Large scale shell model calculation for exotic nuclei—collaboration between Japan and US

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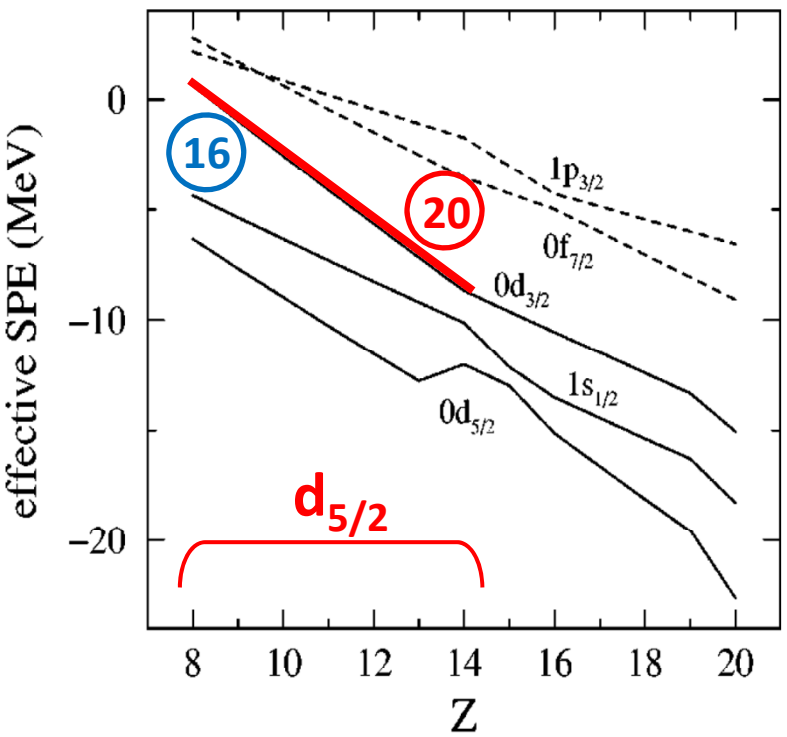
Outline

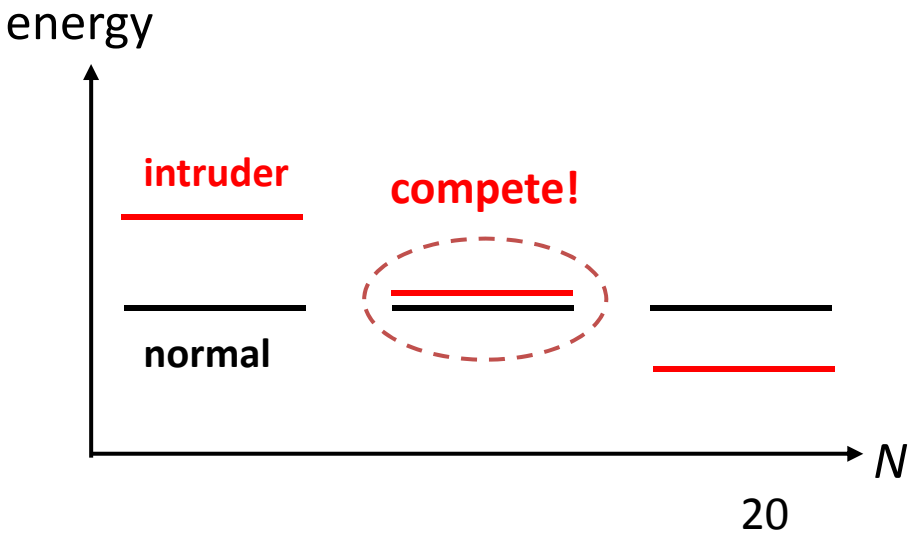
1. Island of inversion—more detailed structure from recent collaboration
2. Heavy pf shell nuclei (M. Honma et al.)
3. New sd-pf shell interaction—toward no monopole correction and high predictive power
4. Quasi-particle basis Monte Carlo shell model (N. Shimizu et al.)

Focus on ongoing and future collaboration with theory/experiment in the US

Issue in “island of inversion”

