

# Shell evolution in neutron-rich calcium region

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# Collaborators

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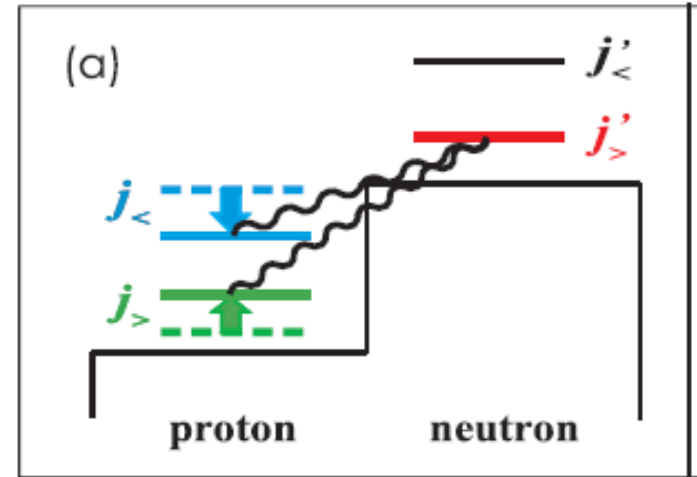
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Takahiro Mizusaki (Senshu Univ.)

Michio Honma (Univ. Aizu)

# spin-orbit splitting: $L$ - $S$ vs. $j$ - $j$ closure

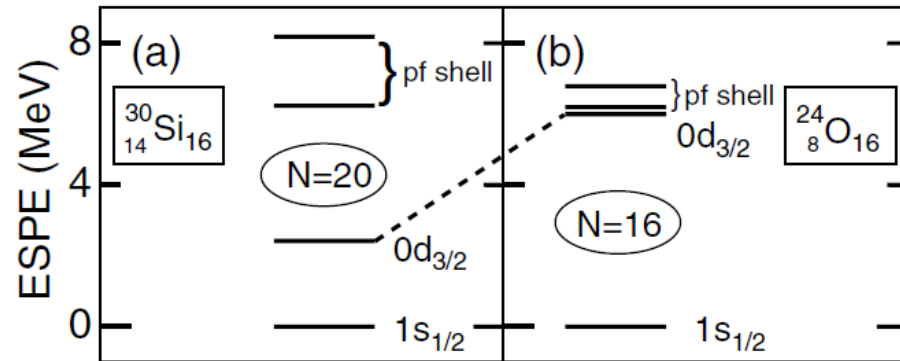
- tensor force
  - reduces the spin-orbit splitting in going from an  $L$ - $S$  closure to a  $j$ - $j$  closure
  - accounts for the appearance of the  $N=16$  magic number in oxygen ( $Z=8$ :  $L$ - $S$  closure) isotopes
    - No direct information on the position of the pf shell
  - should cause a similar evolution in calcium ( $Z=20$ :  $L$ - $S$  closure) isotopes



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

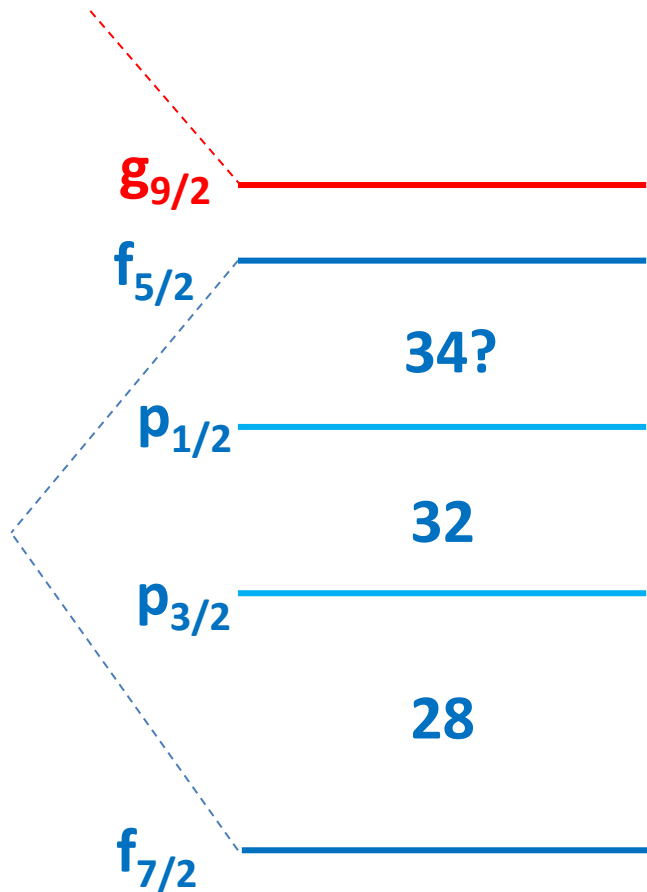


result from the SDPF-M interaction

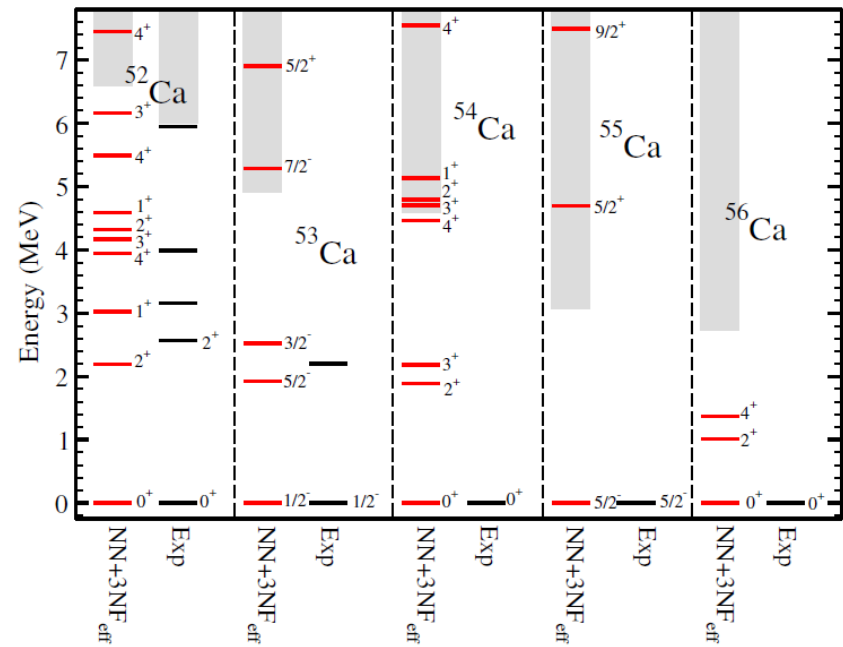


T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001).

