EGAN11
Padova, Italy
June 27 (27-30), 2011

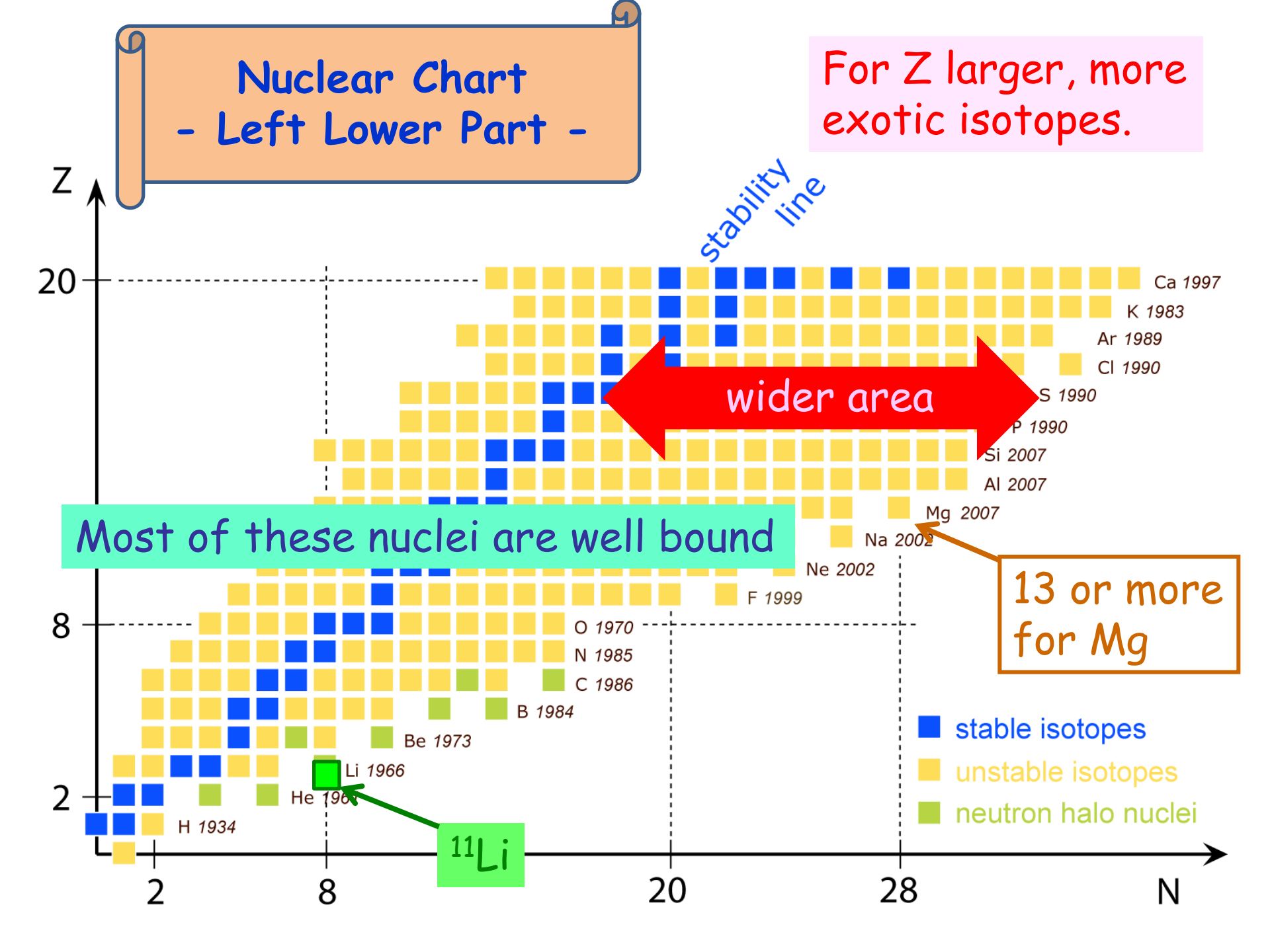
Nuclear forces and spectroscopy

東京大学 THE UNIVERSITY OF TOKYO

Takaharu Otsuka
University of Tokyo / MSU

NSCL

14時12分


Nuclear Chart
- Left Lower Part -
For Z larger, more exotic isotopes.
Z
N
stability line
wider area
Most of these nuclei are well bound
13 or more for Mg
Ca 1997
K 1983
Ar 1989
Cl 1990
S 1990
P 1990
Si 2007
Al 2007
Mg 2007
Na 2002
Ne 2002
F 1999
O 1970
N 1985
C 1986
B 1984
Be 1973
Li 1966
He 1968
H 1934
11Li
stable isotopes
unstable isotopes
neutron halo nuclei
2
8
20
28

How does the nuclear force work in neutron-rich exotic nuclei as manifested by spectroscopy ?

What can we learn about the nuclear force in return ?

