}$$

with $F(R) = \{1 + \exp((R - R_0)/a)\}^{-1}$

Density dependence improves matrix elements of higher nodes.

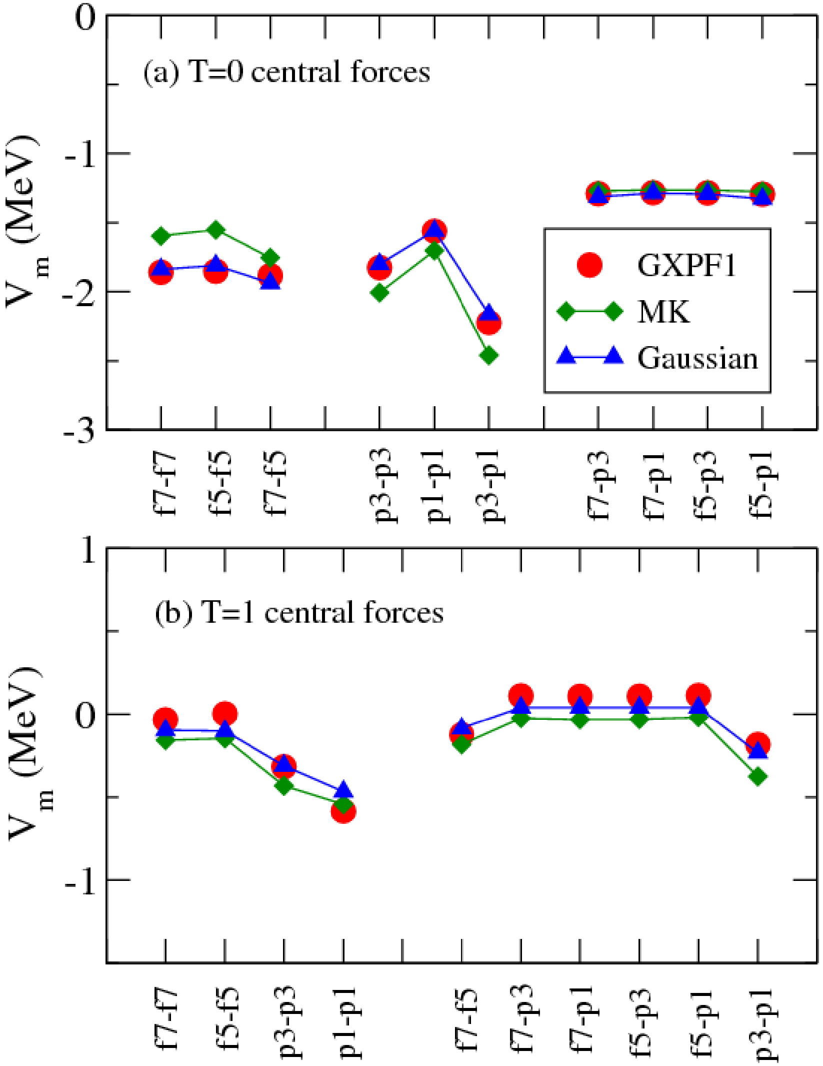
Free parameters: $f^{S,T}$, μ, and A_d (totally six parameters only)

We take $f^{0,0}$=-140 MeV, $f^{1,0}$=0, $f^{0,1}$=0.6$f^{0,0}$, $f^{1,1}$=-0.6$f^{0,0}$, μ=1.2 fm, and A_d=-0.4.

GXPF1 vs. Gaussian for central

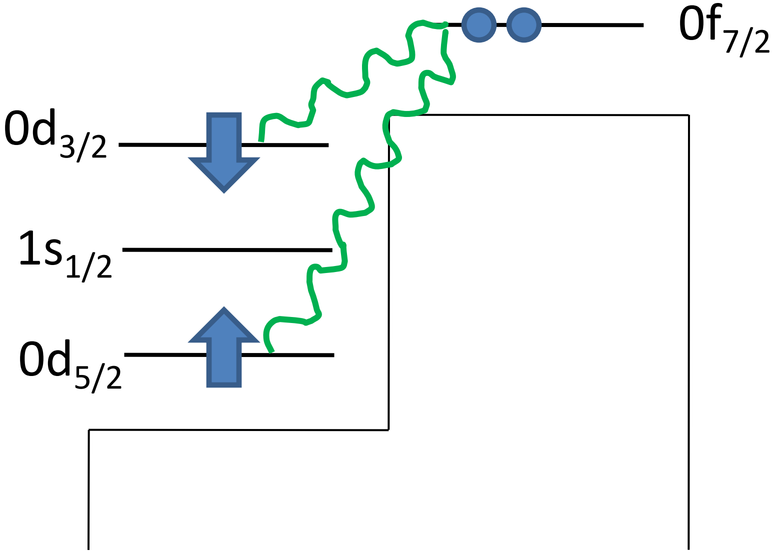
- Extracting the central of GXPF1
  - Spin-tensor decomposition
- Comparison with MK (Millerner-Kurath): Yukawa
  - T=0 f-f: weaker due to the difference of range
  - T=0 p-p: stronger due to the lack of density dependence
  - T=1 overall: stronger due to different S=0 and S=1 ratio

Monopole centroids for the central force



Shell evolution from N=20 to 28

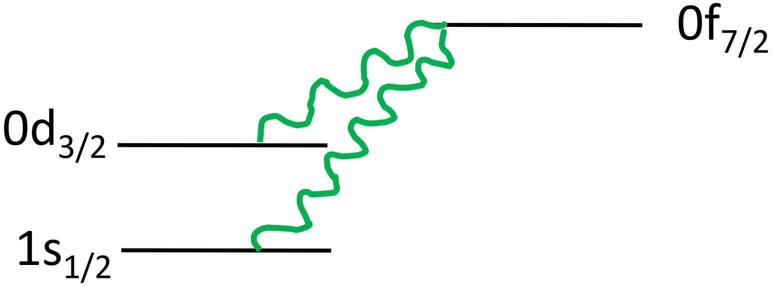
- The effect of the cross-shell interaction
  - π(sd) orbits are of interest.
- Neutron: $f_{7/2}$
  - $V^m(f_{7/2}, sd)$
- To be discussed
  1. Z=16 gap: single hole states in $_{19}$K isotopes
  2. Effects on collectivity: deformation in $^{42}Si_{28}$
  3. Reduction of the LS splitting: distribution of the spectroscopic factor



Monopole interaction in K levels

- $\pi 0d_{3/2}$ vs. $\pi 1s_{1/2}$ from N=20 to 28
  $= V^m(0f_{7/2}, 0d_{3/2})$ vs. $V^m(0f_{7/2}, 1s_{1/2})$
- Central vs. tensor
  - Both the central and the tensor contribute almost to the same extent.

⇨ Sharp change of the gap



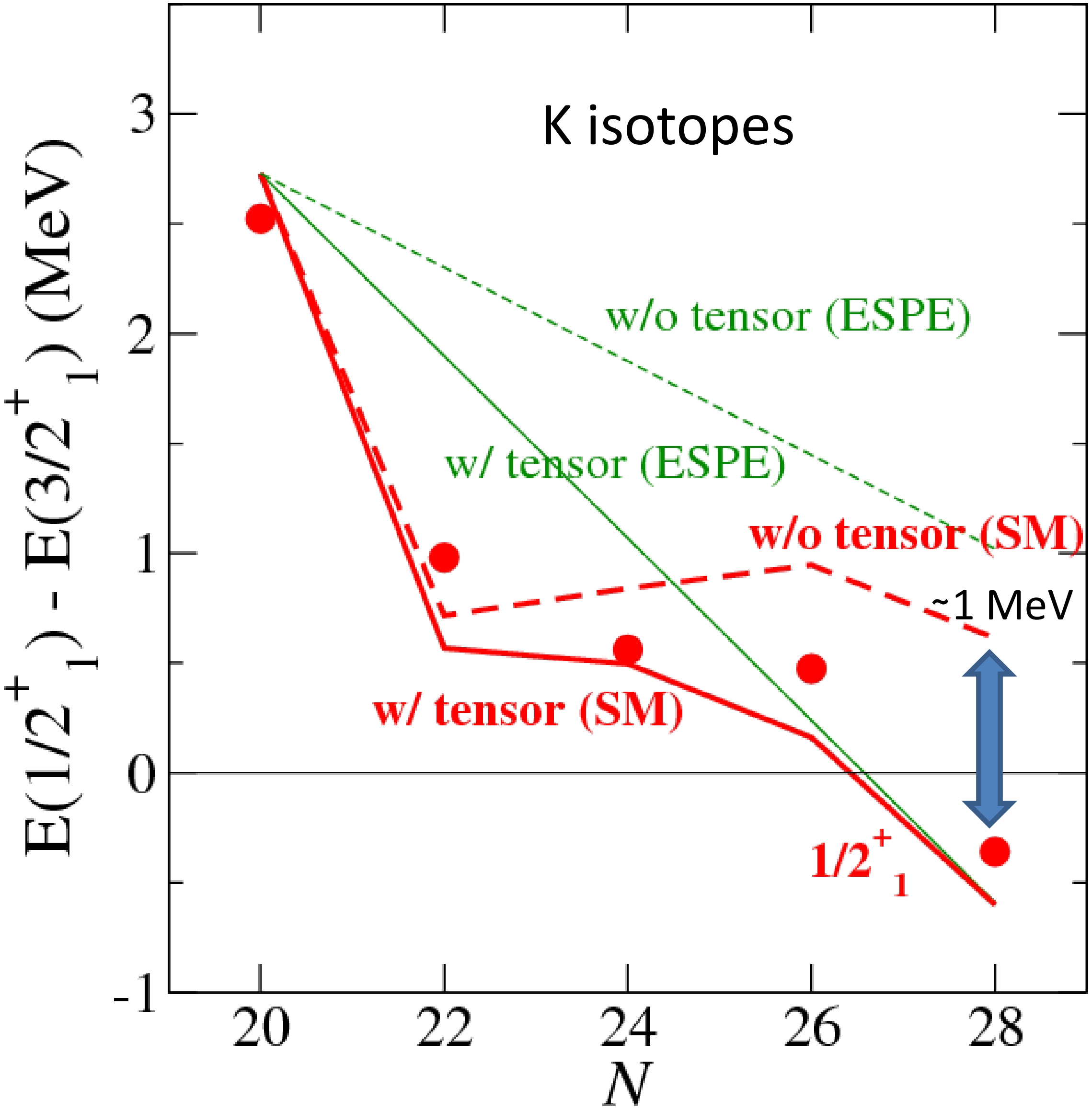
p-n monopole centroid (in MeV)