# Neutron shell structure in Ca isotopes



## Coupled-cluster calculation



G. Hagen et al., Phys. Rev. Lett. 109, 032502 (2012).

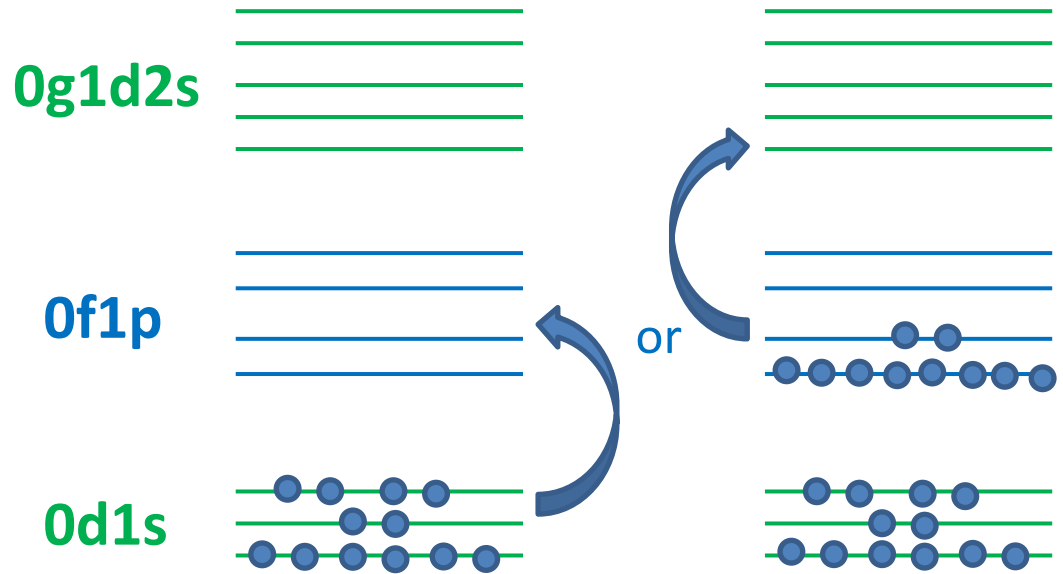
this talk



Although no “direct” information is available about the position of  $g_{9/2}$ , this position can be severely constrained by existing knowledge, particularly with aid of a recent  $\gamma$ -ray experiment (D. Montanari, S. Leoni et al.), together with a shell-model calculation.

# Model space

- Valance shell
  - full sd-pf-sdg shell
- Truncation
  - full  $0\hbar\omega$  for the natural-parity states
  - full  $1\hbar\omega$  for the unnatural-parity states
    - Either sd-to-pf or pf-to-sdg excitation is allowed.
    - Spurious components can be almost completely removed.
    - The  $0\hbar\omega$  correlation is fully included (such as  $(3^- \times 2^+)^{J=1}$ ).
- Code
  - MSHELL64 (T. Mizusaki) modified by N. Shimizu, Y. Utsuno, M. Honma, and Y. Tsunoda: capable of large valence-shell calculation

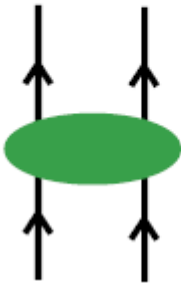


# Effective interaction

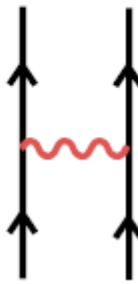
- **A natural extension** of the SDPF-MU interaction (Y. Utsuno et al., Phys. Rev. C 86, 051301(R) (2012).) **to the sd-pf-sdg shell.**
  - **sd**: USD with a d3-d5 monopole correction
  - **pf**: GXPF1B (M. Honma et al.) with a f7-pairing correction
  - **the other** matrix elements: a refined  $V_{\text{MU}}$ 
    - tensor:  $\pi+\rho$  meson exchange (same as the original  $V_{\text{MU}}$ )
    - spin-orbit: taken from M3Y (newly introduced)
    - central: one-range Gaussian in the same way as the original  $V_{\text{MU}}$  but density dependence introduced for the purpose of a better fit to the central part of GXPF1.
  - ✓ up to the pf shell: an **sd-pf shell** interaction (SDPF-MU)
  - ✓ up to the sdg shell: an **sd-pf-sdg shell** interaction (used in this study)

# Monopole-based universal interaction ( $V_{MU}$ )

(a) central force :  
Gaussian  
(strongly renormalized)



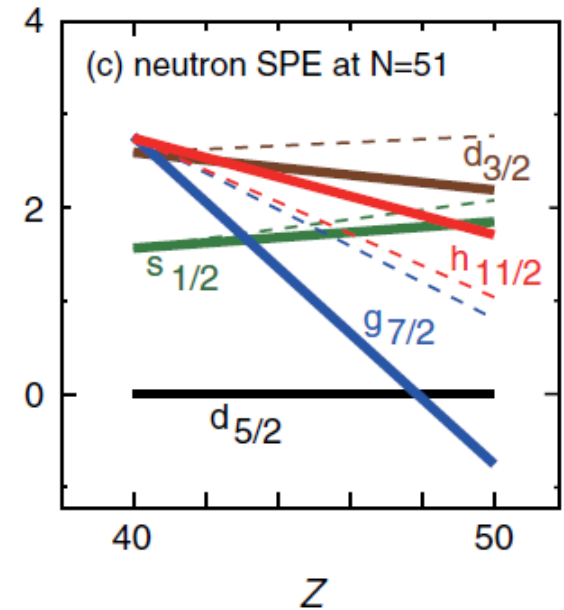
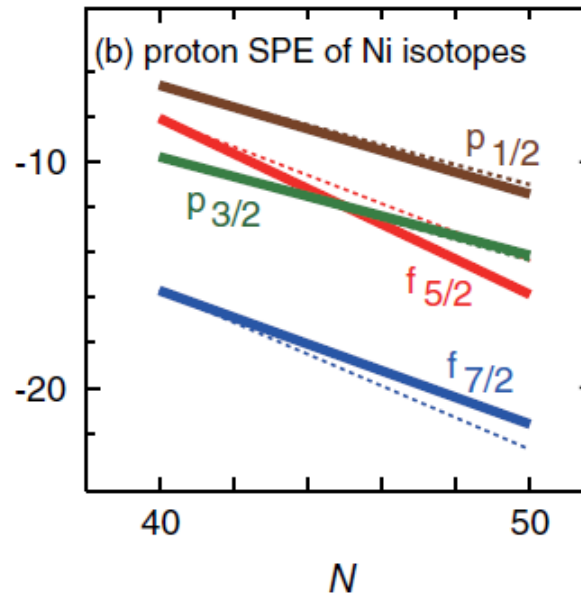
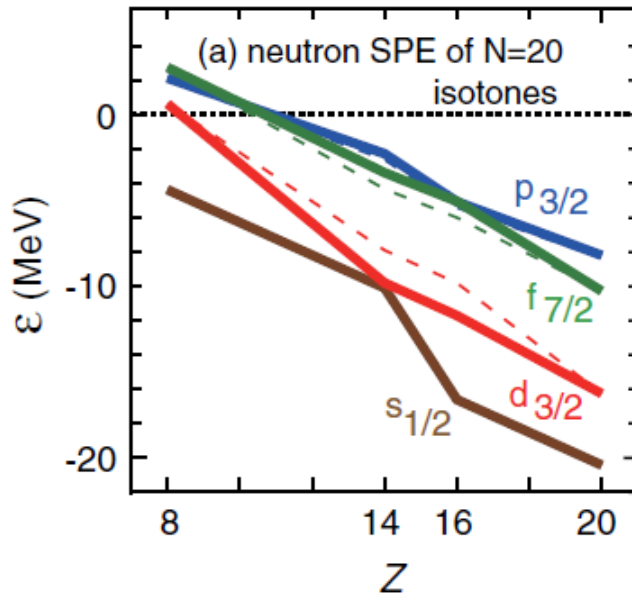
(b) tensor force :  
 $\pi + \rho$  meson  
exchange