- **Tensor force** ⟷ **Spectroscopy of Si isotopes**
- 3-body force ... *not in this workshop*

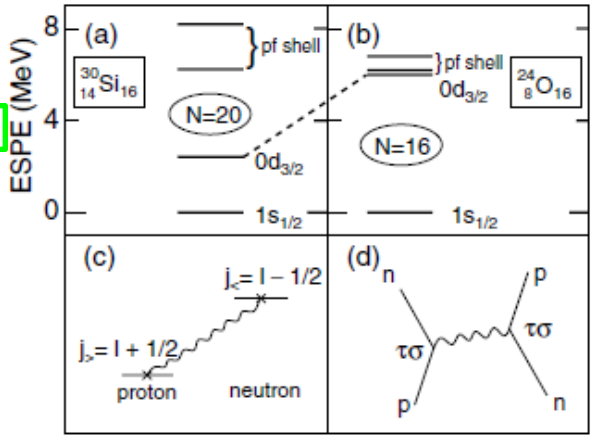
Brief history on our studies on tensor force

VOLUME 87, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 2001

Magic Numbers in Exotic Nuclei and Spin-Isospin Properties of the *NN* Interaction

Takaharu Otsuka,[1,2] Rintaro Fujimoto,[1] Yutaka Utsuno,[3] B. Alex Brown,[4] Michio Honma,[5] and Takahiro Mizusaki[6]
[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*
[2]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*

Magic numbers may change due to spin-isospin nuclear forces

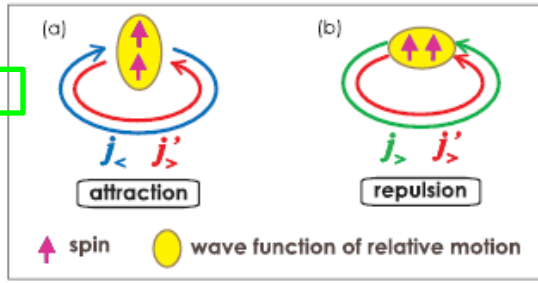


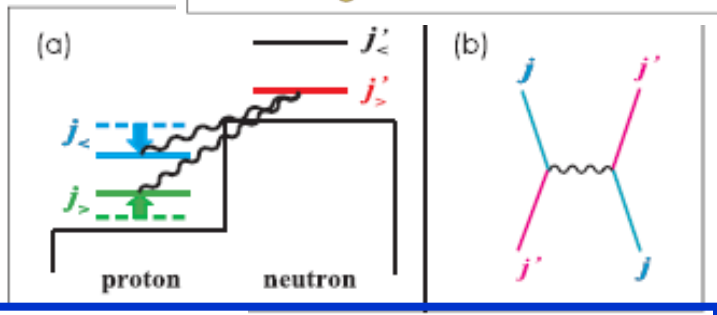
PRL 95, 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Evolution of Nuclear Shells due to the Tensor Force

Takaharu Otsuka,[1,2,3,*] Toshio Suzuki,[4] Rintaro Fujimoto,[1] Hubert Grawe,[5] and Yoshinori Akaishi[6]
[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*

Tensor force produces unique and sizable effect



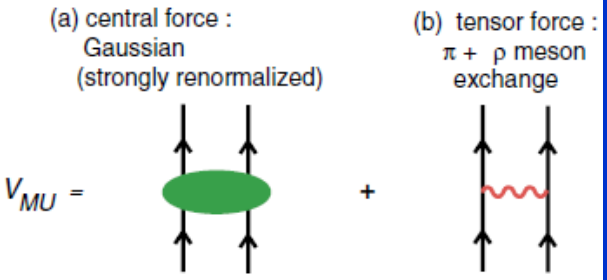


Selected for a Viewpoint in *Physics*
PRL 104, 012501 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

Takaharu Otsuka,[1,2] Toshio Suzuki,[3] Michio Honma,[4] Yutaka Utsuno,[5] Naofumi Tsunoda,[1] Koshiroh Tsukiyama,[1] and Morten Hjorth-Jensen[6]

Tensor and central forces -> Weinberg-type model



As *N* or *Z* is changed to a large extent in exotic nuclei, the shell structure is changed (evolved) by

- Monopole component of the *NN* interaction

$$v_{m;j,j'} = \sum_{k,k'} \langle jkj'k'|V|jkj'k'\rangle \Big/ \sum_{k,k'} 1,$$

➡ **Averaged over possible orientations**

Linearity: Shift $\Delta\epsilon_j = v_{m;j,j'} n_{j'}$ $n_{j'}$: # of particles in j'

$\langle n_{j'} \rangle$ can be ~ 10 in exotic nuclei
-> effect quite relevant to neutron-rich exotic nuclei

Strasbourg group made a major contribution in initiating systematic use of the monopole interaction. (Poves and Zuker, Phys. Rep. 70, 235 (1981))

Monopole component of tensor force
- An intuitive picture -

At collision point:

$$\Psi \propto e^{ik_1 x_1} e^{ik_2 x_2} + e^{ik_2 x_1} e^{ik_1 x_2} = 2\, e^{iK X} \cos(kx)$$