		$d_{3/2}$	$s_{1/2}$	difference
$f_{7/2}$	central	-1.10	-0.88	-0.22
	tensor	-0.21	0	-0.21

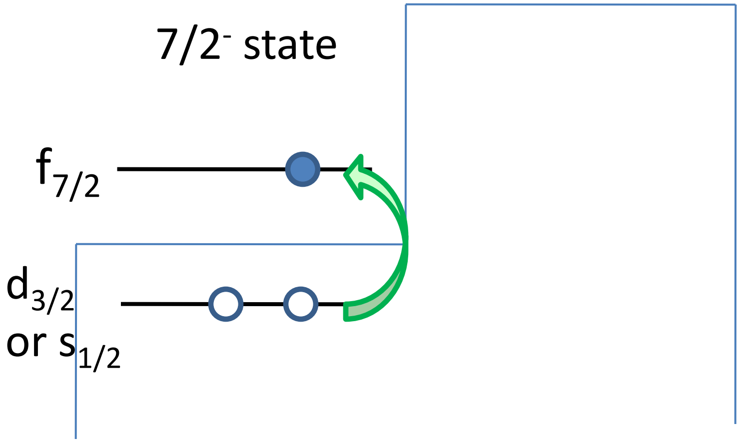
strength scaled at A=42

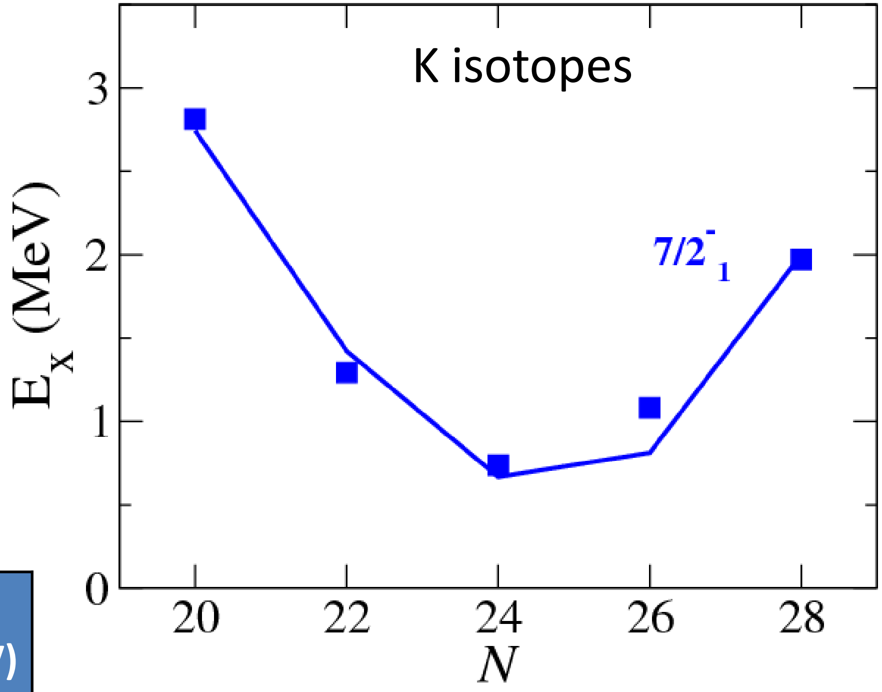
Evolution of $\pi d_{3/2}$-$s_{1/2}$ gap in K isotopes

- Energy levels
  - Significance of the tensor force is clear.
  - Directly reflect the gap between $\pi(d_{3/2})$ and $\pi(s_{1/2})$ at N=20 and 28
  - $1/2^+_1$ has a large mixing with $\pi(d_{3/2}) \otimes \nu(2^+)$ in N=22, 24, and 26.



Unnatural parity states: probing Z=20 gap



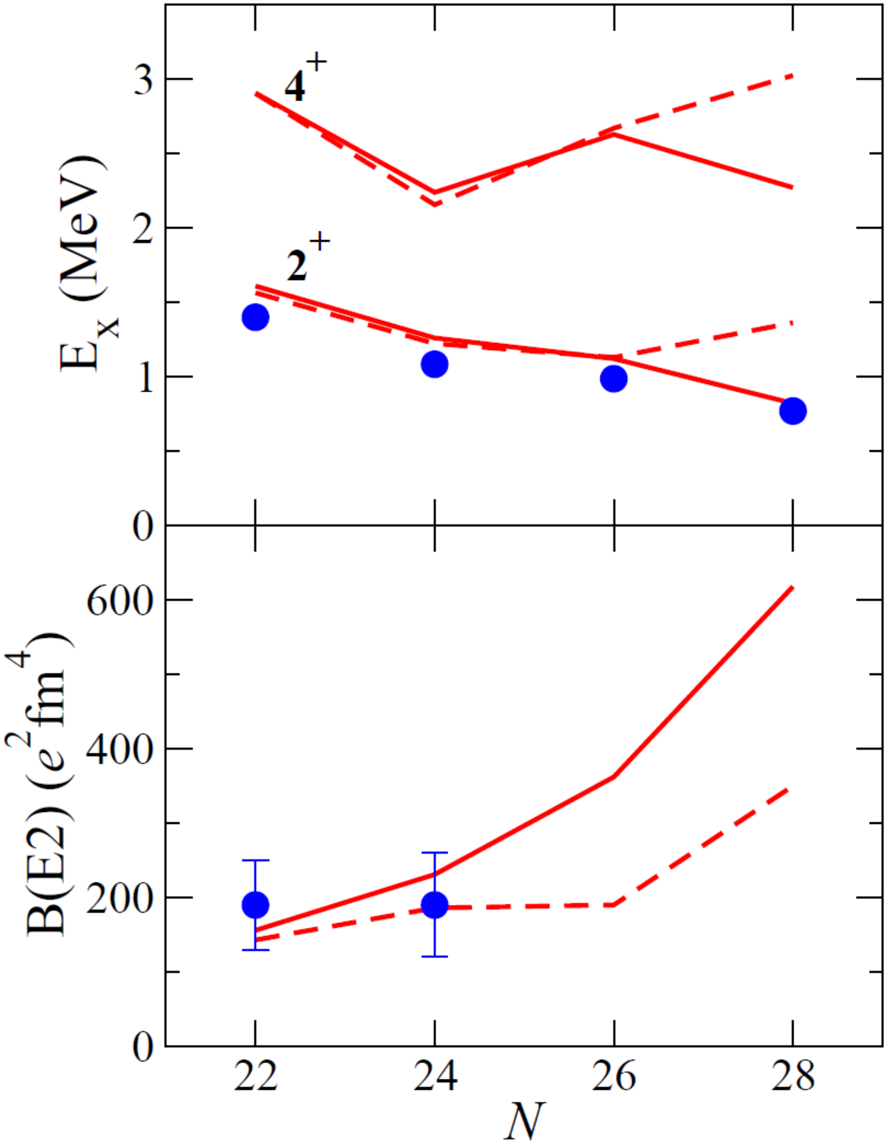


$^{47}K_{28}$	Ex.($7/2^-_1$) (MeV)	Effective shell gap (MeV)	Correlation energy (MeV)
Exp.	**1.97**		
Present	**2.00**	8.54	6.54
SDPF-NR	5.62	11.45	5.83

- Correlation energy: large but similar among interactions
- Effective shell gap: crucial for the level

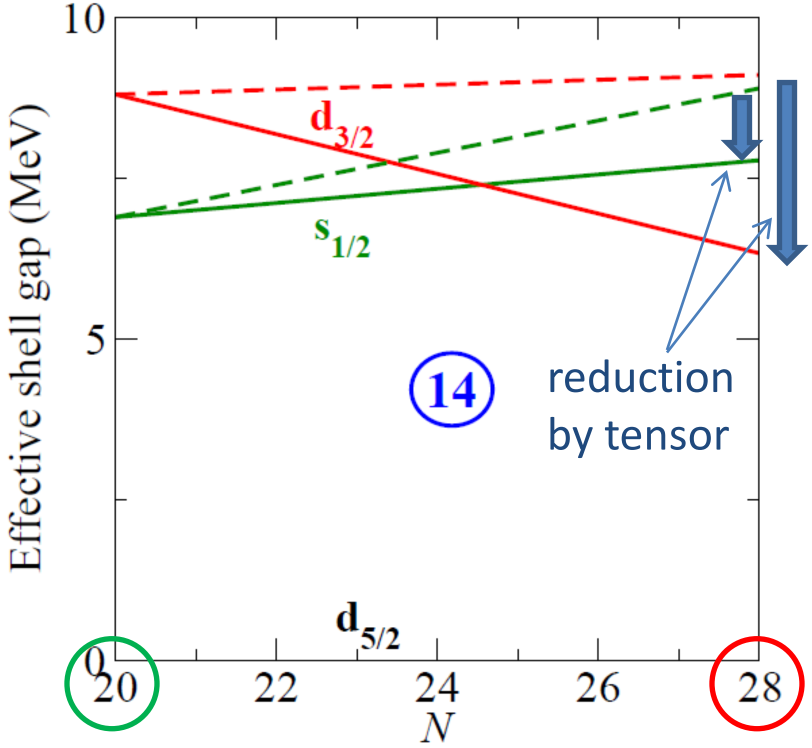
Collectivity of Si isotopes: N=28 magicity