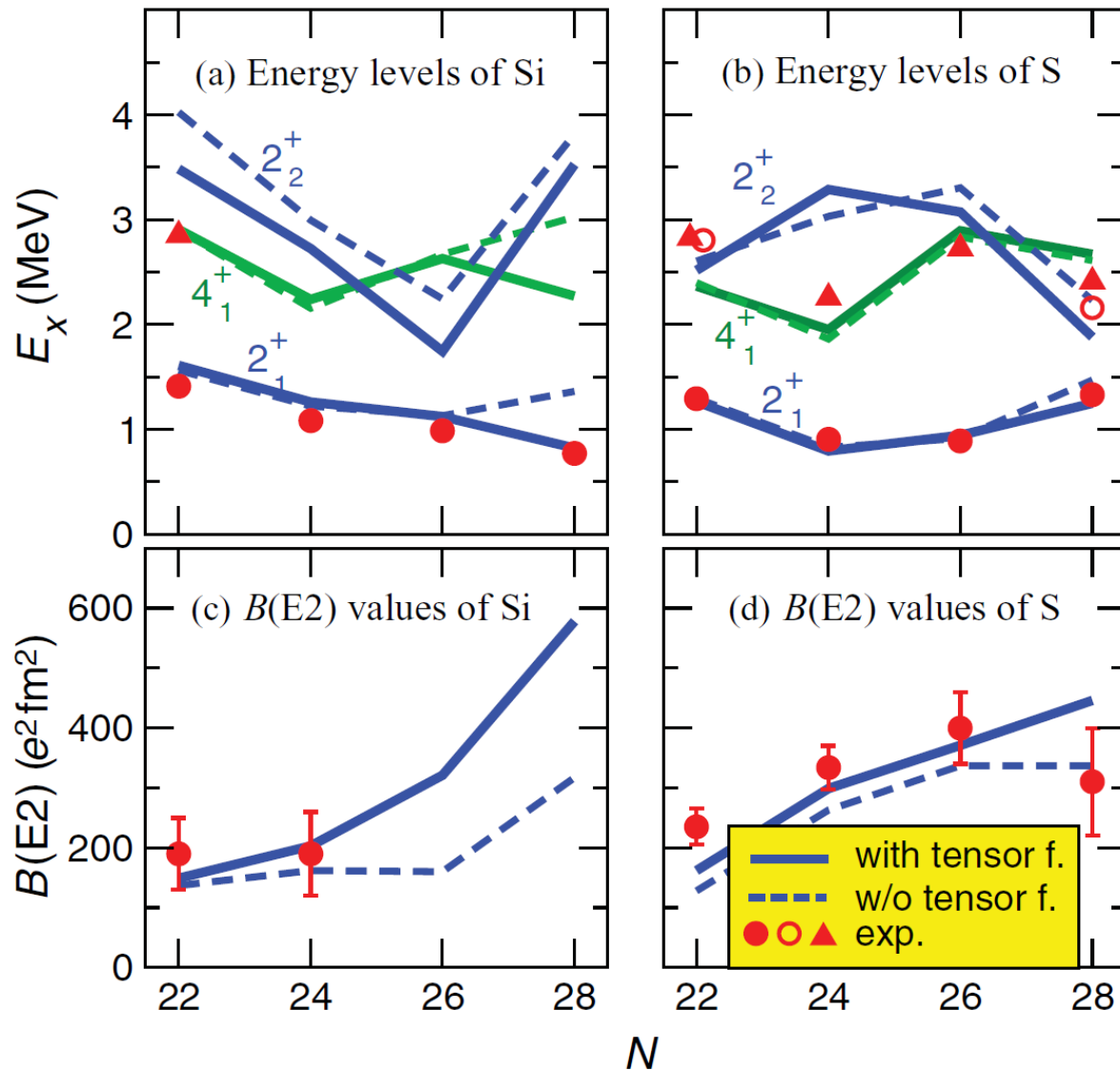
$$V_{MU} =$$

+

- tensor
  - spin dependence
- central
  - node dependence  
(strong for same n)

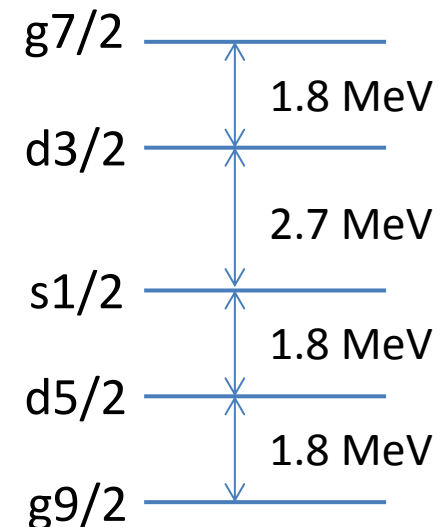


# descriptive power of $V_{\text{MU}}$ : sd-pf shell case



# Single-particle energy

- sd and pf orbits: **standard way based on experiment**
  - sd: taken from USD's. Very close to experimental  $^{17}\text{O}$  levels.
  - pf: determined so that the energy levels of  $^{41}\text{Ca}$  can be the same as those of GXPF1B. Very close to experimental C<sup>2</sup>S-weighted levels.
- sdg orbits: **no empirical way in the region of interest**
  - A very simple splitting within the sdg shell assumed:  
 $V_{ls} \mathbf{l} \cdot \mathbf{s}$  ( $V_{ls}$ : constant and taken from Bohr & Mottelson's textbook)
  - determined so that neutron's sdg splitting at  $^{48}\text{Ca}$  can be the above value
- **The gap between pf and sdg**
  - The only fitting parameter specific to this study (see later discussions)