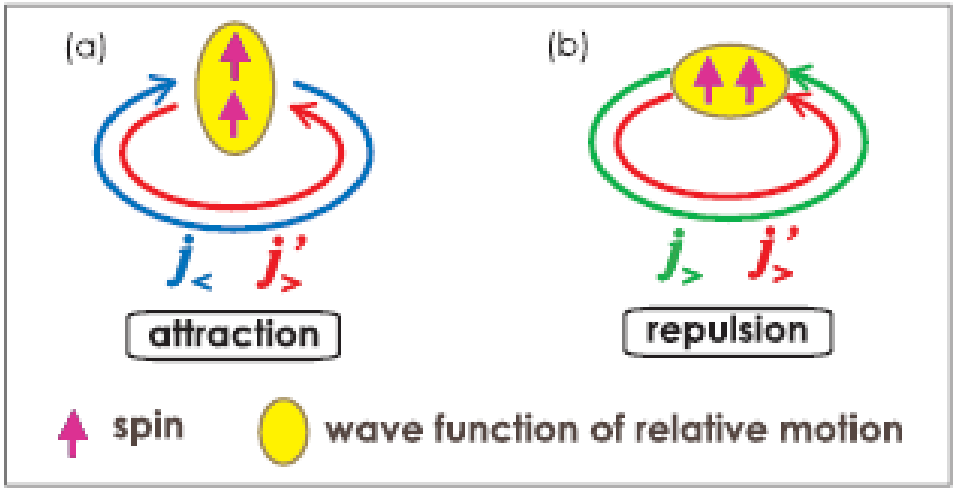
k_2 k_1

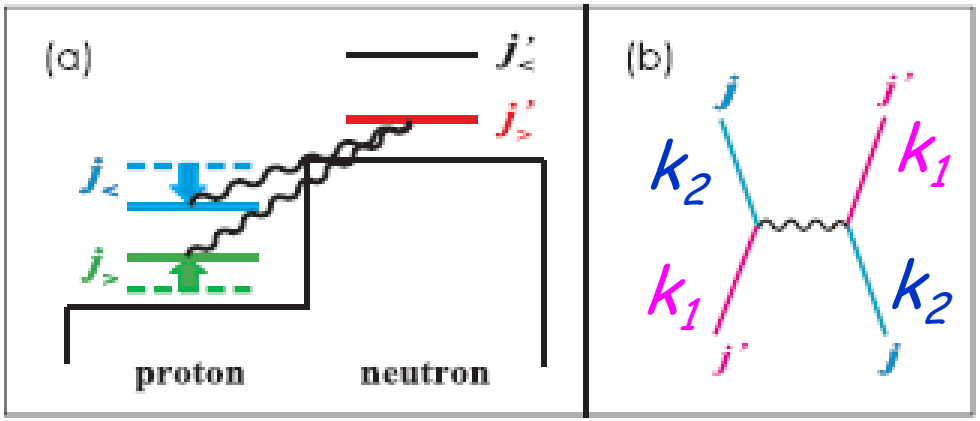
large relative momentum k

strong damping

wave function of relative coordinate

$k = k_1 - k_2$, $K = k_1 + k_2$





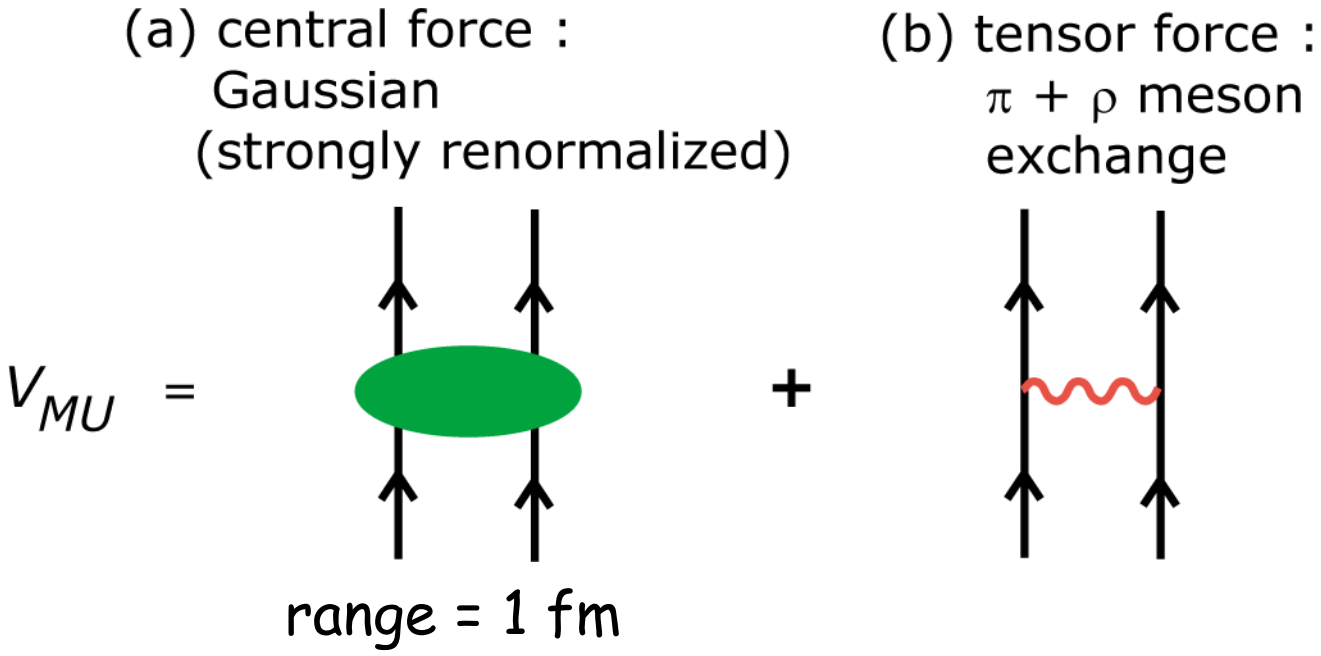
k_2 k_1

small relative momentum k

loose damping

wave function of relative coordinate

From a comparison to shell model interactions which can reproduce many experimental data in *sd* and *pf* shells, an extremely simple interaction "Monopole-based Universal Interaction V_{MU} has been introduced.