- Energy levels N≤26
  - 2^+_1 is dominated by $\nu(f_{7/2})^2$
    - Pairing and q-pairing in $f_{7/2}$ are more sensitive.
- Large difference at N=28
  - Disappearance of the magic number

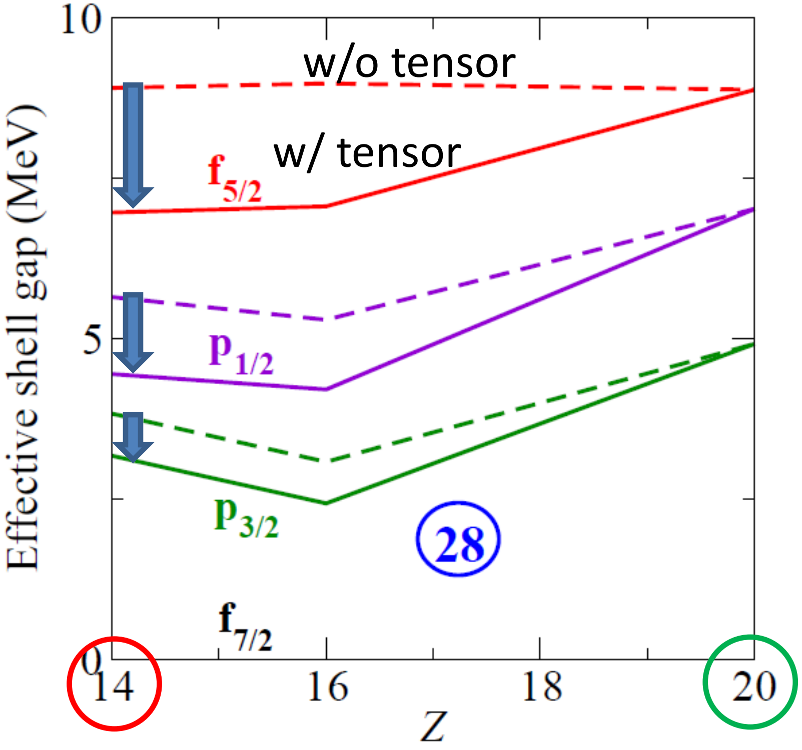


Exp.) ^{40}Si: C.M. Campbell et al., Phys. Rev. Lett. 97, 112501 (2006).
^{42}Si: B. Bastin et al. Phys. Rev. Lett. 99, 022503 (2007).

Comparison of the effective SPE



Proton shell gap as function of N



Neutron shell gap as function of Z

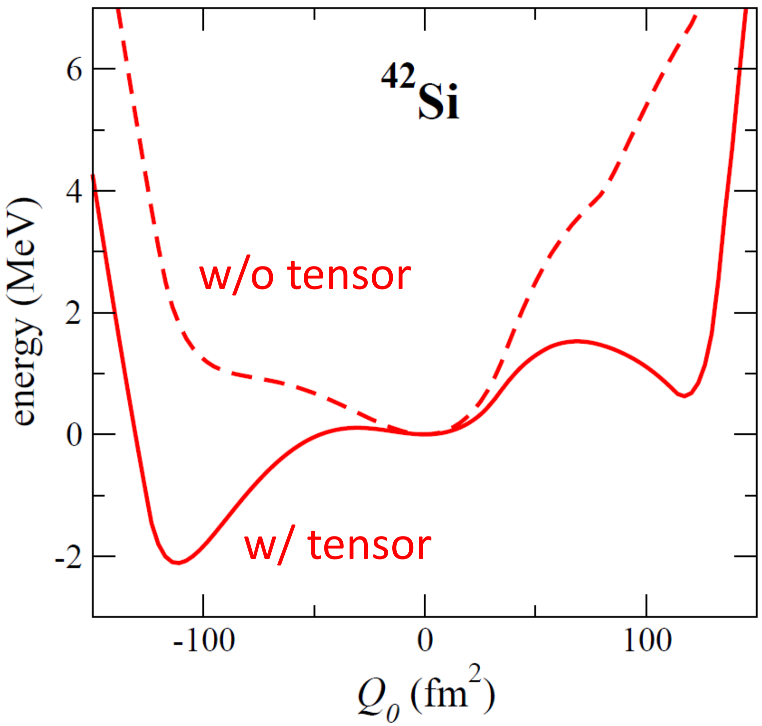
L-S closure ⇒ j-j closure

j-j closure ⇐ L-S closure

- Coherent quenching of proton and neutron shell gaps which increase toward the j-j closure

Potential energy surface (PES) for ^{42}Si

- PES: constrained (Q_0) Hartree-Fock calculation in the shell model space
  - Successful in the shape coexistence in ^{56}Ni (T. Mizusaki et al., Phys. Rev. C 59, R1846 (1999).)
- Effect of the tensor force: large
- Oblate deformed g.s. caused by the tensor
  - Consistent with calculated Q moment of the 2^+_1: +23 e^2fm^4

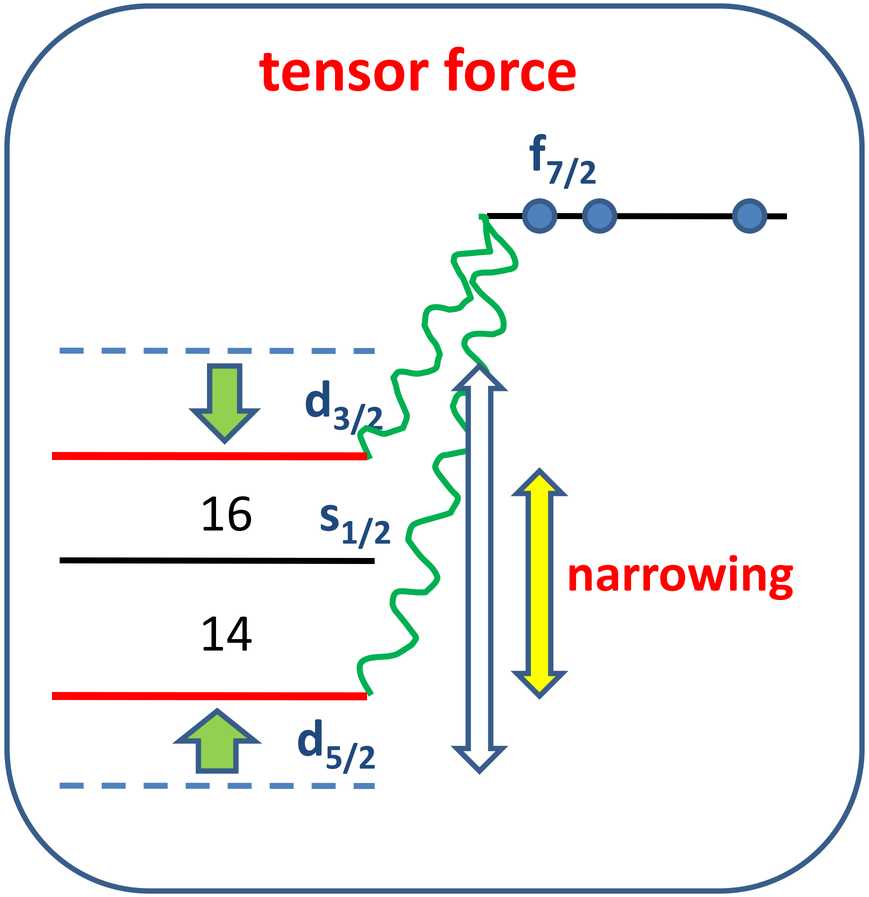


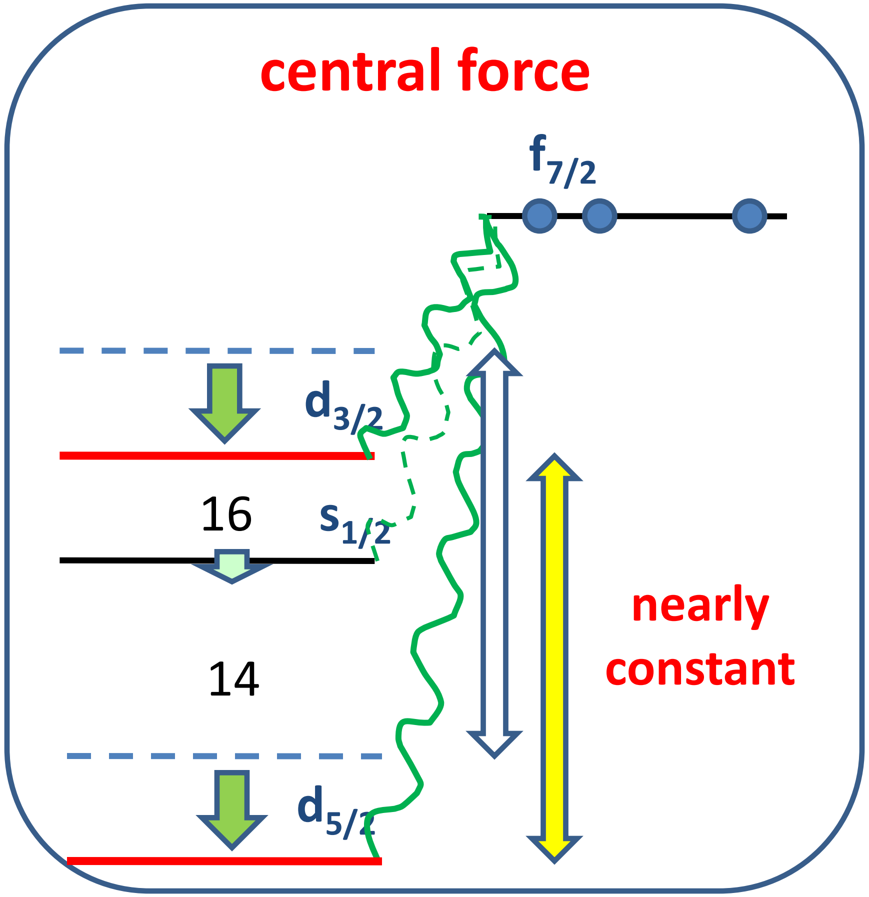
Sulfur isotopes

2^+_1 energy

	Exp. (MeV)	Cal. (MeV)
22	1.292	1.264
24	0.900	0.794
26	0.890	0.943
28	1.315	1.248