SDPF-M interaction



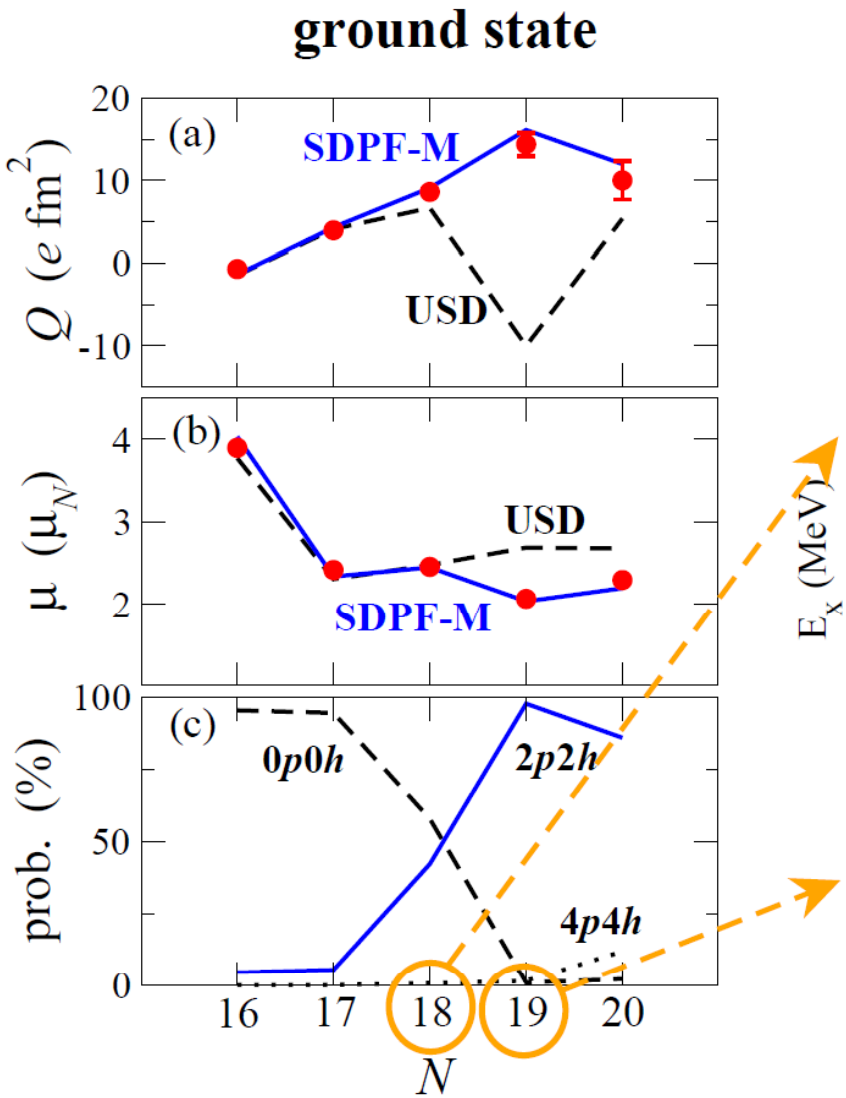


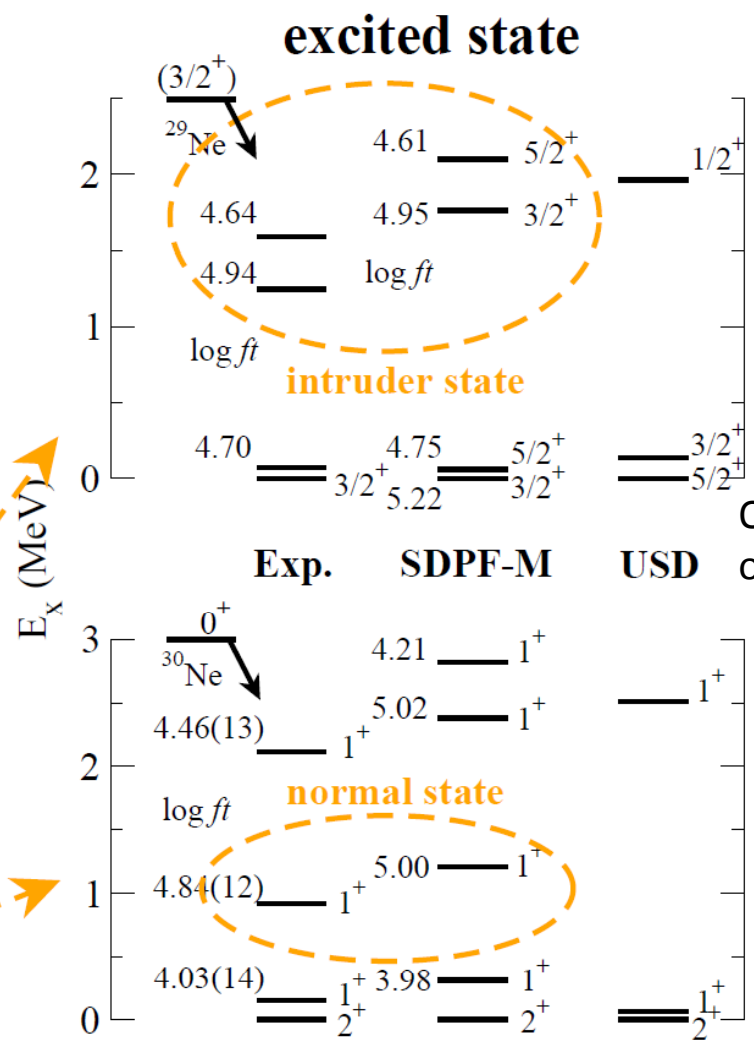
It is important to determine the boundary and surrounding property to examine the shell structure.

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

Phenomenologically introduced sharp change of $d_{3/2}$ is likely due to the tensor force.

Competition and coexistence of normal and intruder states in Na isotopes





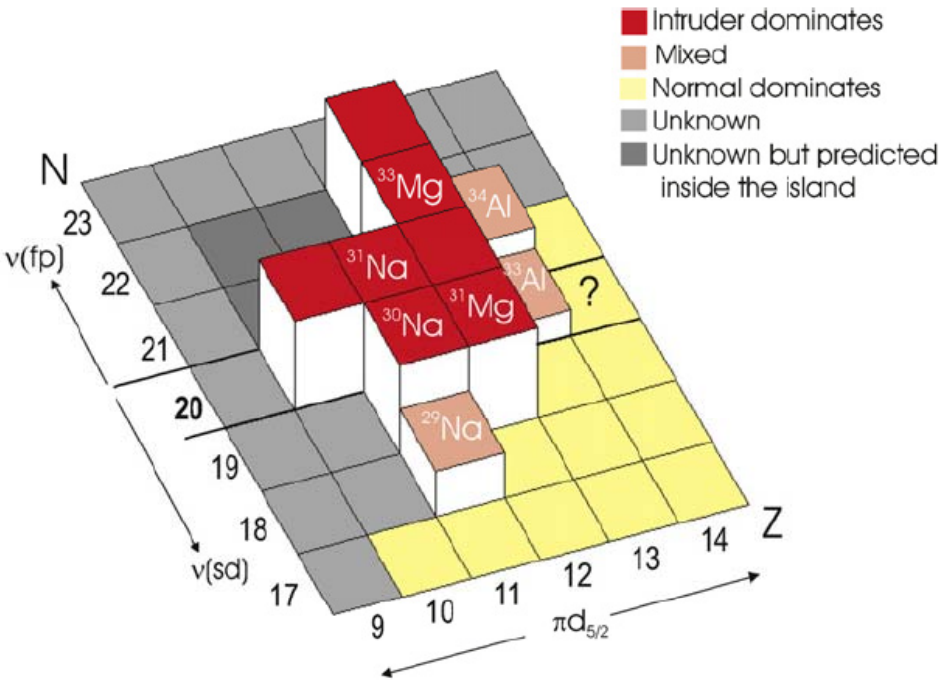
Quenching of g_A/g_V: 0.9

Y. Utsuno et al., Phys. Rev .C 70, 044307 (2004).

Exp.) V. Tripathi et al. (2005 and 2007)

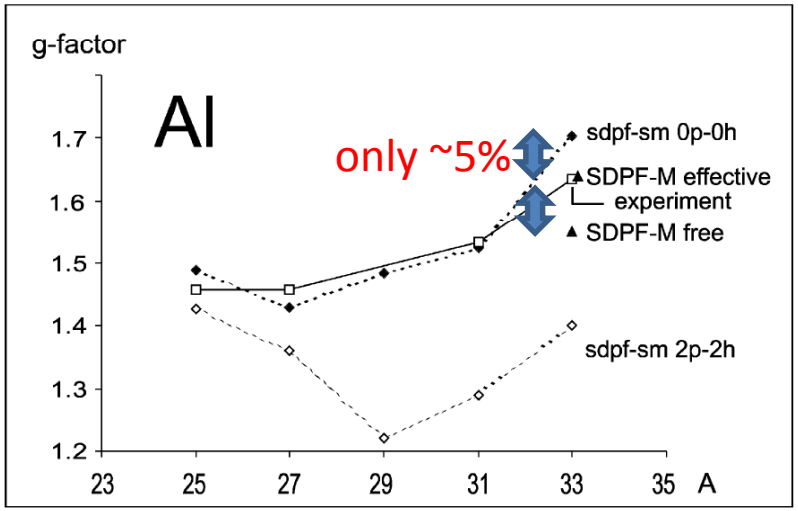
Exploration of the “boundary”