The same interaction for all nuclei

This Ansatz is tested

- theoretically

  introducing Renormalization Persistency

  Tsunoda, O, Tsukiyama, H.-Jensen (2011)

- experimentally

  (i) (e,e'p) on ^{48}Ca

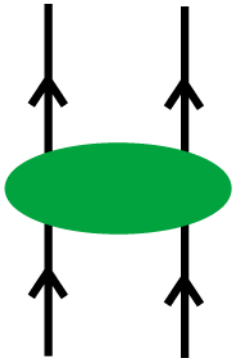
  (ii) by recent data on ^{42}Si

Monopole-based Universal Interaction V_{MU}

(a) central force :
Gaussian
(strongly renormalized)

(b) tensor force :
π + ρ meson
exchange

V_{MU} =



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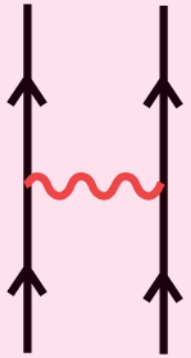


monopole component of
tensor force in nuclear medium

recent theories -> almost equal

monopole component of
tensor force in free space

A renormalization process

- short-range correlations
- in-medium corrections

$V = V_c + V_{LS} + V_T$

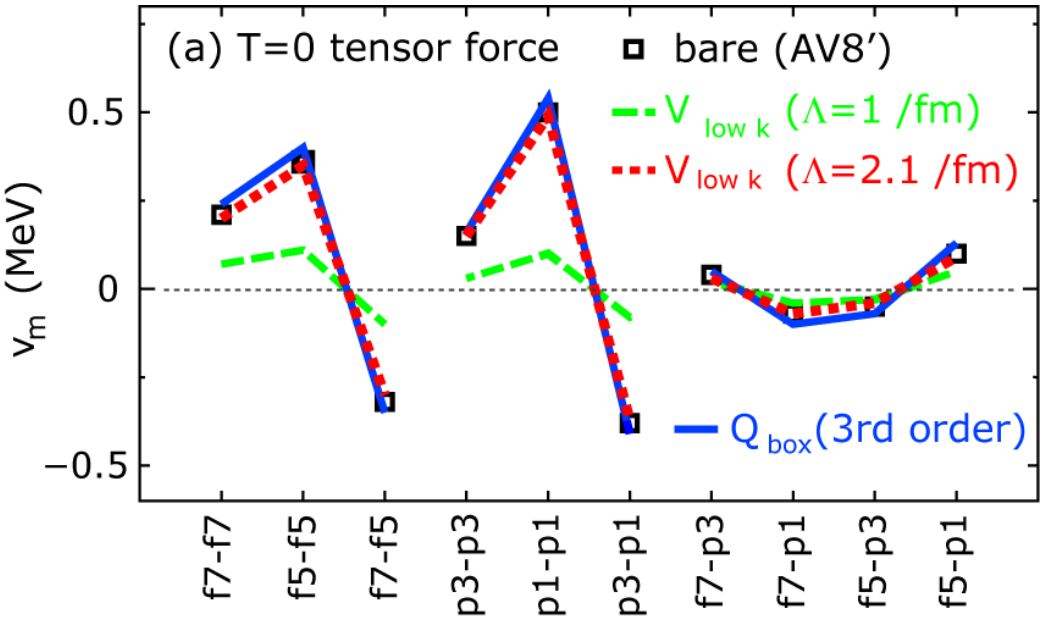
$V = V'_c + V'_{LS} + V'_T + V_{NNN} + \cdots$

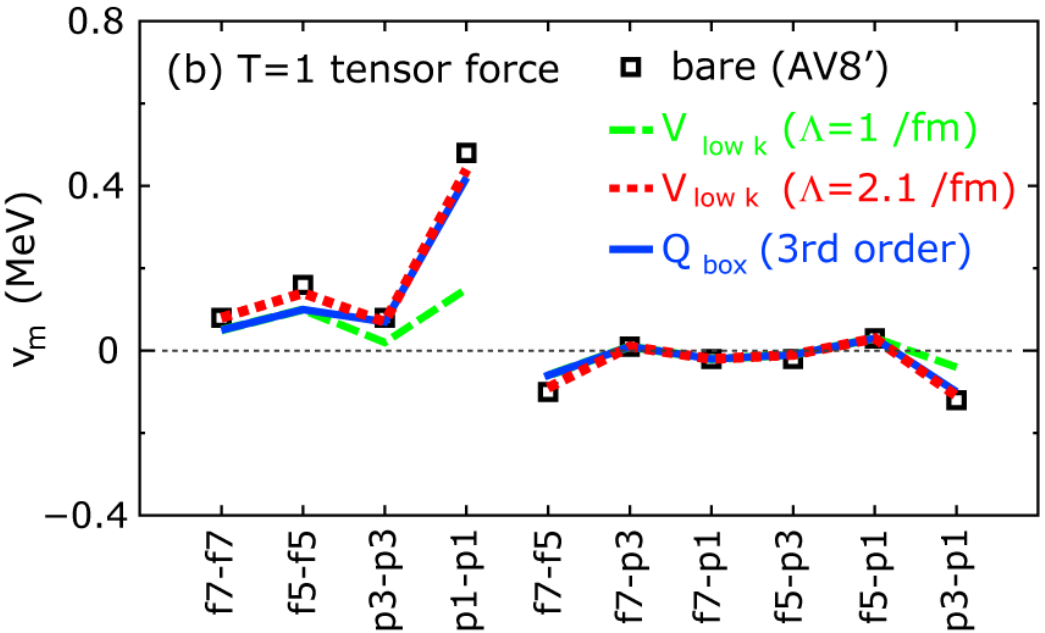
In general, V_x differs from V'_x (x=c, LS, T).