Difference between tensor and central



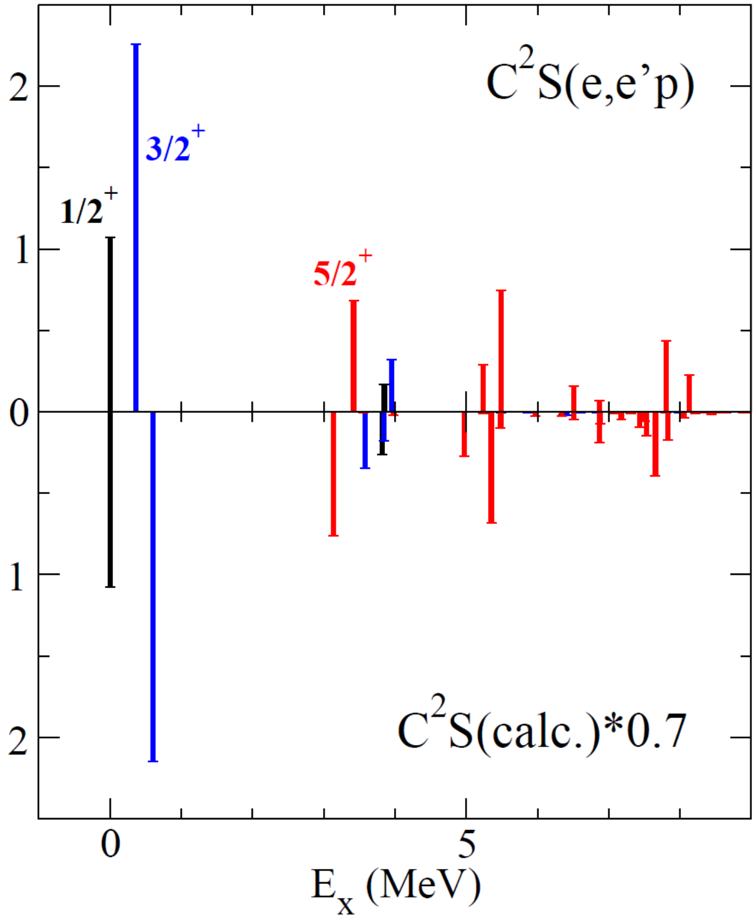


- Both tensor and central affect the reduction of the Z=16 gap.
- Almost only tensor contributes to **the reduction of the LS splitting**.

Spectroscopic factor for 1p removal from ^{48}Ca

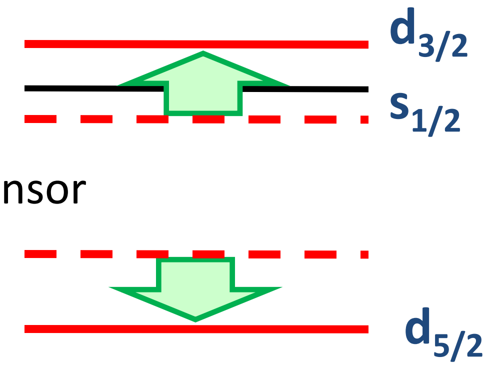
- $\pi d_{5/2}$ hole state
  - Ex.: high
  - Fragments into many states
- Spectroscopic factor
  - The centroid gives the single particle energy.
- Comparison between experiment and calculation
  - Quenching factor 0.7 is needed.
  - Very good : both position and strength

Present interaction (w/ tensor)



(e,e'p): G.J. Kramer et al., Nucl. Phys. A 679, 267 (2001).

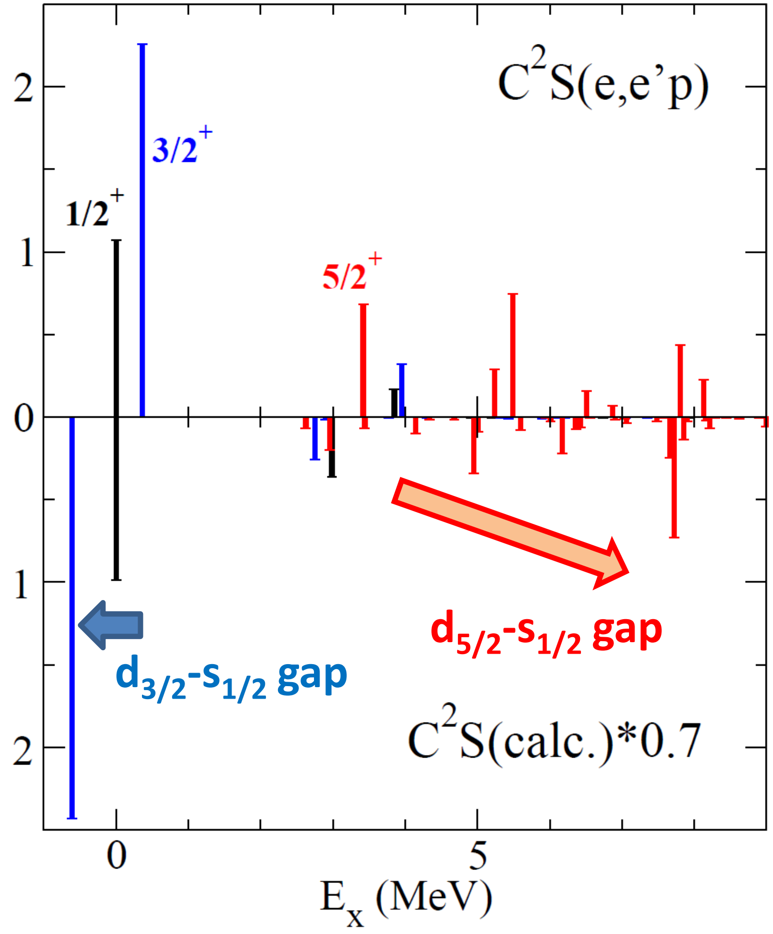
What happens without the tensor force?



Without tensor

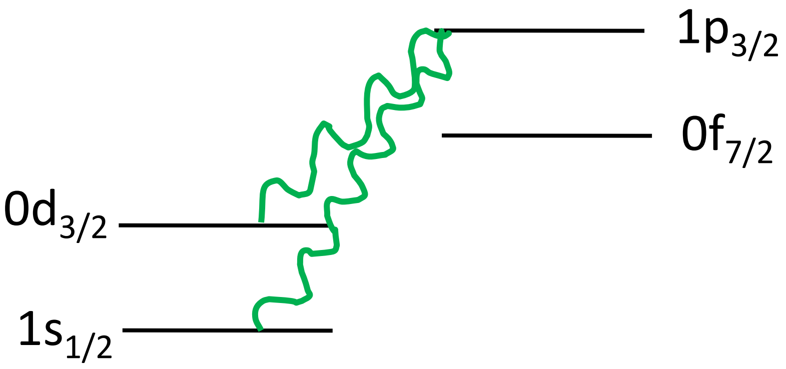
- $d_{3/2}$
  - The position of the single-hole state shifts to the left.
- $d_{5/2}$
  - $5/2^+$ levels exist from around 3 MeV, but the strength shifts to higher excitation energy.

w/o tensor in the cross shell int.



Shell evolution beyond N=28

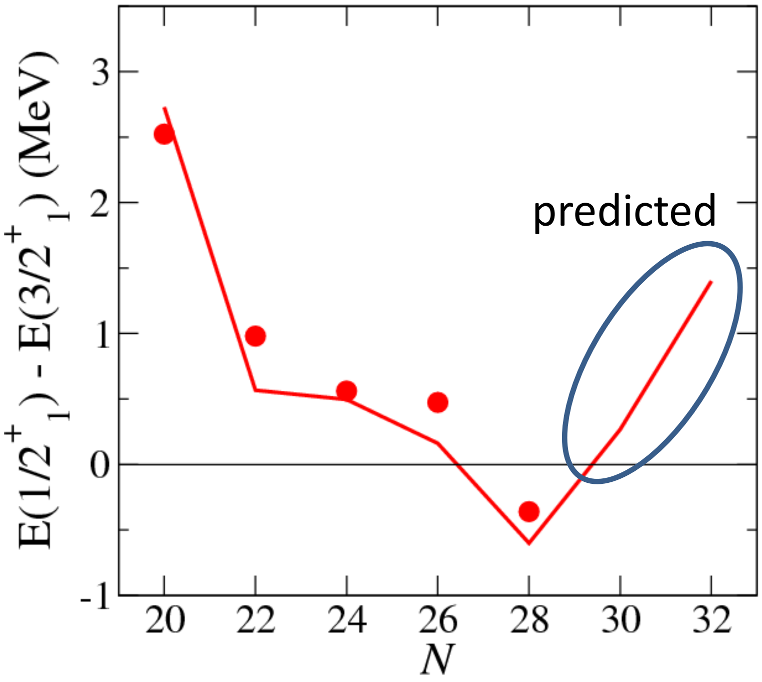
- Fermi surface: $\nu 1p_{3/2}$
  - $V^m(1p_{3/2}, 0d_{3/2})$ vs. $V^m(1p_{3/2}, 1s_{1/2})$



		$d_{3/2}$	$s_{1/2}$	difference
$f_{7/2}$	central	-1.10	-0.88	-0.22
	tensor	-0.21	0	-0.21
$p_{3/2}$	central	-0.68	-1.15	+0.47
	tensor	-0.05	0	-0.05

The 1/2+ level is predicted to turn.