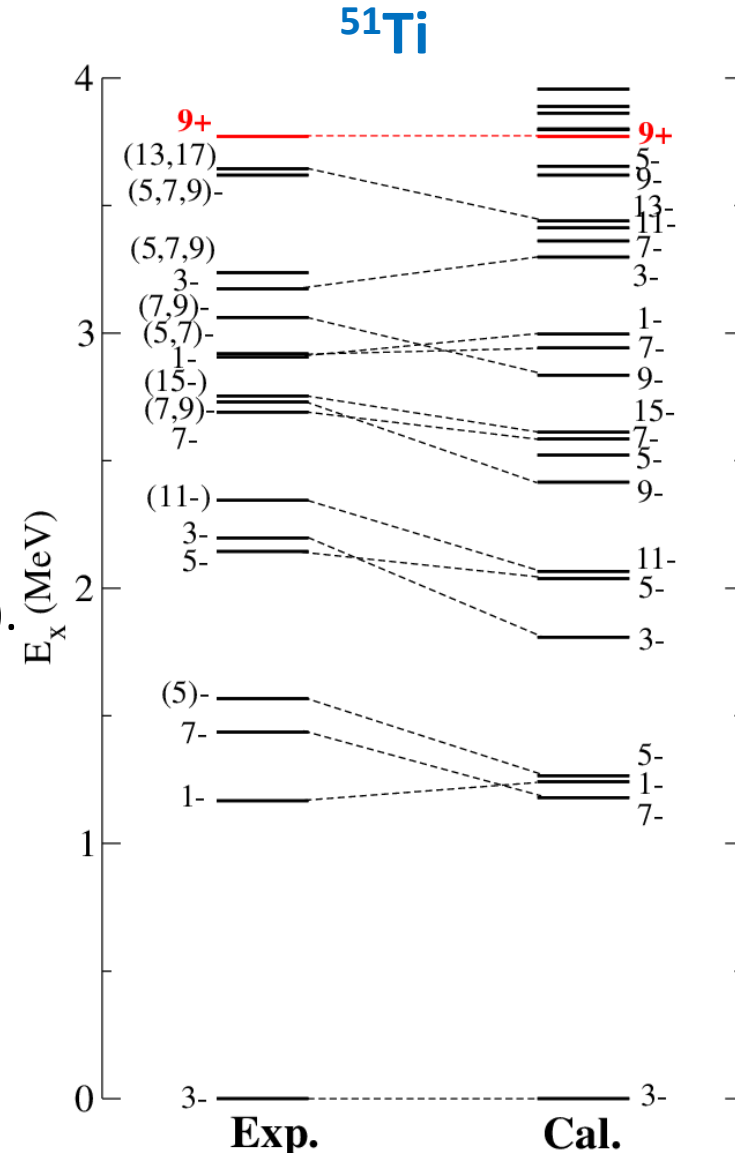


# How to determine the pf-sdg shell gap?

- The only free parameter
- No direct experimental information available for Ca
- $9/2^+_1$  of  $^{51}\text{Ti}_{29}$ 
  - Large  $g_{9/2}$  component deduced from the  $^{50}\text{Ti}(d,p)$  reaction
  - The gap is determined to adjust the  $E_x(9/2^+_1)$ .
  - C<sup>2</sup>S is in good agreement.

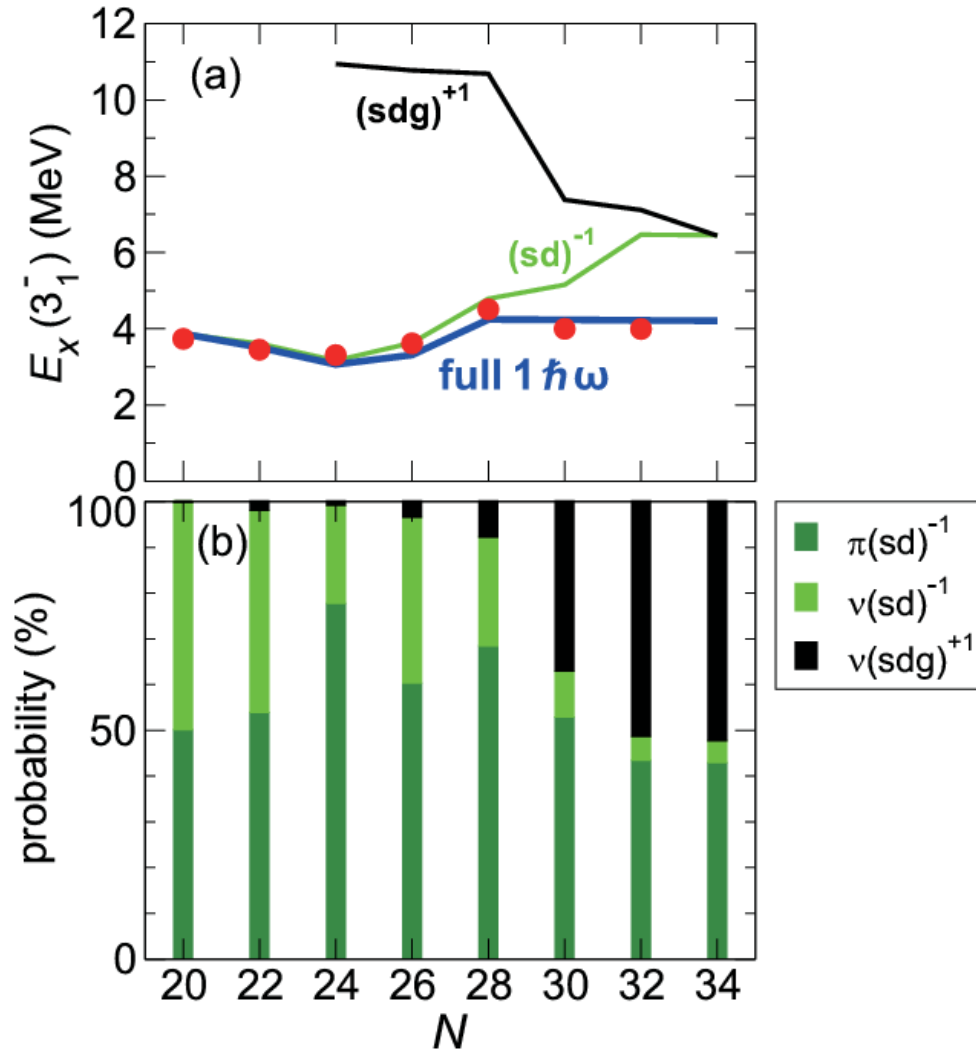
	Expt.		Calc.
Optical pot.	B4	CA	
C <sup>2</sup> S( $g_{9/2}$ )	0.54	0.37	0.47

P. Wilhelm et al., Phys. Rev. 166, 1121 (1968).



# Systematics of the $3^-_1$ state in even-A Ca

- Three calculations
  - excitations from sd to pf only
  - excitations from pf to sdg only
  - full  $1\hbar\omega$  configurations
- $3^-_1$  levels
  - sd-pf calc.
    - good agreement for  $N \leq 28$
    - large deviation for  $N > 28$   
(no interaction dependence)
  - full  $1\hbar\omega$  calc.
    - Strong mixing with the sdg configuration accounts for the stable  $3^-$  levels.



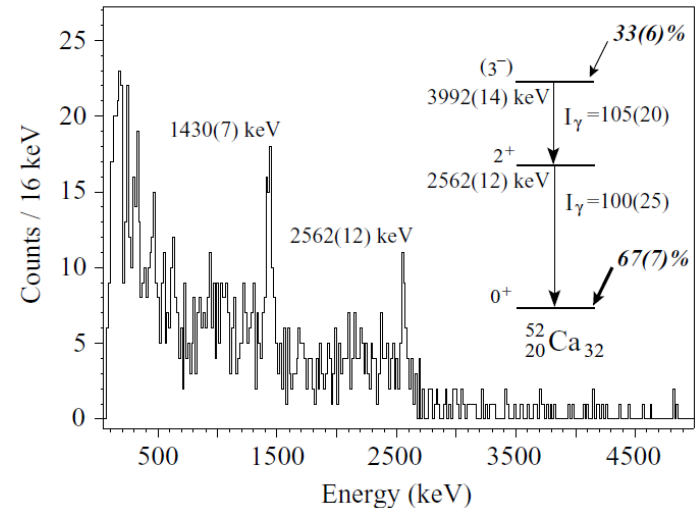
# $3^-_1$ configuration probed by direct reaction

- $^{50}\text{Ca}$ : strongly populated by the  $^{48}\text{Ca}(t,p)$  reaction
  - dominated by **neutron** excitation
- $^{52}\text{Ca}$ : strongly populated by the 2p knockout from  $^{54}\text{Ti}$ 
  - dominated by **proton** excitation