If $V_x = V'_x$, Renormalization Persistency holds.

- not rigorous (good approx. makes sense)
- new way of anatomy of nuclear forces

Treatment of tensor force by $V_{low\ k}$ and Q box (3rd order)





Monopole component of tensor interactions in *pf* shell

Bare (AV8′)

⇓ short-range correlation by $V_{low\ k}$

⇓ in-medium correction with intermediate states (> 10 hw, 3rd order)

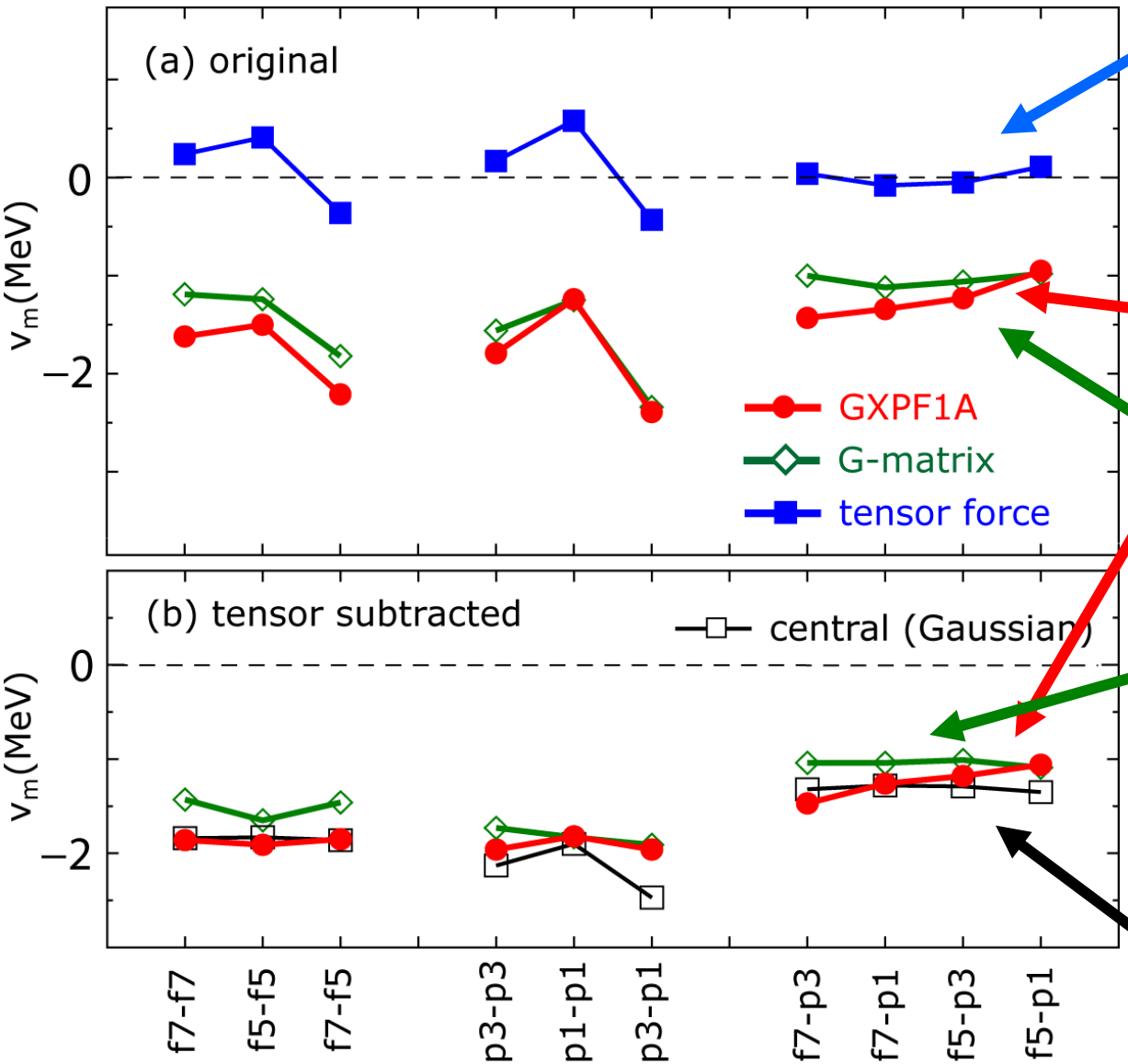
only for comparison

$V_{low\ k}$: Bogner, Kuo, Schwenk

This remarkable property has been put into shell-model effective interactions without explicitly knowing it.

See an example in the next page.