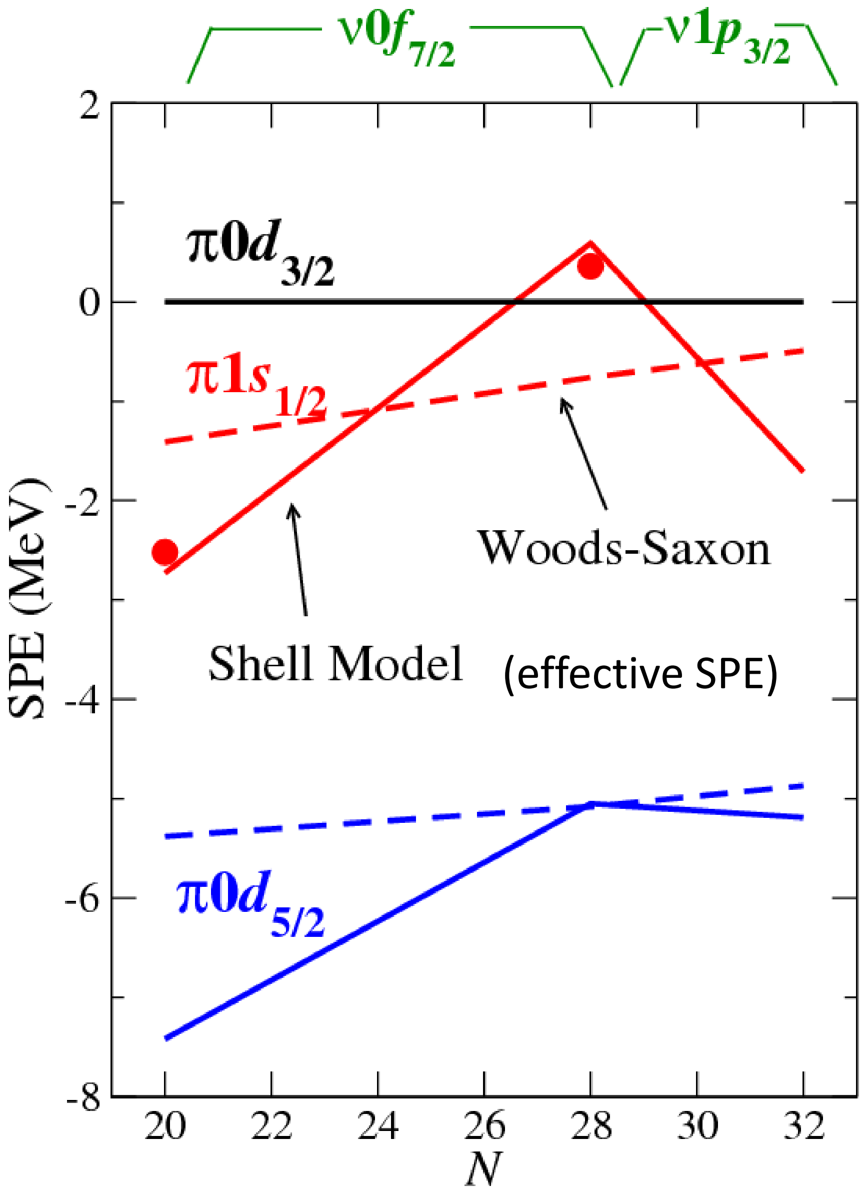
- Example of non-monotonic change



Comparison to Woods-Saxon potential

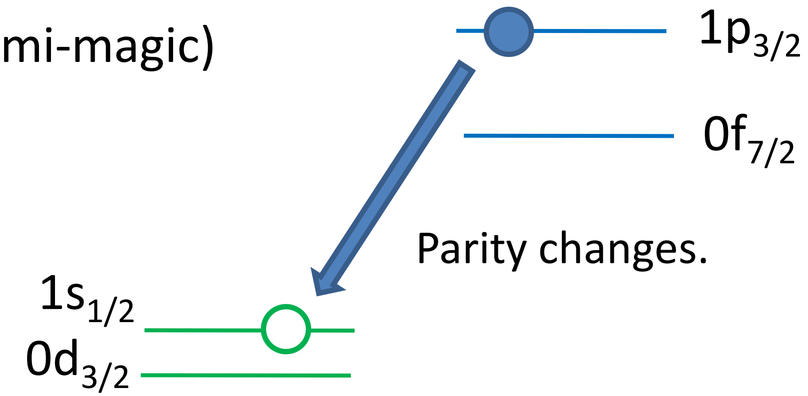
- Woods-Saxon
  - Very slow and monotonic change
  - Very small reduction of LS splitting from N=20 to 28

Independent of parameters used



How to probe the change?

- No direct measurement of the spin/parity in the g.s. of K isotopes beyond N=28
- The only experimental data available: β decay to Ca isotopes
  - Parity of low-lying states: different between K and Ca
    → first forbidden decay
- First forbidden decay as a probe of the ground state of K: promising
  - Structure of daughter: Ca isotopes (semi-magic)
    - Simple: ambiguity is small
    - Very low level density: one-to-one correspondence to experiment



Parity changes.

First forbidden β decay

- Somewhat complicated (for accuracy of electron w.f.)
- We follow the formalism given by Warburton et al.

  E.K. Warburton et al., Ann. Phys. 187, 471 (1988).
- Operator: [(polar vector) × (axial vector or scalar)]$^{(0,\ 1,\ \text{or}\ 2)}$t^{-}

  parity change no parity change

  - Rank 0 (two operators)

    $$[rC^{(1)}\otimes\sigma]^{(0)}t^{-}\rightarrow M_{0}{}^{S}\qquad [\sigma\otimes\nabla]^{(0)}t^{-}\rightarrow M_{0}{}^{T}$$

  - Rank 1 (three operators)

    $$rC^{(1)}t^{-}\rightarrow x\qquad [rC^{(1)}\otimes\sigma]^{(1)}t^{-}\rightarrow u\qquad \nabla t^{-}\rightarrow \xi' y$$

  - Rank 2 (one operator): unique first forbidden decay

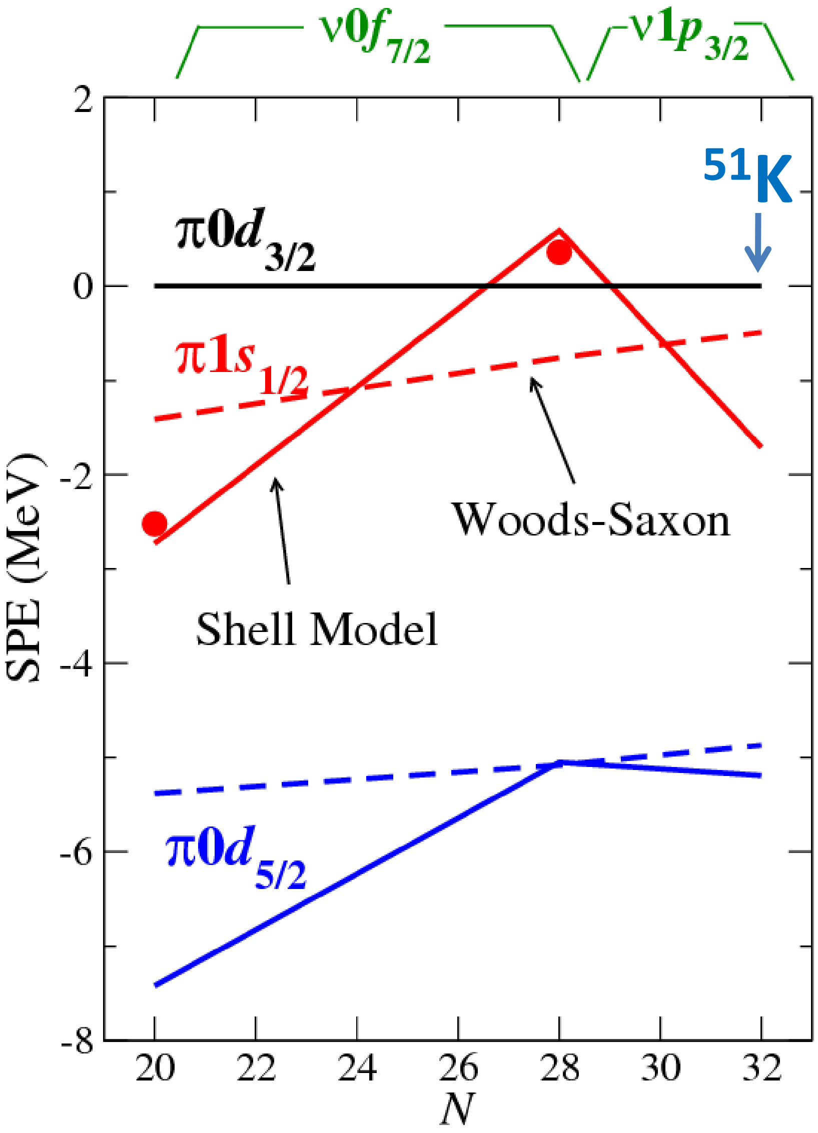
    $$[rC^{(1)}\otimes\sigma]^{(2)}t^{-}\rightarrow z$$

- Decay rate: incoherent sum of R0, R1, and R2

Some remarks on first forbidden decay

- The number of independent matrix elements
  - R0: one (M_0^T=-$E_{osc}M_0^S$ for H.O. basis)
  - R1: two ($\xi' y$=$E_\gamma x$ from CVC theory and isospin symmetry)
  - R2: one
- Systematic study
  - R0 and R2 are studied rather extensively.
    - Effective operator: correction of meson enhancement (M_0^T) and small model space
  - R1: less expensively
    - Ambiguity to extract the R1 matrix element from experiment
    - Cancellation of *x* and *u* sometimes makes predictive power worse.
    - We use the bare operator following Warburton et al.