Relative  $^{48}\text{Ca}(t,p)$  maximum cross section

State	Energy (MeV)	$\theta$ (angle in c.m. system)	$\frac{d\sigma(\theta)}{d\Omega}$ (exp)	$\frac{d\sigma(\theta)}{d\Omega}$ (th. $\epsilon^2 = 0$ )	$\frac{d\sigma(\theta)}{d\Omega}$ (th. $\epsilon^2 = 0.02$ )
g.s.	0	$5^\circ$	100	100	100
$2^-_1$	1.03	$20^\circ$	42	39	32
$2^-_2$	3.00	$20^\circ$	36	40	36
$0^-_3$	3.53	$5^\circ$	2	5.5	2.4
$(3^-)$	3.99	$28^\circ$	21	43	37
$0^-_3$	4.47	$5^\circ$	2.2	1.0	0.5

R. A. Broglia et al., Nucl. Phys. A 106, 421 (1968).



A. Gade et al., Phys. Rev. C 74, 021302(R) (2006).

Without the strong mixing between proton and neutron excitations, these properties are hard to explain.

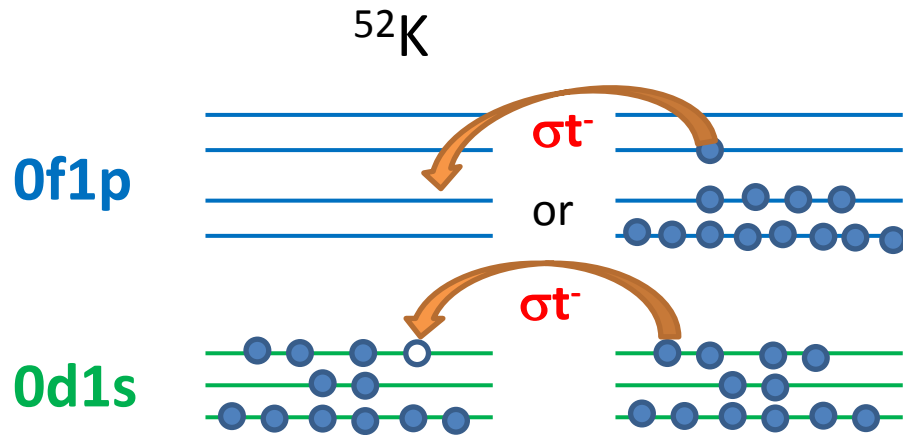
# Suggestion of strong configuration mixing

- Population of  $3^-_1$  in  $^{50}\text{Ca}$  by  $^{48}\text{Ca}(t,p)$ 
  - analysis of R. A. Broglia et al., Nucl. Phys. A 106, 421 (1968)
    - $3^-$  of  $\nu(p_{3/2})^{-1}(g_{9/2})^{+1}$  configurations **overestimates** the cross section by a factor of two
- Population of  $3^-_1$  in  $^{52}\text{Ca}$  by 2p knockout of  $^{54}\text{Ti}$ 
  - analysis of A. Gade et al., Phys. Rev. C 74, 021302(R) (2006).
    - $3^-$  of a superposition of  $\pi(d_{3/2})^{-1}(pf)^{+1}$  and  $\pi(s_{1/2})^{-1}(pf)^{+1}$  configurations **overestimates** the cross section by a factor of two to four.

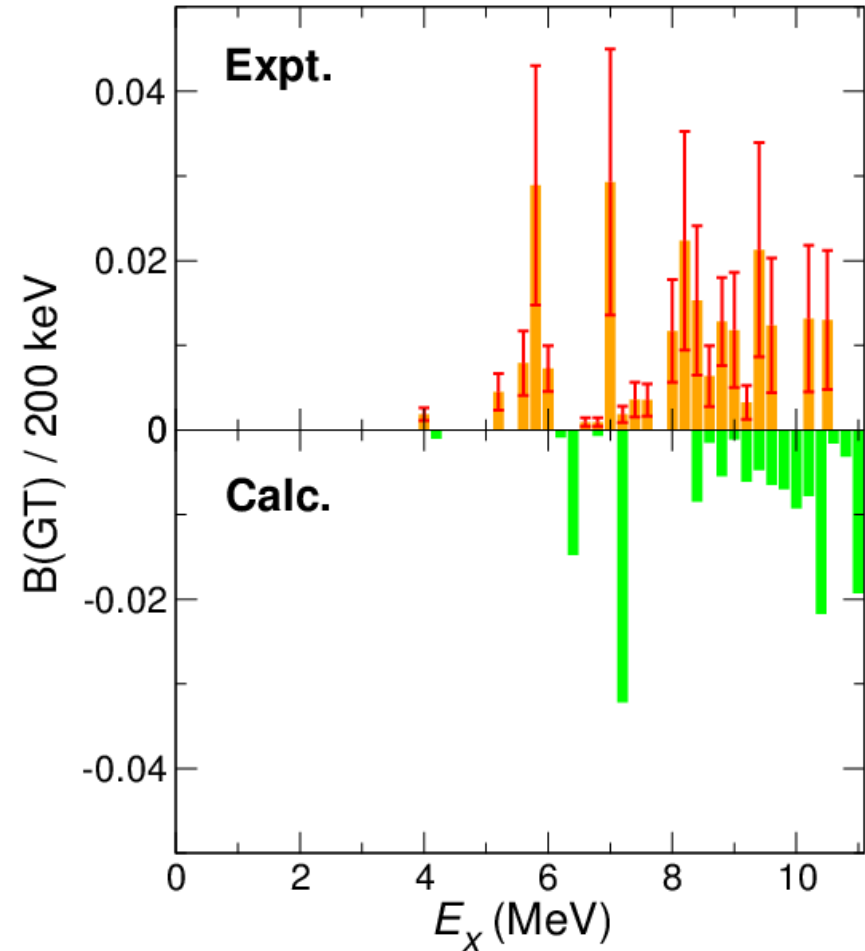


Configuration mixing reduces the cross section.