Extent of the island of inversion compiled from electromagnetic properties



P. Himpe et al., Phys. Lett. B 658, 203 (2008).

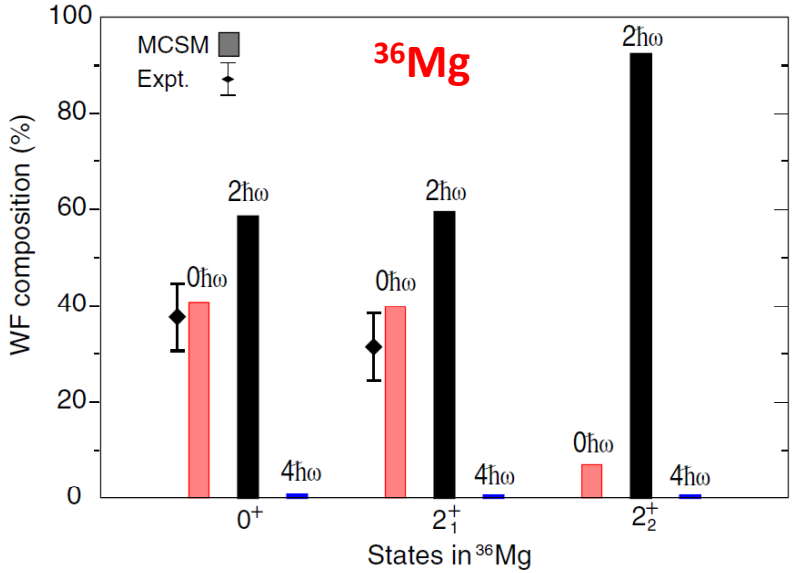
- Some of the electromagnetic properties are sensitive to the dominance of the intruder state, but some are not.
- Other probes are desired.



P. Himpe et al., Phys. Lett. B 643, 257 (2006).

Spectroscopic factor

- Good measure to see
  1. Single-particle property (1p or 1n transfer)
  2. Overlap between initial and final states (amount of mixing etc.)
- Knockout reaction (MSU)
  - -2p: a new direct reaction
    (D. Bazin et al., Phys. Rev. Lett. 012501 (2003).)
  - Recent measurement around the island—^{36}Mg (see right)
- Spectroscopic- factor code in MCSM
  - Applied to -2p of ^{34}Si->^{32}Mg
  - Reduction of S is predicted for the yrast state due to small overlap of the neutron part.

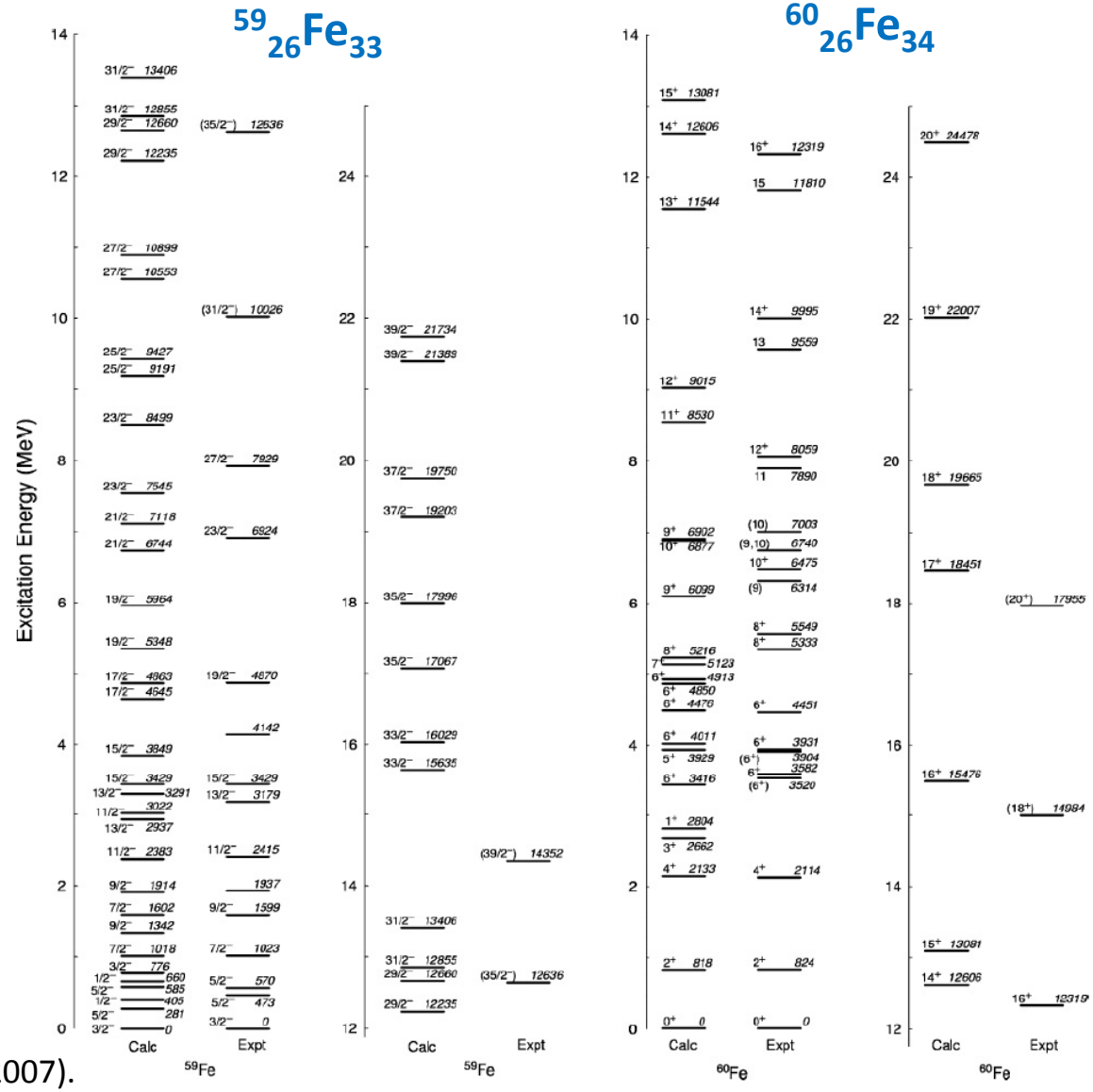


Extracted from ^{38}Si->^{36}Mg

A. Gade et al. Phys. Rev. Lett. 99, 072502 (2007).

Heavier pf shell nuclei—test for GXPF1A

- GXPF1: semi-empirical interaction reproducing many pf nuclei
  M. Honma et al., Phys. Rev. C 65, 061301(R) (2002); 69, 034335 (2004).
- Recent data that are not used for fitting
  - Good test
  - probing the effect of $g_{9/2}$ in a similar way to "island of inversion"
- Good agreement in low-lying states of ^{59}Fe and ^{60}Fe



A. N. Deacon et al., Phys. Rev. C 76, 054303 (2007).

A strategy to construct an interaction for exotic nuclei—case for sd-pf shell

- Cross shell interaction: most unknown part
- Making use of knowledge obtained so far
  - Phenomenology
    - Importance of the shell evolution caused by the tensor force (from island of inversion)
  - Quantitativeness
    - GXPF1(A) must have good matrix elements, leading to a good guide to make the interaction
- To be answered
  - What is the proper strength of the tensor force? Is there universality?
  - What kind of central force?