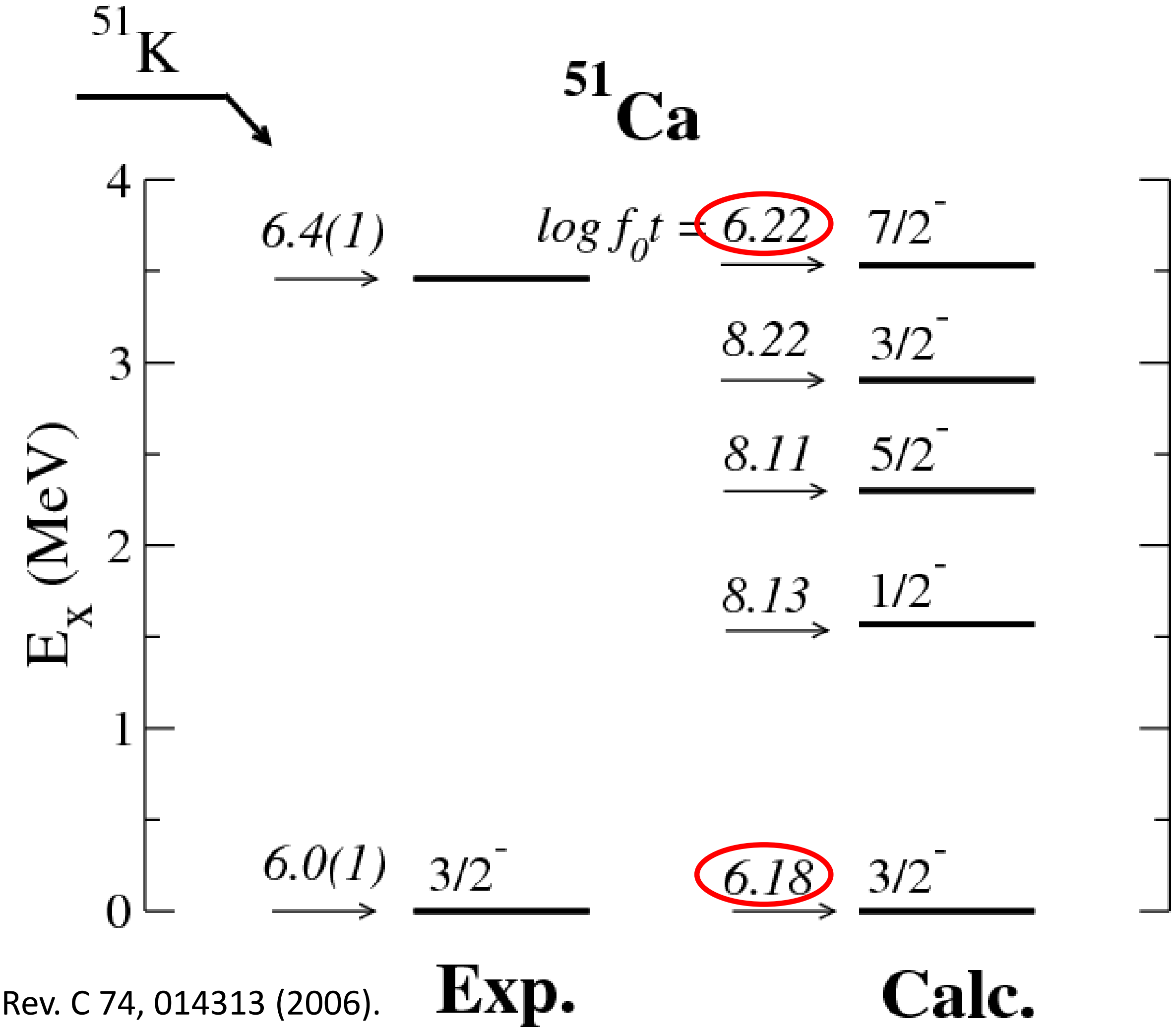
^{51}K: 1/2$^+$ or 3/2$^+$?



$\nu 0f_{7/2}$
$\nu 1p_{3/2}$
^{51}K
$\pi 0d_{3/2}$
$\pi 1s_{1/2}$
$\pi 0d_{5/2}$
Woods-Saxon
Shell Model
SPE (MeV)
2
0
-2
-4
-6
-8
20
22
24
26
28
30
32
N