# Gamow-Teller distribution for the $^{52}\text{K}$ decay

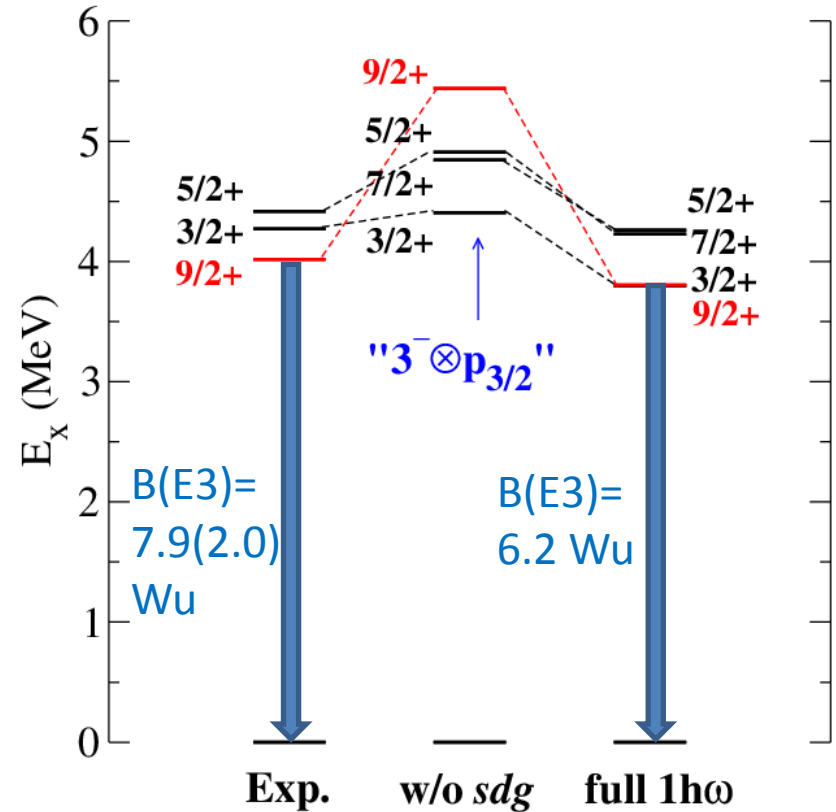


- sensitive to  $sd \rightarrow pf$  configuration
  - Mixing with  $sdg$  shell reduces the GT strength
- agreement with experiment
  - low-lying discrete levels ( $\sim 6$  and  $7$  MeV)
  - broad peaks ( $\geq 8$  MeV)



# Energy levels of $^{49}\text{Ca}$

- $^{48}\text{Ca} + n$  system
  - Good to see the single-particle structure
  - Core-coupled state can compete for higher states
- $9/2^+$  state at 4.017 MeV
  - firm spin-parity assignment by Montanari, Leoni et al. (PLB 697, 288 (2011); PRC 85, 044301 (2012).)
    - interpreted as core-coupled state
  - Present calc.: Strong mixing with  $g_{9/2}$  is also important.
    - Good B(E3)

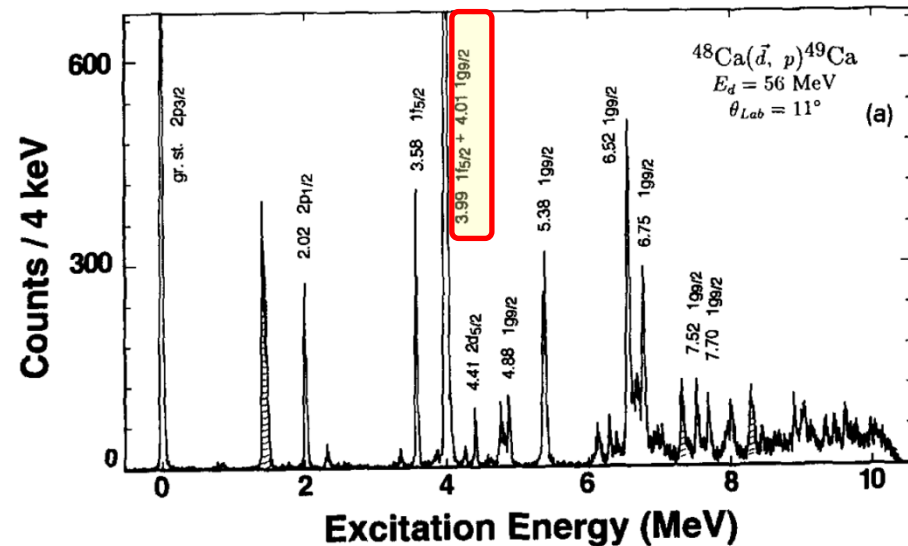


	$3/2^+_1$	$5/2^+_1$	$7/2^+_1$	$9/2^+_1$
% of sdg	6	9	7	<b>51</b>

# Systematics of $g_{9/2}$ strength in N=29 isotones

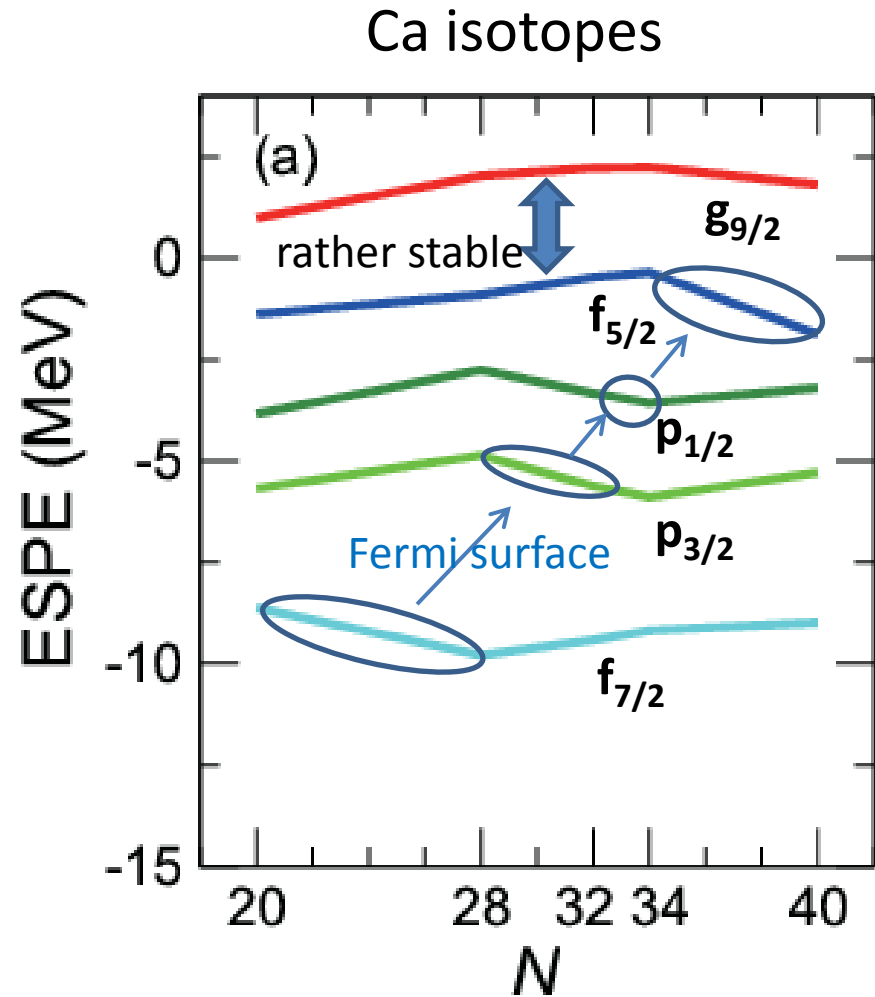
	dimension	$E_x$ (MeV)		$C^2S$ ( $n$ attached)	
		Expt.	Calc.	Expt.	Calc.
$^{49}\text{Ca}$	2,515,437	4.02	3.80	0.14	0.42
$^{51}\text{Ti}$	187,386,759	3.77	3.77	0.37	0.47
$^{53}\text{Cr}$	3,411,147,908	3.71	4.04	0.52	0.47

- $9/2^+$  of N=29 isotones
  - Shell-model calc. is possible up to  $^{53}\text{Cr}$ .
  - Strong mixing with  $g_{9/2}$  for all the isotones in calc. but small  $C^2S$  for  $^{49}\text{Ca}$  in expt.
    - Effect of the doublet? (see right)