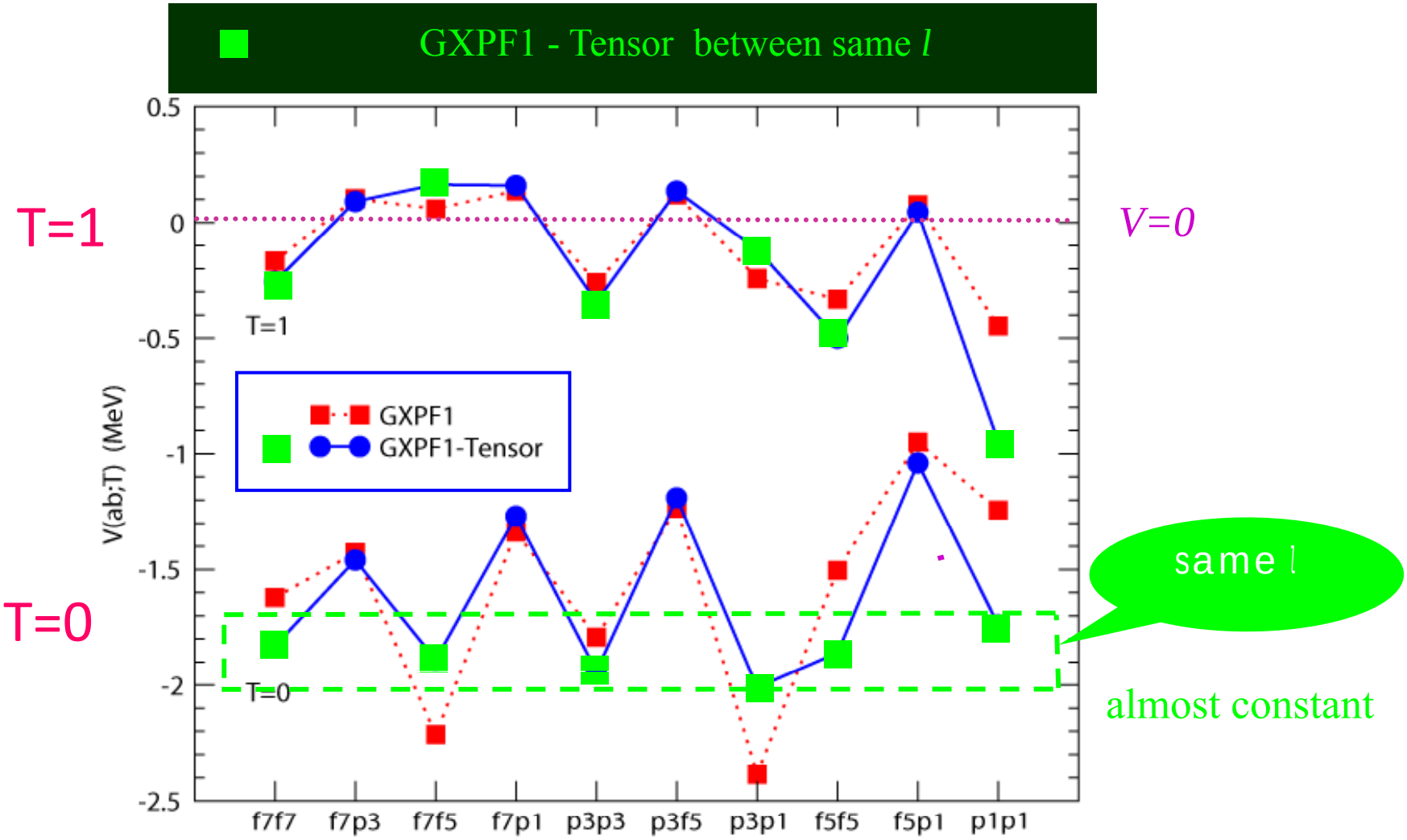
Tensor monopole interaction

- $\pi+\rho$ and GT2
  - Successful in explaining the shell evolution in medium-heavy nuclei
    T. Otsuka et al., Phys. Rev .Lett. 95, 232502 (2005); 97, 162501 (2006).
- Millerner-Kurath (MK)
  D.J. Millener and D. Kurath, Nucl. Phys. A 255, 315 (1975).
  - Often adopted as the cross-shell interaction in the p-sd and sd-pf shell regions.
  - Yukawa-type potential

T=0 monopole interaction (MeV)