β decay of ^{51}K: end of $\nu p_{3/2}$

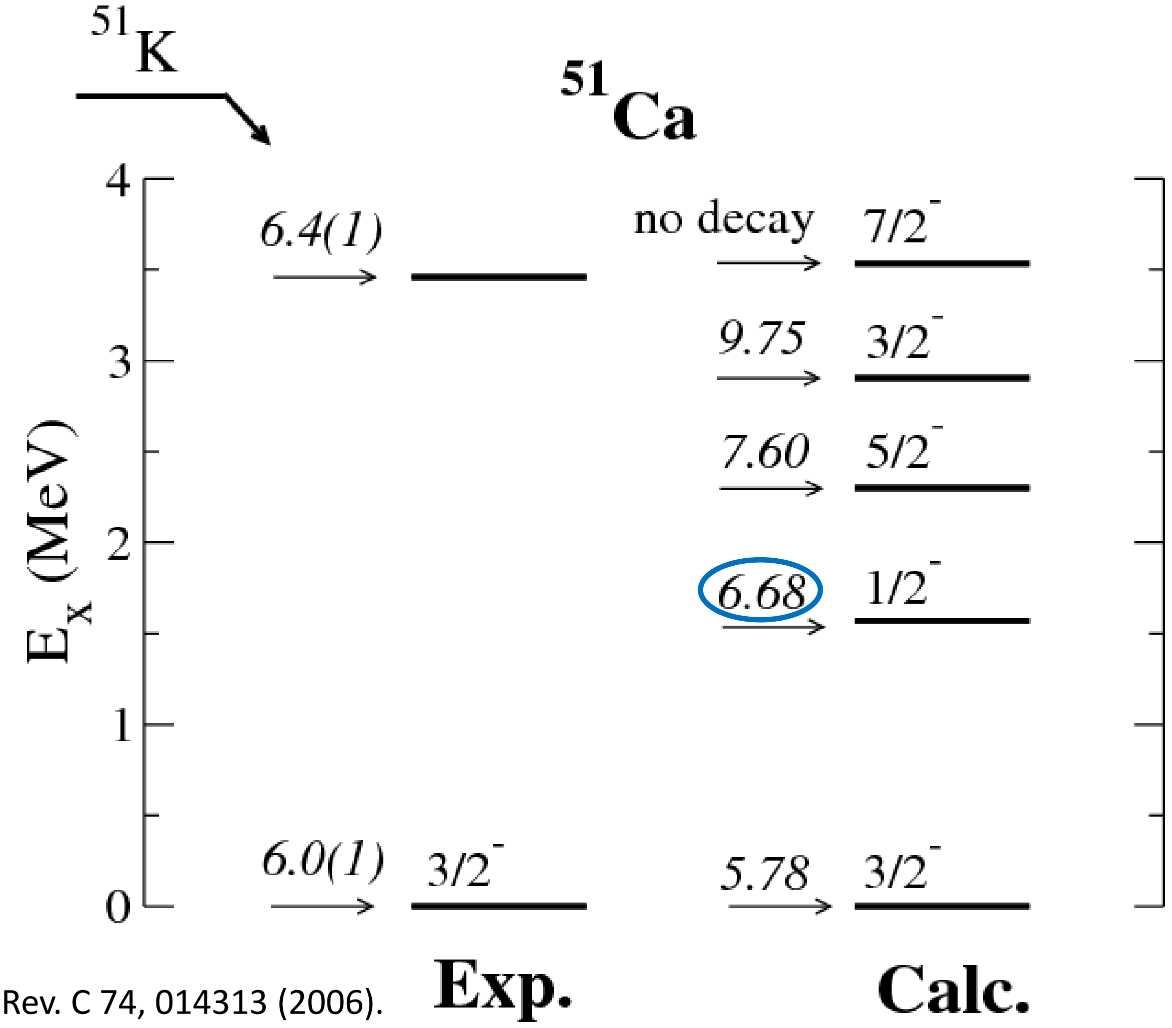
- Ground state assumed: $3/2^+$



F. Perrot et al., Phys. Rev. C 74, 014313 (2006).

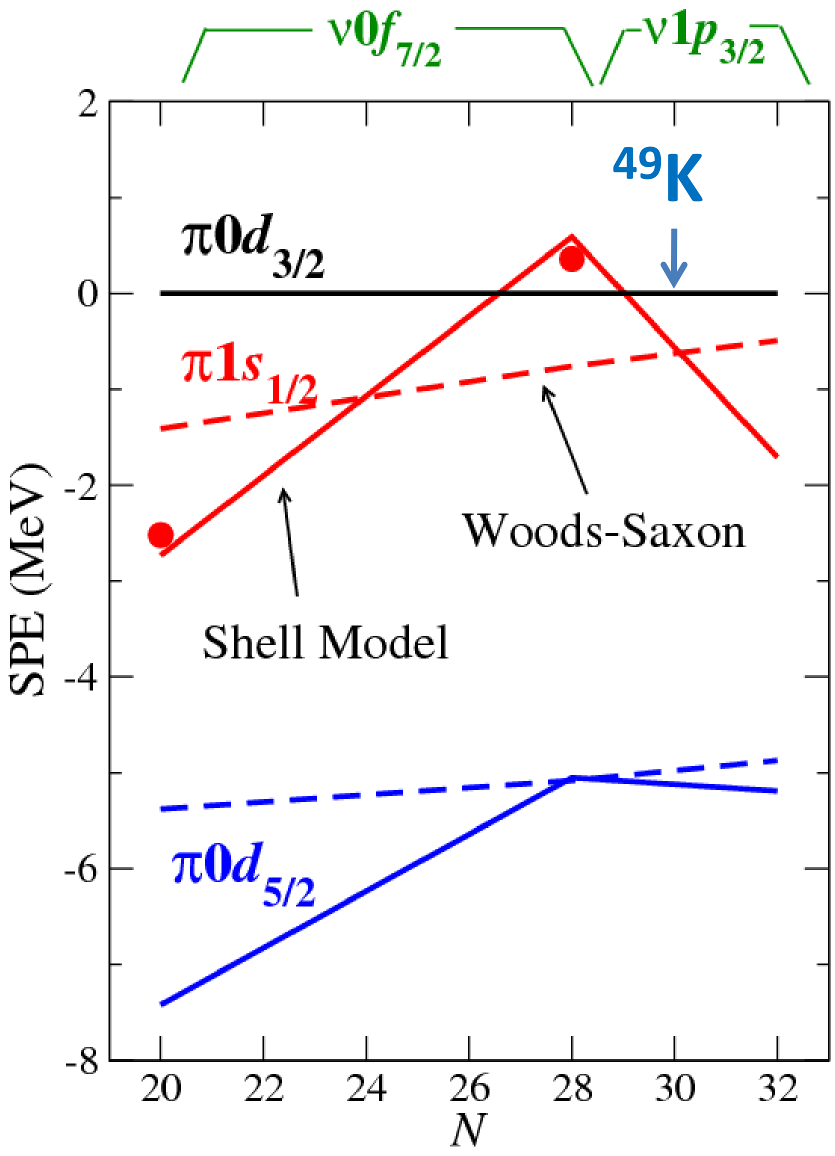
β decay of ^{51}K: end of $\nu p_{3/2}$

- Ground state assumed: $1/2^+$



F. Perrot et al., Phys. Rev. C 74, 014313 (2006).

^{49}K: $1/2^+$ or $3/2^+$?


$\nu 0f_{7/2}$
$\nu 1p_{3/2}$
^{49}K
$\pi 0d_{3/2}$
$\pi 1s_{1/2}$
$\pi 0d_{5/2}$
Woods-Saxon
Shell Model
SPE (MeV)
2
0
-2
-4
-6
-8
20
22
24
26
28
30
32
N