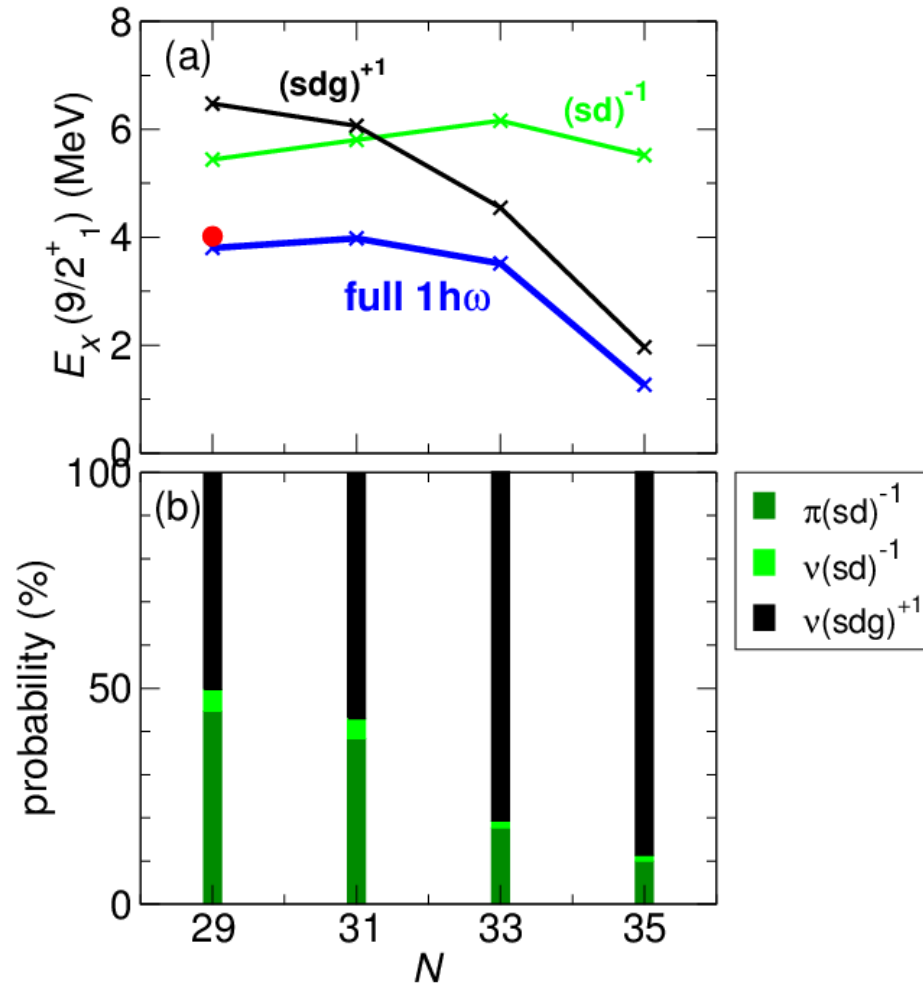
# Neutron effective single-particle energy

- Global behavior
  - rather stable
    - very weak  $T=1$  monopole interaction: due to  $V_{\text{MU}}$  and systematics
- Location of  $g_{9/2}$ 
  - 2-3 MeV higher than  $f_{5/2}$
  - Possibility of a nearly single-particle state?
    - competition with core-coupled state



# Systematics of the $9/2^+_1$ state in odd-A Ca

- $9/2^+_1$  in the sd-pf calculation
  - main component of core-coupled state
  - located stably at 5-6 MeV
- $9/2^+_1$  in the pf-sdg calculation
  - sharply decreasing due to the shift of the Fermi level
- $9/2^+_1$  in the full  $1\hbar\omega$  calc.
  - 3-4 MeV up to N=33 but drops considerably at N=35
  - The state at N=55 is nearly a single-particle character.

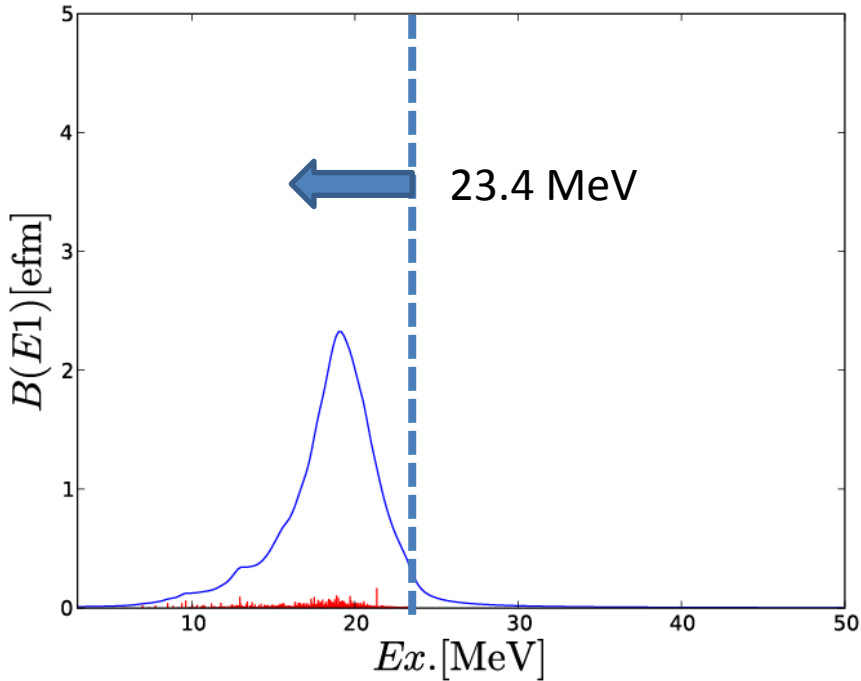


# Application to E1 strength

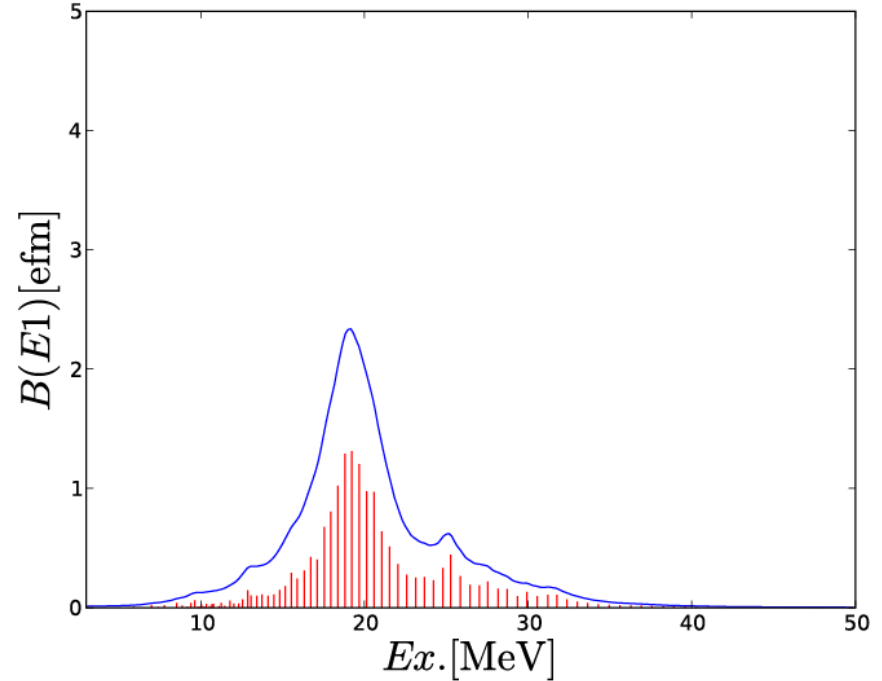
- Ongoing work with N. Shimizu et al.
- Present model space: full  $1\hbar\omega$ 
  - capable to study pygmy and giant dipole resonances in the shell model  
cf., for oxygen isotopes: H. Sagawa and T. Suzuki, Phys. Rev. C 59, 3116 (1996).
- M-scheme dimension:  $3 \times 10^6$  for  $1^-$  of  $^{48}\text{Ca}$ 
  - Exact diagonalization for low-lying states
  - Lanczos strength function for the distribution of high-lying states
    - Initial vector:  $O(E1)|g.s.\rangle$
    - Lanczos diagonalization with this initial vector
    - Good distribution obtained in a few hundred Lanczos iterations