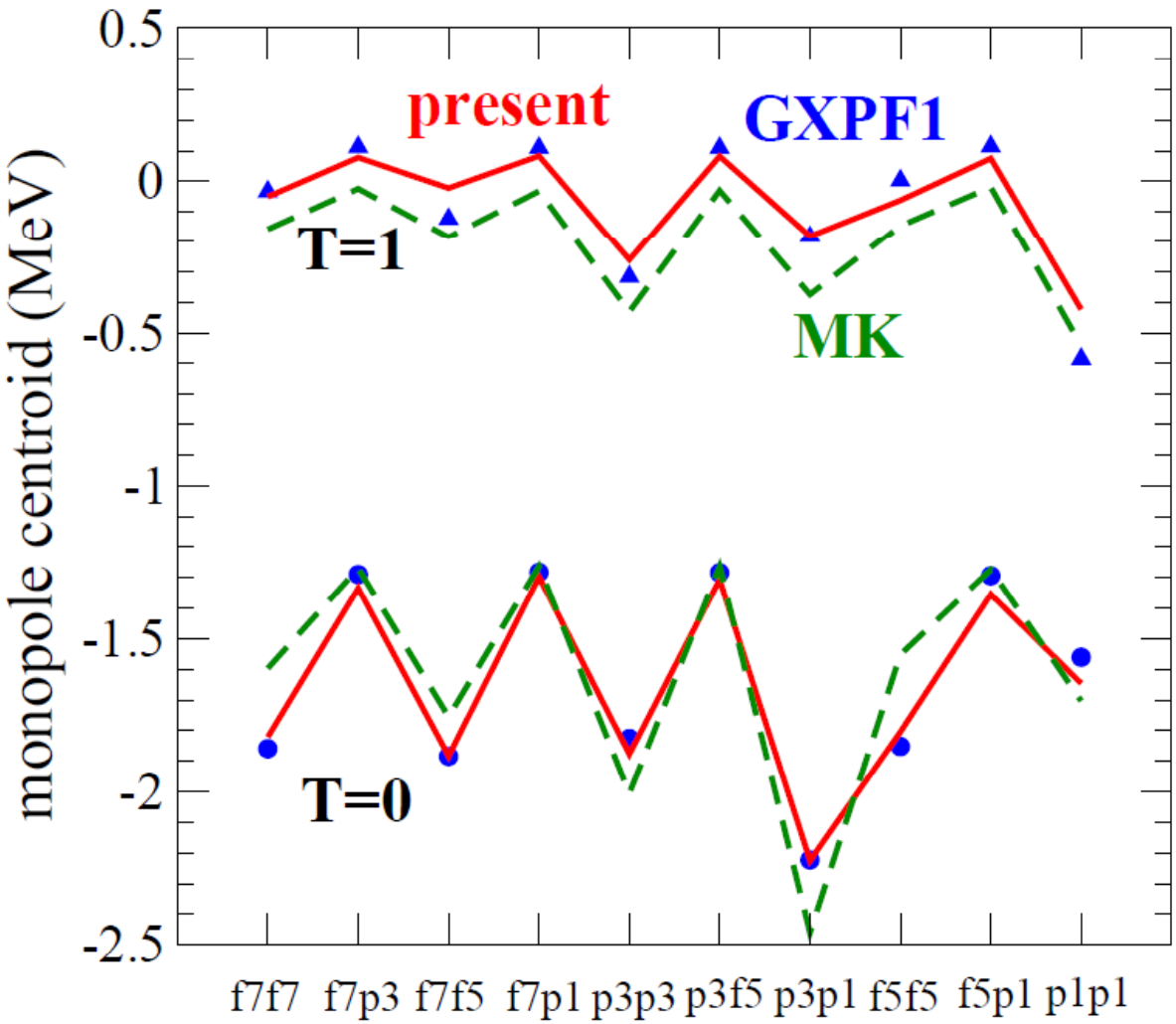
i	j	GXPF1	$\pi+\rho$	GT2	MK
f7	**f7**	0.223	0.210	0.244	0.080
f7	**p3**	0.036	0.035	0.044	0.013
f7	**f5**	-0.335	-0.315	-0.365	-0.120
f7	**p1**	-0.073	-0.070	-0.088	-0.026
p3	**p3**	0.092	0.150	0.154	0.064
p3	**f5**	-0.048	-0.046	-0.058	-0.017
p3	**p1**	-0.229	-0.376	-0.386	-0.160
f5	**f5**	0.382	0.360	0.418	0.137
f5	**p1**	0.097	0.093	0.117	0.034
p1	**p1**	0.306	0.501	0.515	0.213

Monopole interaction of GXPF1 :
full (original) and
part after subtraction of tensor part ($\pi + \rho$)



T. Otsuka et al., in preparation

Central part



Present interaction:
much close to GXPF1

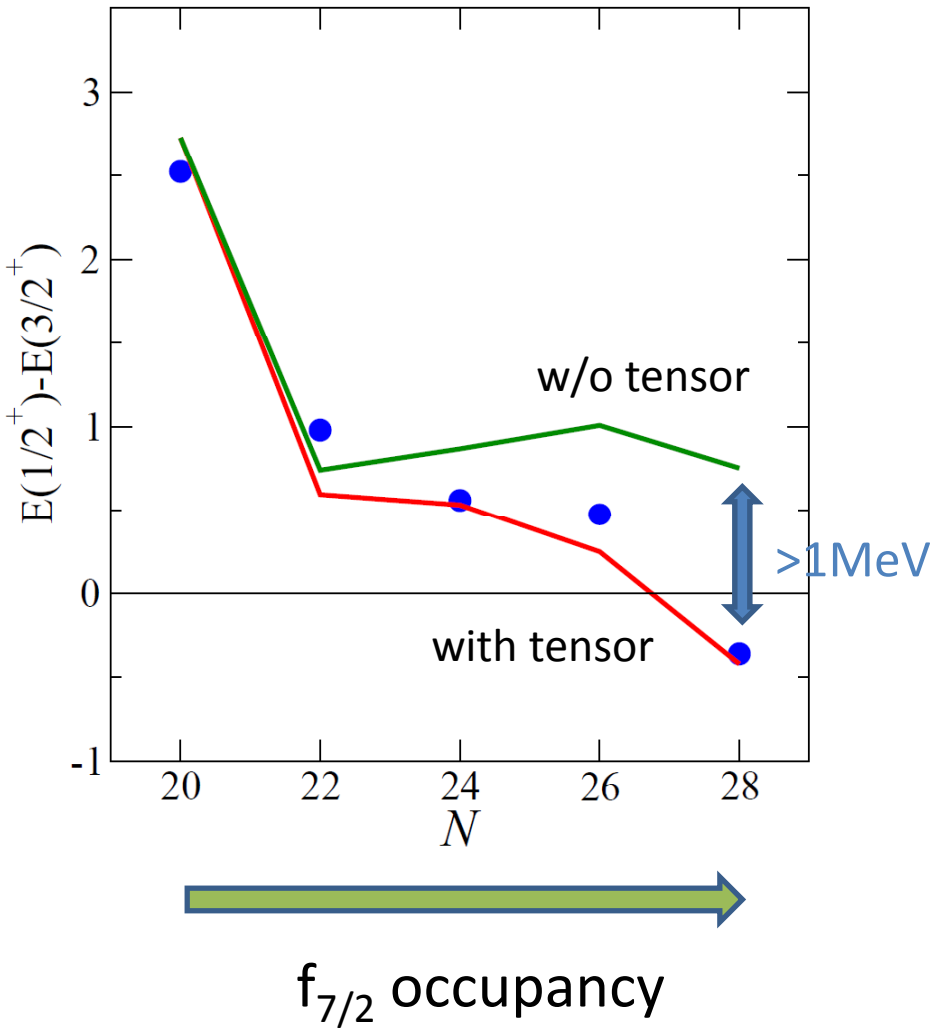
Only 6 parameters!
(i.e., strength of each (S,T) channel, range of Gaussian, and density dependence parameter)

New interaction:
Basically USD (sd) + GXPF1A (pf) + new one (cross)