T=0 monopole interactions in the pf shell



Tensor force
(π+ρ exchange)

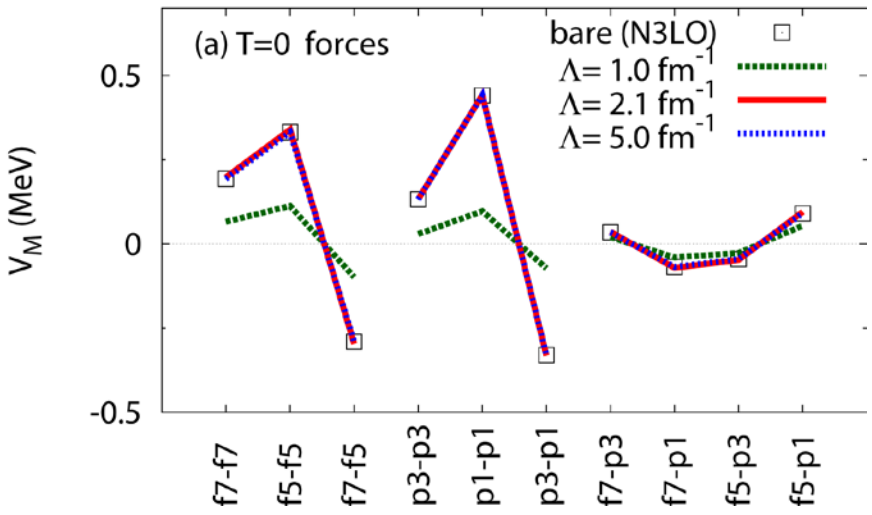
GXPF1A
shell-model int.

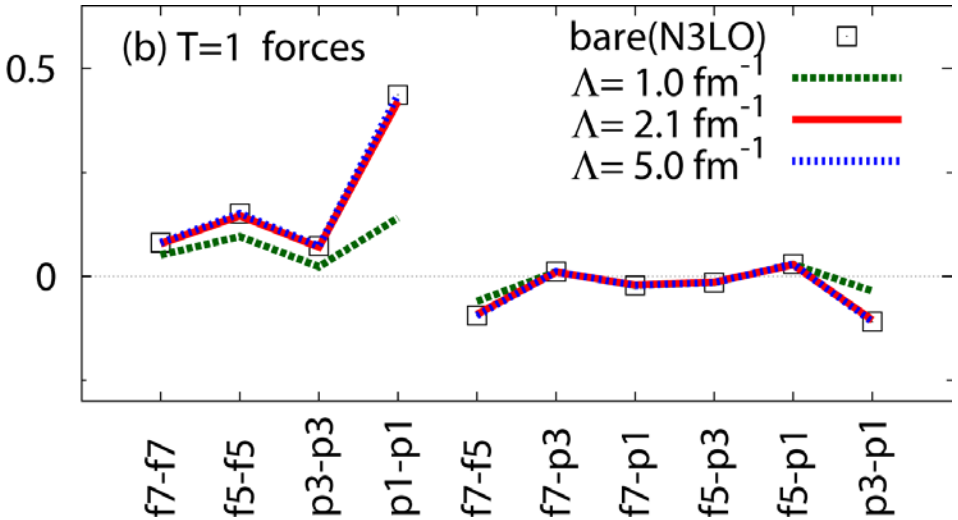
G-matrix
(H.-Jensen)

central part of
V_{MU}

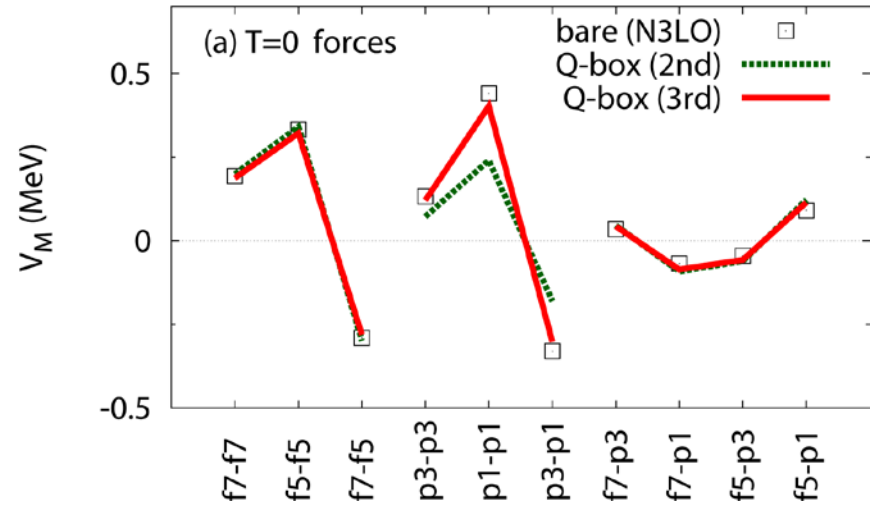
N3LO (EFT of QCD) for pf-shell

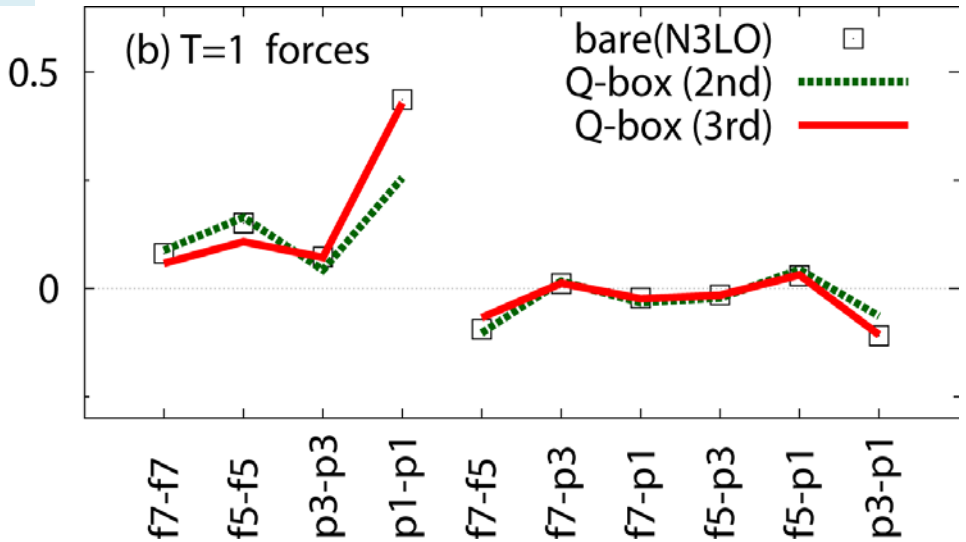
short-range correl.