# Exact diagonalization vs. strength function

Exact lowest 3,000 states



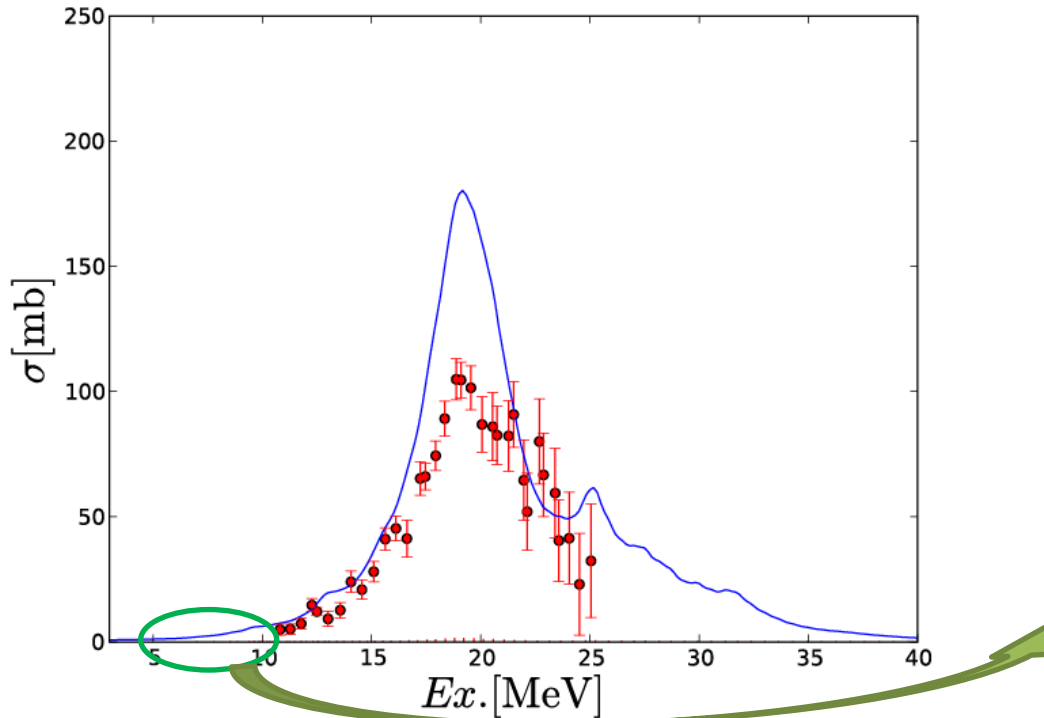
Lanczos strength function (300 iter.)



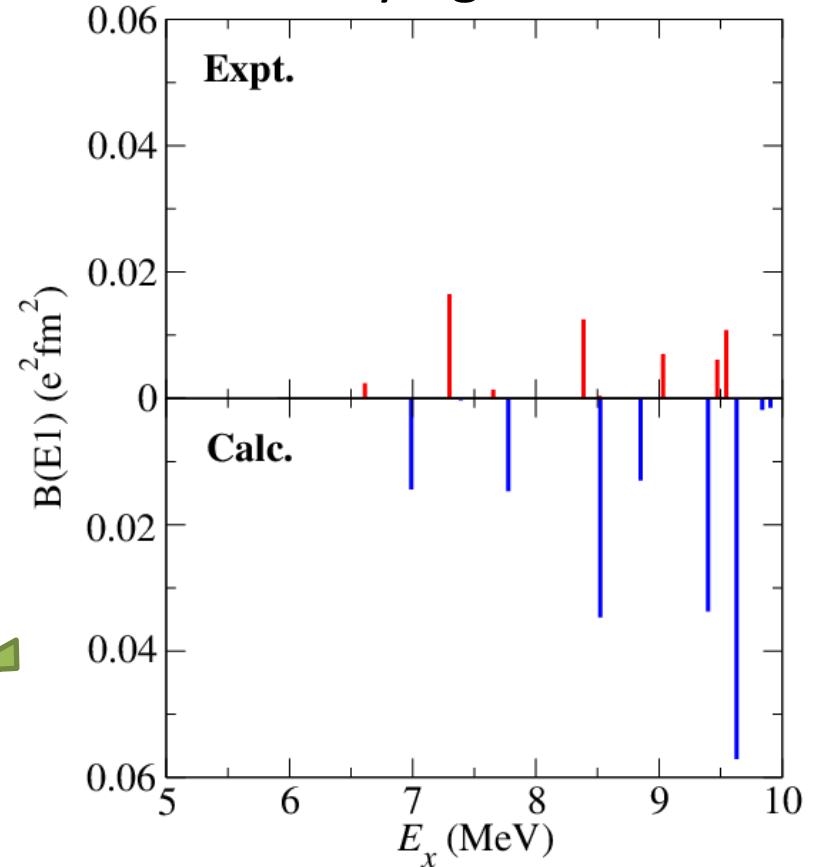
- Smearing width:  $\Gamma=1$  MeV
- No visible difference between the two methods

# Comparison with experiment for $^{48}\text{Ca}$

GDR with  $\Gamma=1$  MeV



Low-lying  $1^-$  states



- GDR peak position: good
  - GDR peak height: overestimated
  - Low-lying states: shifted left or less fragmented
- } need for  $2\hbar\omega$  (g.s.) and  $3\hbar\omega$  ( $1^-$ )?

# Summary

- Shell-model calculations are carried out for probing the  $g_{9/2}$  in neutron-rich calcium isotopes.
  - full  $1\hbar\omega$  calculations in the sd-pf-sdg shell
  - A natural extension of the SDPF-MU interaction
  - pf-sdg gap: the only parameter; fixed by  $9/2^+_{1}$  of  $^{51}\text{Ti}$
- Energy levels sensitive to  $g_{9/2}$ 
  - competition and coupling with sd-to-pf excitation
  - $3^-_{1}$  states of even-A isotopes with  $N>28$
  - $9/2^+_{1}$  states of odd-A isotopes with  $N>28$ 
    - $^{49}\text{Ca}$  provides good information
    - The single-particle state is predicted to appear at  $^{55}\text{Ca}$ .
- Distribution of E1 strength can be studied in the same framework.