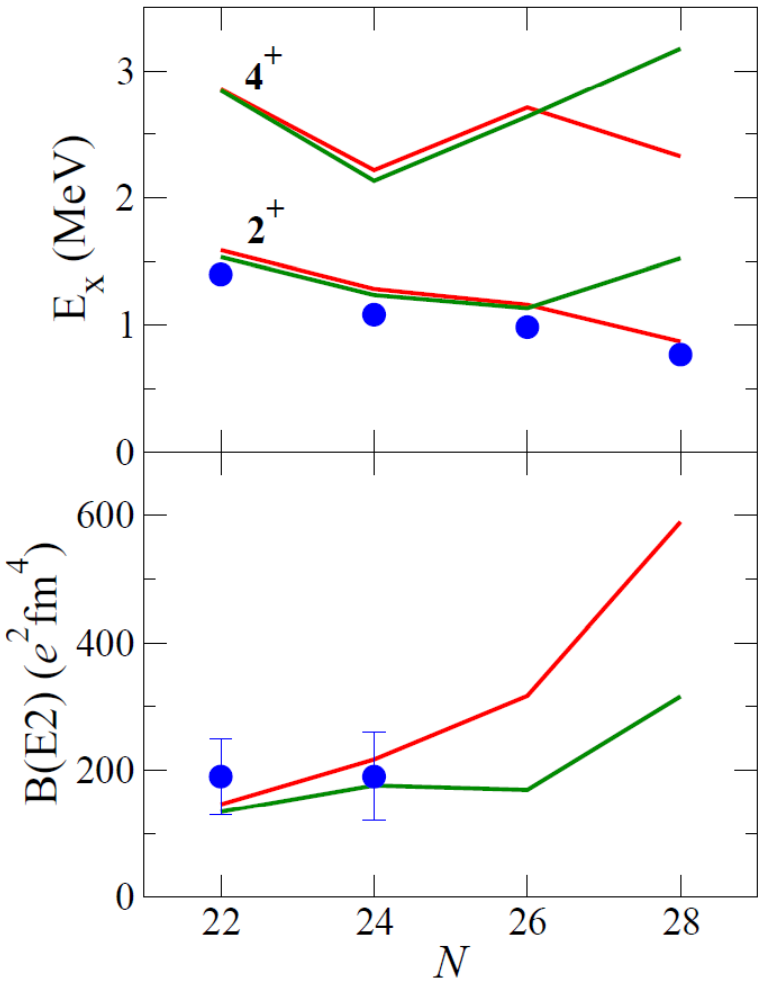
K isotopes: proton hole state

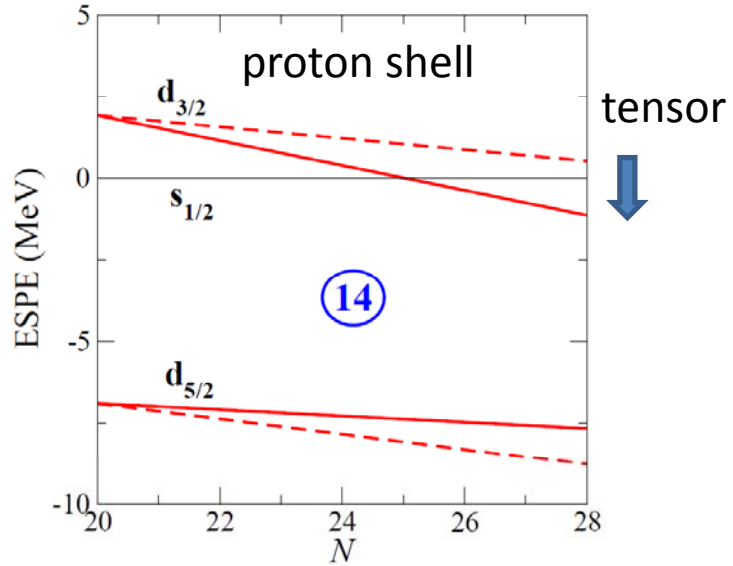
- Large discrepancy at N=28 without the tensor force
  - For N=22, 24 and 26, $1/2^+$ has large $\pi(d_{3/2})^{-1}\nu(2^+)$ component being not sensitive to $s_{1/2}$.
- Rough estimate of the shift from N=20 to 28
  - Exp.: 2.52-(-0.36)=2.88 MeV
  - T=0 monopole (for A=42): central: 0.375*8*0.5=1.50 MeV tensor: 0.313*8*0.5=1.25 MeV
  - About half of the shift is accounted for by the tensor force.

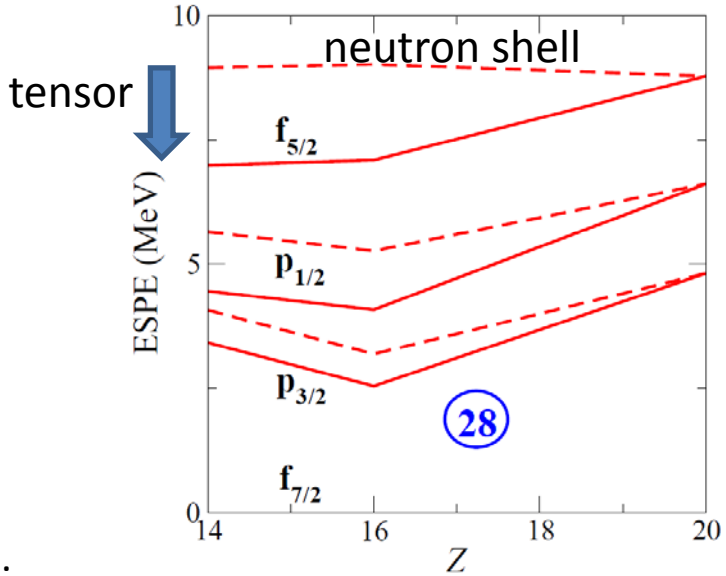
Evolution of $1/2^+$-$3/2^+$ spacing



Si isotopes







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).

NuShell at MSU (Brown and Rae)

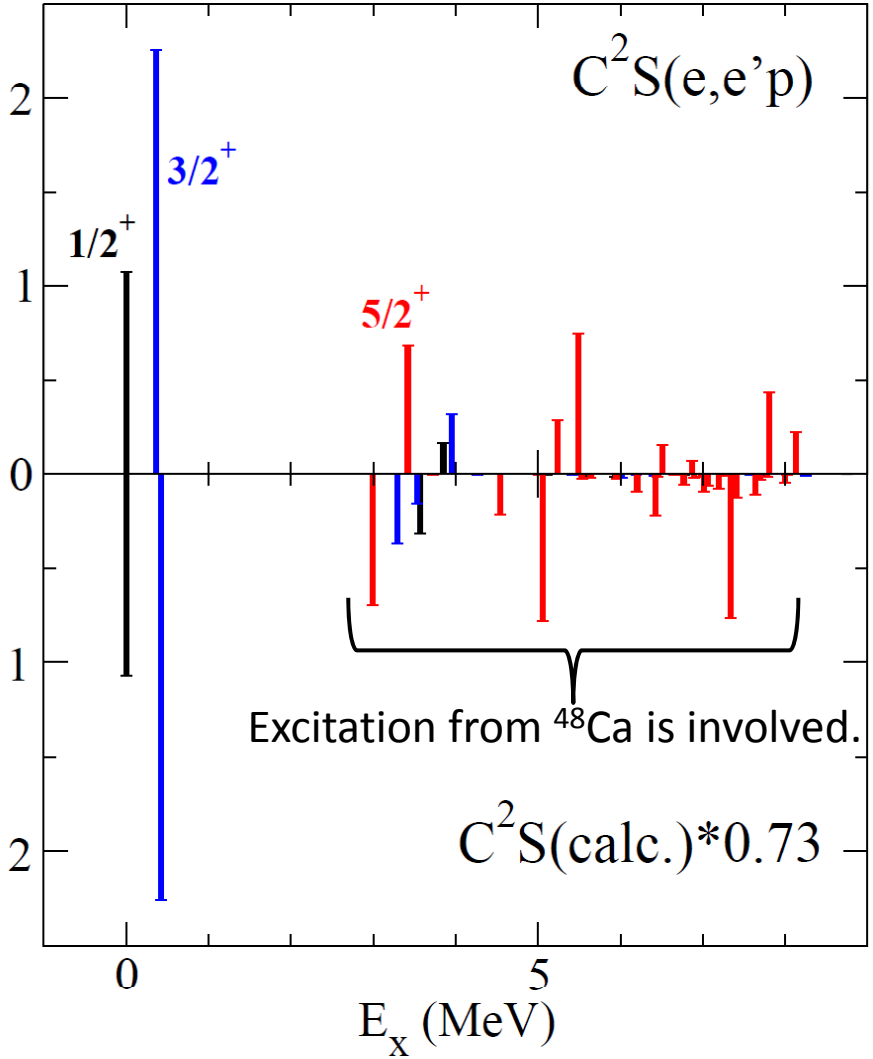
- Based on NuShell - a new set of core programs by Bill Rae written in 2007
- Techniques the same as Oxbash – JT-sheme basis expanded in terms of the M-scheme basis Suitable to calculate S up to high Ex.
- Fortran 95, allocated variables and OpenMP multiprocessing
- Wavefunctions, one- and two-nucleon spectroscopic factors, one- and two-body transition densities, cluster overlaps, LS basis for atomic cluster physics
- Input and output in user-friendly Oxbash style
- MPI version is being developed by Hang Liu for the MSU HPCC
- Open-source code with executables ready to run under Windows and Unix, 32 and 64 bit