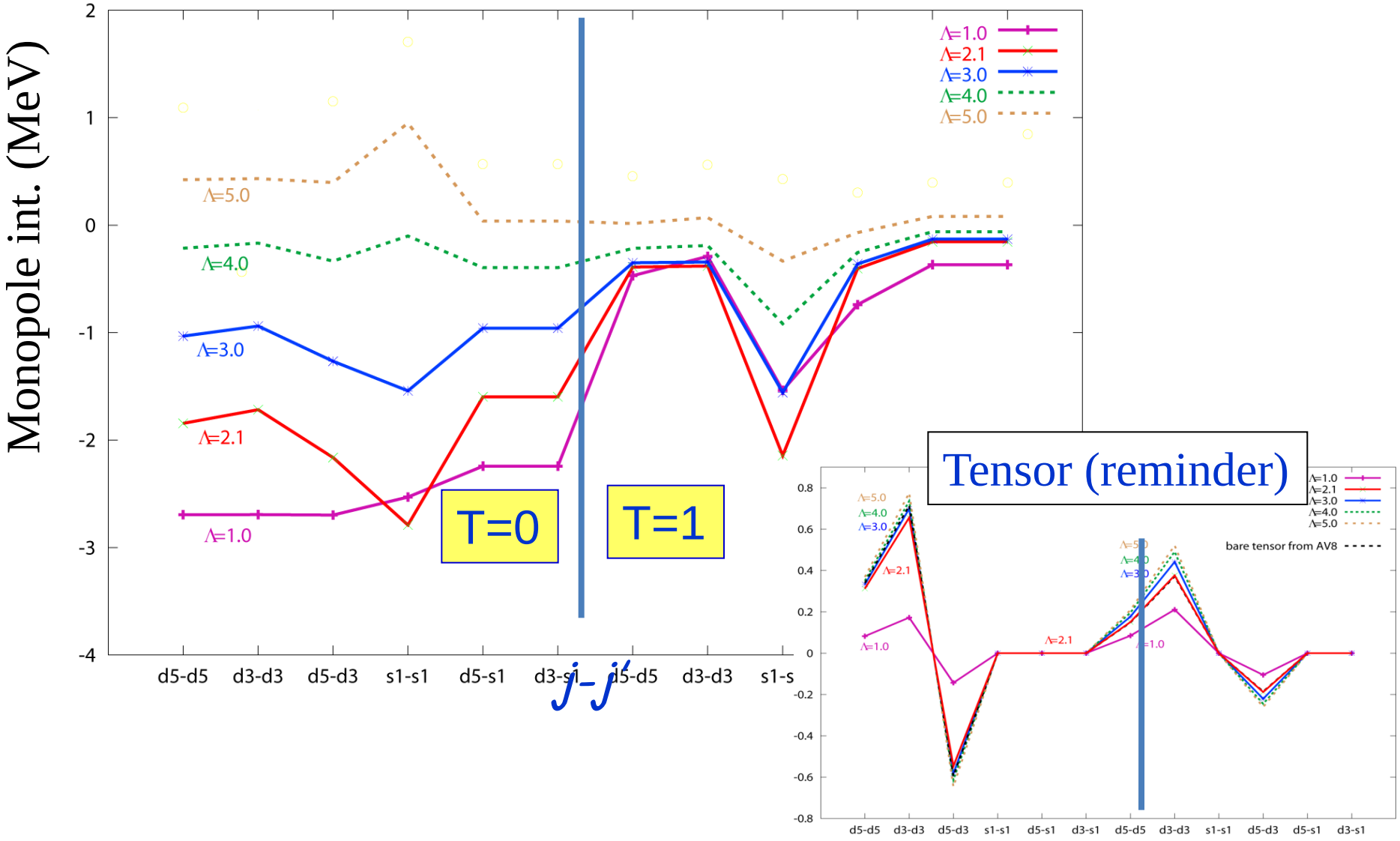
in-medium correc. Λ = 2.1 fm^{-1}





No Renormalization Persistency for Central Force

Central part changes as the cut-off Λ changes



Test by experiments

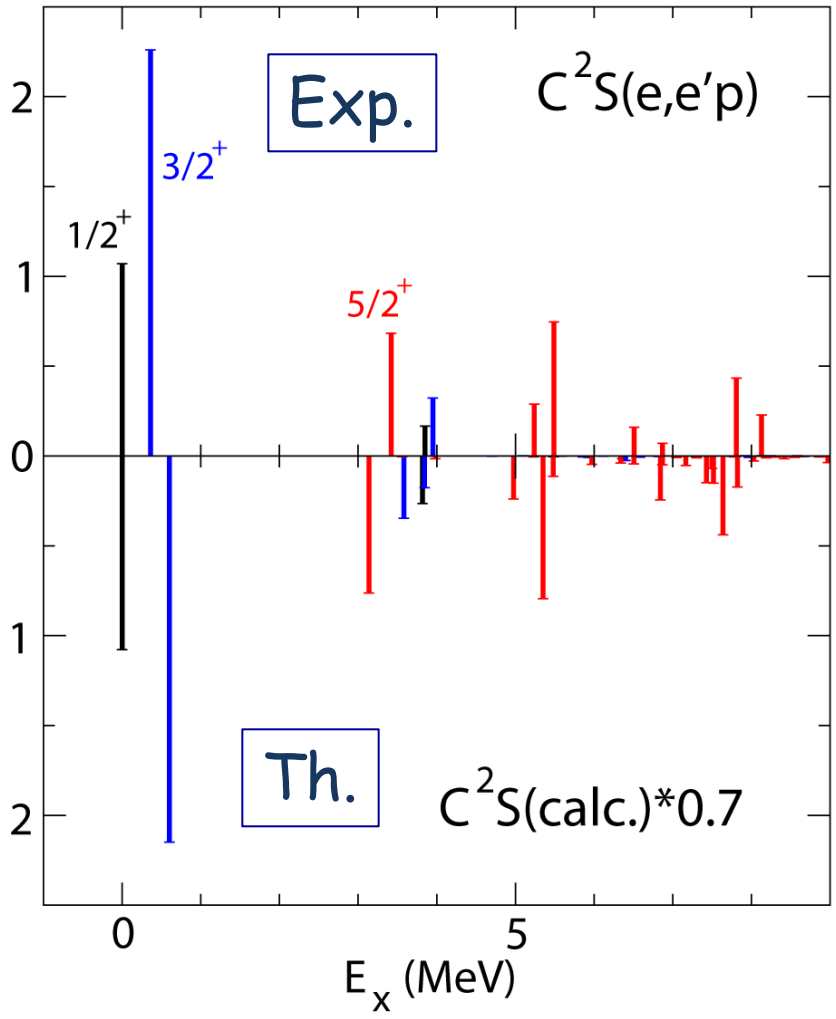
Spectroscopic factors obtained by (e,e'p) on ^{48}Ca and the tensor force

Collaboration with Utsuno and Suzuki

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