β decay of ^{49}K

- Ground state assumed: 3/2$^+$

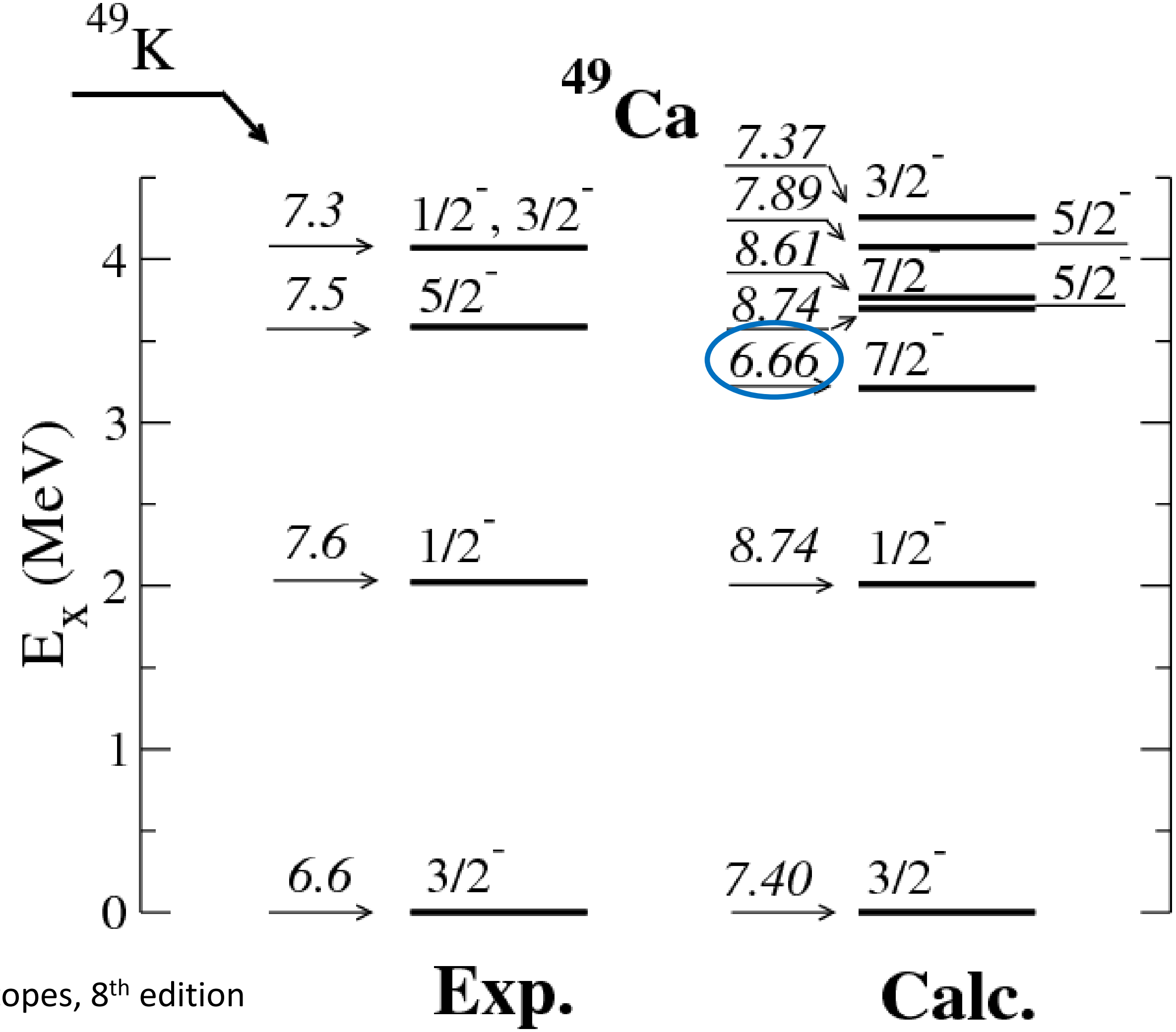


Table of Isotopes, 8th edition

β decay of ^{49}K

- Ground state assumed: 1/2$^+$

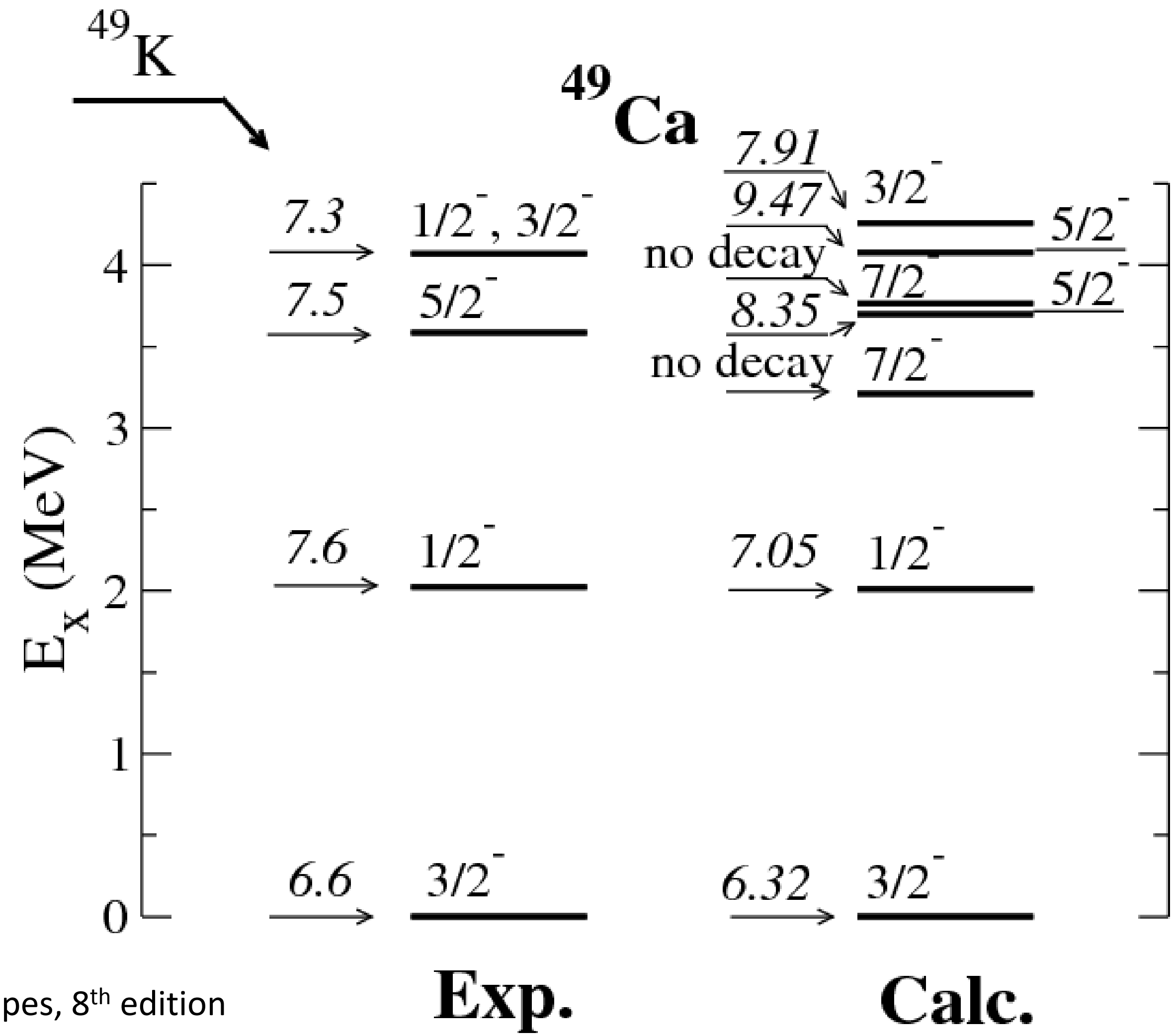
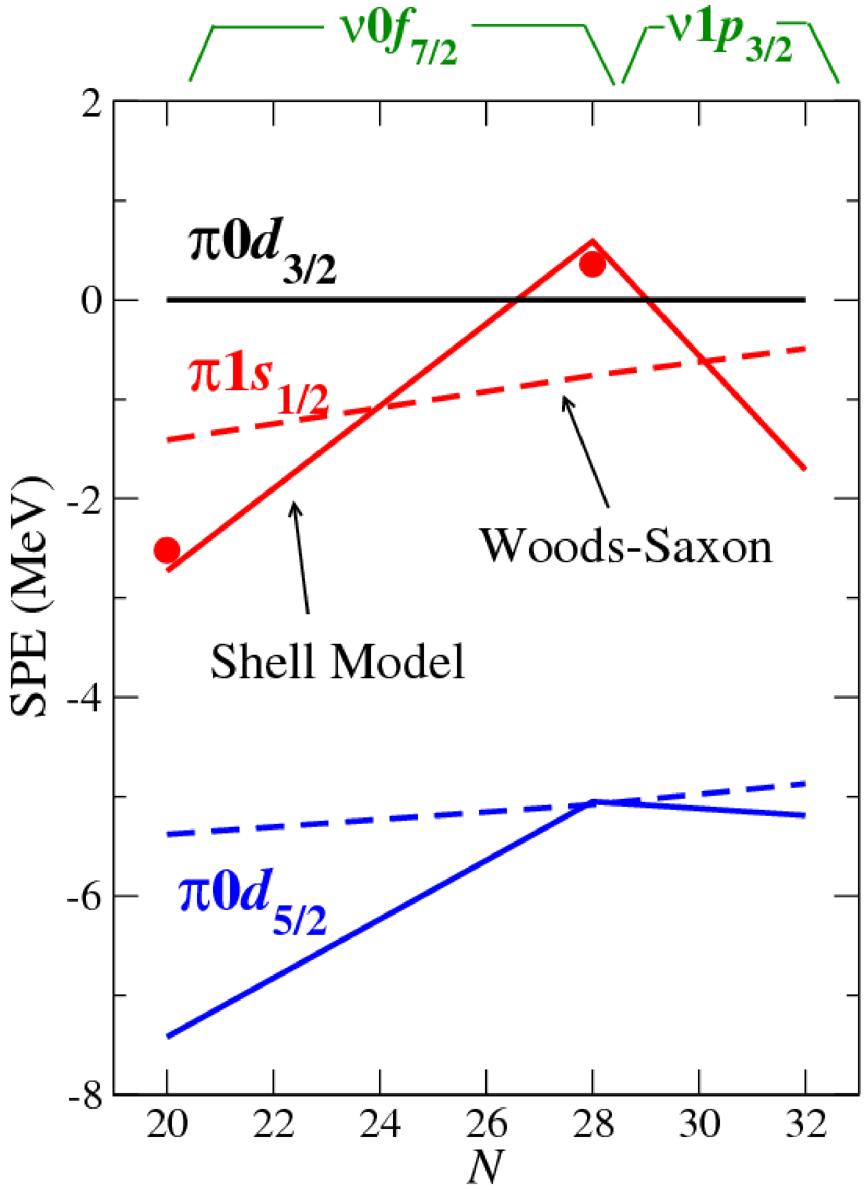


Table of Isotopes, 8th edition

Summary of the proton shell evolution

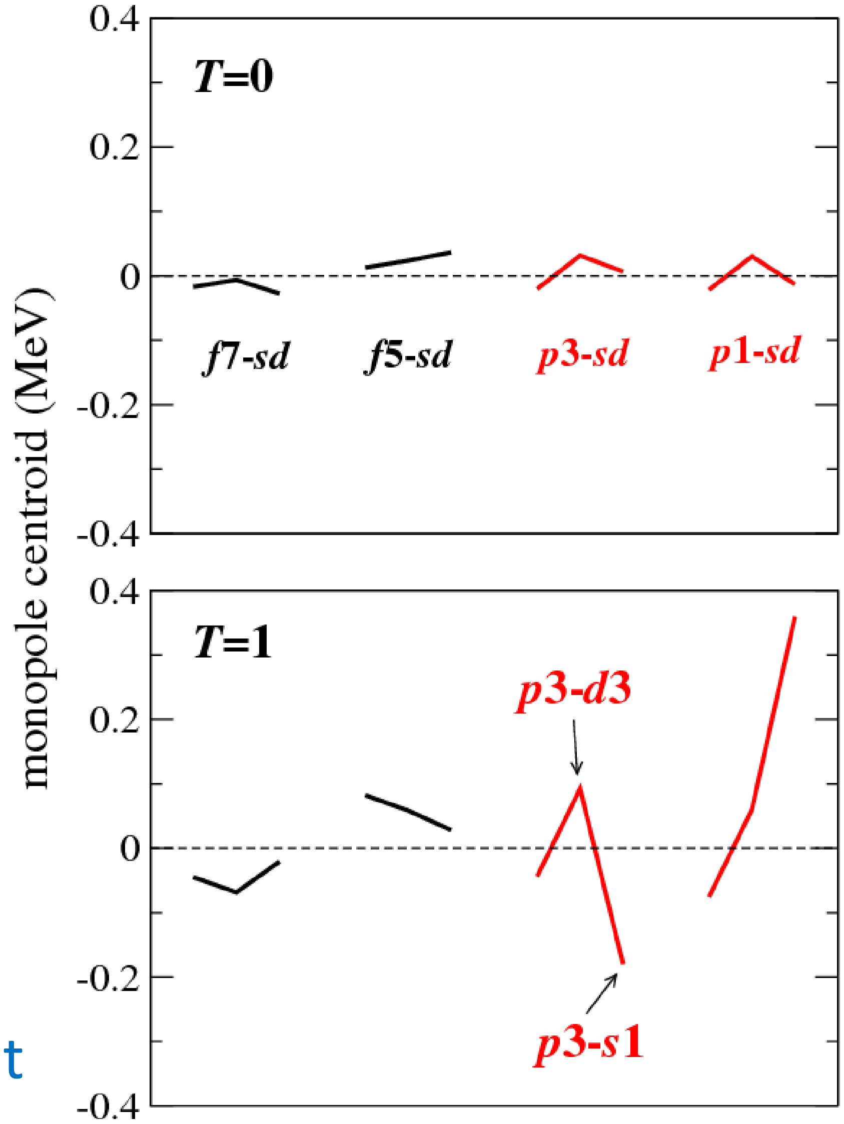
- From N=20 to 28
  - Level inversion at N=28 due to central and tensor
- Beyond N=28: from first forbidden β decay
  - $d_{3/2}$ is again the highest at N=32.
  - $1/2^+$ g.s. at N=30 accounts for experimental data better.

    Calc.: 3/2+ is slightly (~0.2 MeV) lower



Two-body LS force and shell evolution

- Two-body LS
  - Order of 10 keV for f-sd channel: much smaller than ~1 MeV of central and ~100 keV of tensor
  - Negligible up to N=28 where $f_{7/2}$ is occupied
  - p-sd channel: large
  - Different sign between $p_{3/2}$-$d_{3/2}$ and $p_{3/2}$-$s_{1/2}$
    - Makes $s_{1/2}$ more stable by ~600 keV (2*300 keV) at ^{51}K



Determining $1/2^+$-$3/2^+$ spacing at ^{51}K would provide a good measure about the LS strength.

Summary

- The shell structure described by the two-body (monopole) force can evolve in a unique way: sharp and non-monotonic behavior
- The strength of monopole interaction is well described by the universal tensor force and a simple Gaussian central force.
- It was demonstrated that an interaction based on this picture works quite well and gives the characteristics above.
  - From N=20 to 28: $\pi d_{3/2}$ moves very sharply to be lower than $\pi s_{1/2}$ at N=28
  - Beyond N=28: $\pi d_{3/2}$ is again the highest suggested by first forbidden β decay.