NuShellx, a code much faster and accessible to large dimension, is comimg!

NSCL

One-hole state of ^{48}Ca

- Proton hole state of ^{48}Ca explored by the spectroscopic factor
  - Distribution: good agreement, especially for the existence of three large peaks of $5/2^+$
  - Need for overall quenching by about 0.73 compared with electron scattering data
  - Systematic lower positioning by about 500 keV



Exp.) G.J. Kramer et al., Nucl. Phys. A 679, 267 (2001).

^{47}Ar: reduction of LS splitting?

- Measurement of Ex(1/2$^-$) of ^{47}Ar and its spectroscopic factor (L. Gaudefroy et al., Phys. Rev. Lett. 97, 092501 (2006); see right).
  - N=29; ground state 3/2$^-$
  - $P_{1/2}$ dominance from the large spectroscopic factor
  - Reduction of $p_{3/2}$-$p_{1/2}$ shell gap from ^{49}Ca to ^{47}Ar is deduced to be 890(75) keV.
  - Claiming that such a large reduction of the LS splitting is hard to understand

What causes the reduction?
LS splitting by the tensor force or something?

TABLE I. Experimental energies in keV (E^*), angular momenta (ℓ), vacancies $(2J+1)C^2S$ of the levels identified in ^{47}Ar are compared to shell model calculations.

Experiment			Shell model		
E^*	ℓ	$(2J+1)C^2S$	E^*	J^π	$(2J+1)C^2S$
0	1	2.44(20)	0	$3/2^-$	2.56
1130(75)	1	1.62(12)	1251	$1/2^-$	1.62
1740(95)	3	1.36(16)	1365	$7/2^-$	0.8
2655(80)	3,(4)	1.32(18)	2684	$5/2^-$	0.78
3335(80)	3,(4)	2.58(18)	3266	$5/2^-$	2.76
3985(85)	4,(3)	3.40(40)	...	...	...
4790(95)	...	...	...	...	...
5500(85)	4	2.10(10)	...	...	...
6200(100)	...	...	...	...	...

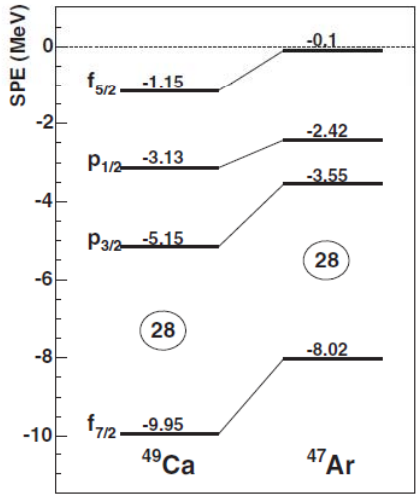


FIG. 3. Neutron single-particle energies (SPE) of the fp orbitals for the $^{47}Ar_{29}$ and $^{49}Ca_{29}$ nuclei (see text for details).

From shell model calculation

- Reduction of $3/2^-$-$1/2^-$ splitting:
  1.057 MeV (calc.) vs. 0.893(75) MeV (exp.)
- Good agreement with the experimental spectroscopic factor

^{47}Ar	$(2J+1)C^2S$	
	Exp.	Calc.
$3/2^-$	2.44(20)	2.47
$1/2^-$	1.62(12)	1.73

^{49} Ca	$(2J+1)C^2S$	
	Exp.	Calc.
$3/2^-$	3.36(48)	3.79
$1/2^-$	1.82(30)	1.93

- Good wave function
- Possible to relate to the single-particle energy

Reduction of the gap by monopole int.

- Simple estimate by the filling configuration of $(d_{3/2})^{-2}$

$$1/2\times 0.96\times 2\times\{\underbrace{(\overset{\text{Cent.}}{-0.077}-\overset{\text{LS}}{0.001}+\overset{\text{Tens.}}{0.205})}_{T=0}+\underbrace{(-0.010-0.032+0.074)}_{T=1}\}$$

= 0.15 MeV

- Taking into account the fraction of protons

$d_{3/2}$ $$1/2\times 0.96\times 1.12\times\{(-0.077-0.001+0.205)+(-0.010-0.032+0.074)\}$$

$s_{1/2}$ $$+1/2\times 0.96\times 0.73\times\{(0-0.030+0)+(0+0.208+0)\}$$

$d_{5/2}$ $$+1/2\times 0.96\times 0.15\times\{(0.052+0.001-0.137)+(0.007+0.032-0.096)\}$$

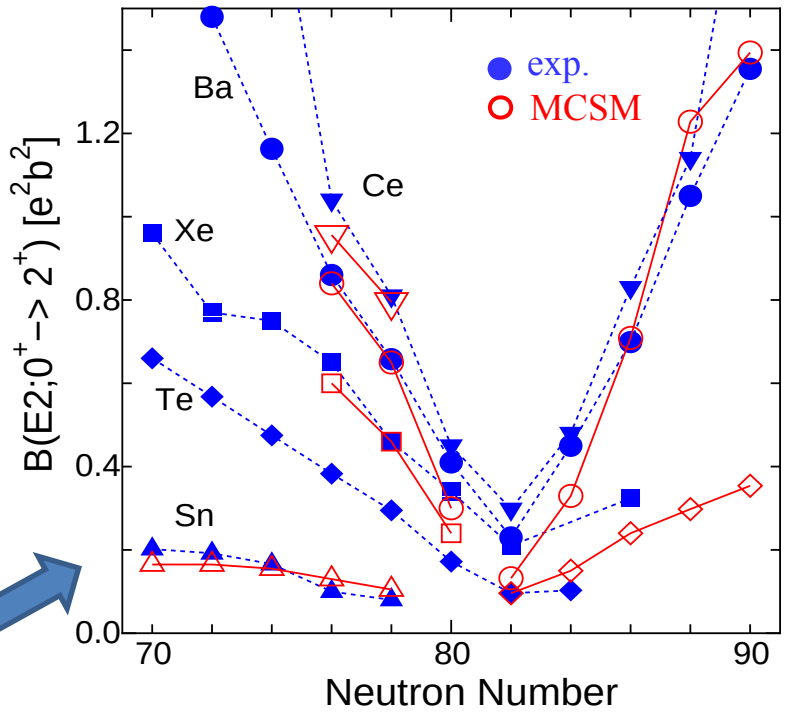
= 0.14 MeV

Tensor (wrt $d_{3/2}$) and LS (wrt $s_{1/2}$) reduces the gap to a certain extent.
But it is not enough to explain the observed reduction.
The correlation plays an important role!
(see also A. Signoracci and B. A. Brown, Phys. Rev. Lett. 99, 099201 (2007).)

MCSM with quasi-particle basis

- Slater determinant basis
  - Good for light region such as sd and pf
- Heavier nuclei
  - Many valence orbits are involved.
  - Pairing is getting more important.
- MCSM with pair-condensed bases (N. Shimizu et al.)
  - Equivalent with q.p. with number projection
  - Successful to describe yrast properties of medium heavy nuclei (see right)
  - Some difficulty in applying to odd number, to non-separable interaction, and to many valence particles

B(E2; $0^+ \rightarrow 2^+$) of Sn, Te, Xe, Ba, and Ce isotopes

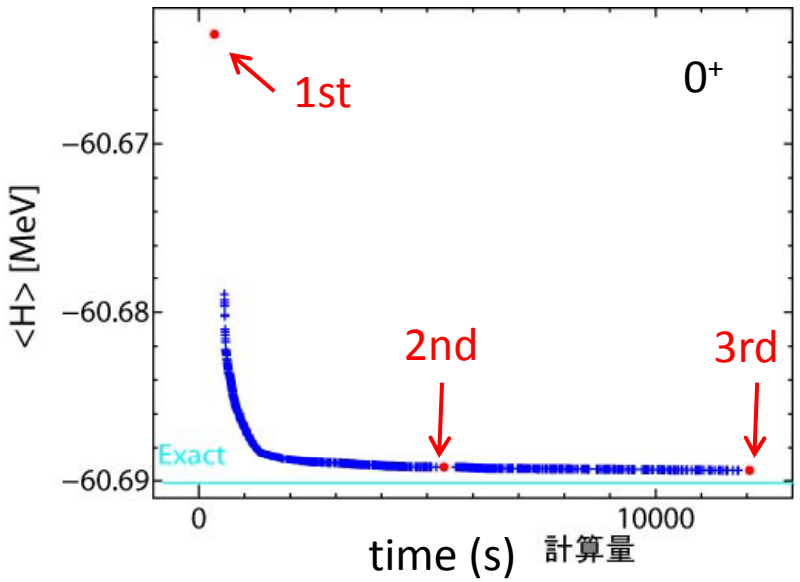


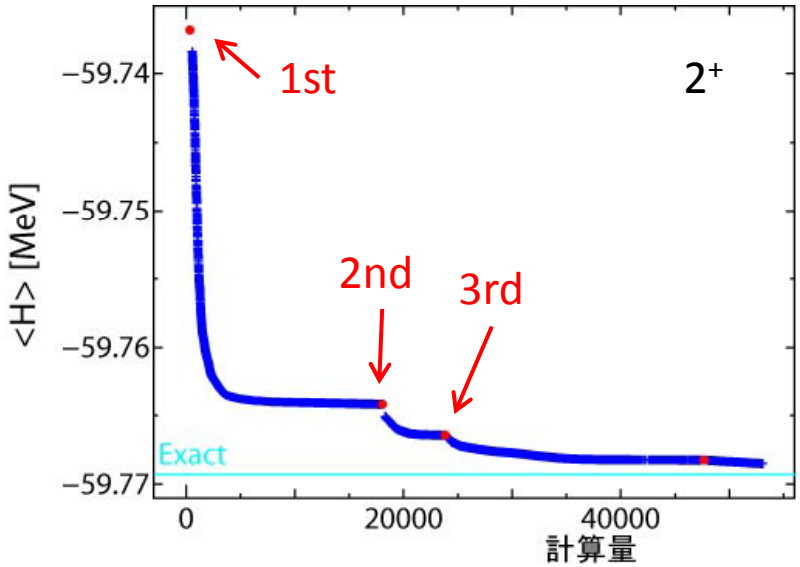
N. Shimizu et al., Phys. Rev. Lett. 86, 1171 (2001); Phys. Rev. C 70, 054313 (2004); J. Phys.: Conf. Ser. 49, 178 (2006).

Quasi-particle basis is promising.

Test for non-separable interaction

- N and J projected HFB(q.p.)-MCSM
  - Axially symmetric basis
- System
  - ^{138}Ba on top of ^{132}Sn core (6 valence protons)
  - Valence shell: $g_{7/2}$+$d_{5/2}$
  - CWG interaction
    (B.A. Brown et al., Phys. Rev. C 71, 044317 (2005).)





Typical energy scale: ~1 MeV (Ex.(2+))
vs.
Accuracy: less than 1 keV with a few bases!

High performance computing is needed.

Summary

- We are making large-scale shell model calculations in some regions with collaboration of various groups (exp. and theor.):
  - Island of inversion (N~20):
    Investigating the boundary using probes of β decay, nuclear moment and spectroscopic factor
  - Heavy pf-shell nuclei:
    Difference in parity between pf and g orbits would keep pf-shell dominance until a certain number (around N=36?)
  - Constructing a new interaction for the sd-pf (cross) shell:
    "Universal" tensor strength and simulating the monopole of GXPF1 with quite small number of parameters
    Applying the NuShell code to the spectroscopic factor
  - Starting MCSM calculation with quasi-particle basis:
    More computation power will be desired.

List of collaboration

- MCSM, shell evolution

  T. Otsuka (Univ. Tokyo)

  M. Honma (Univ. Aizu)

  T. Mizusaki (Senshu Univ.)

  N. Shimizu (Univ. Tokyo)

- Spectroscopic factor

  B. A. Brown (MSU)

  Many experimentalists (especially MSU and its users)