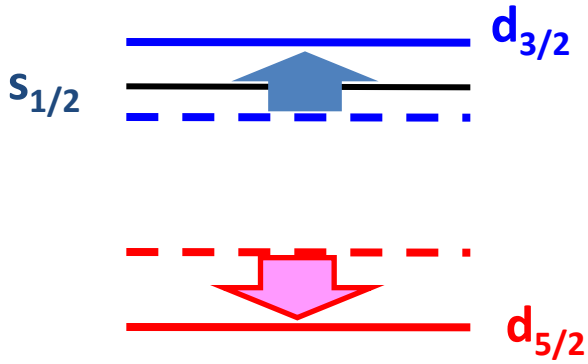
Same interaction as the one for ^{42}Si

- $\pi d_{5/2}$ deep hole state
  - More fragmentation
- Distribution of strength
  - quenching factor 0.7 is needed (as usual).
  - Agreement between experiment and theory for both position and strength

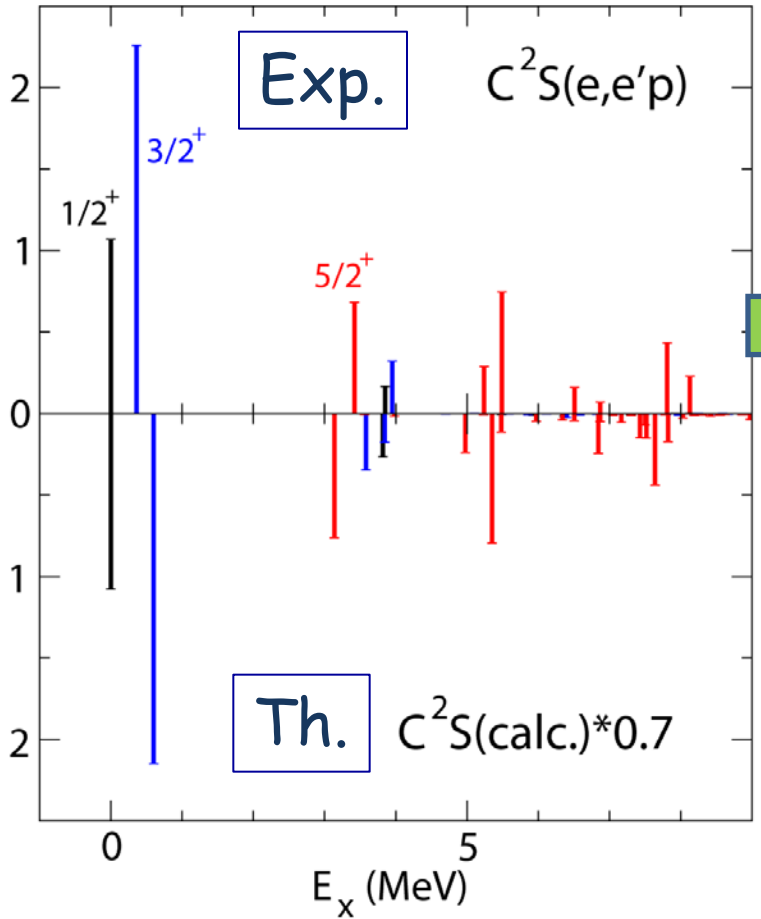


(e,e'p): Kramer et al., NP A679, 267 (2001)

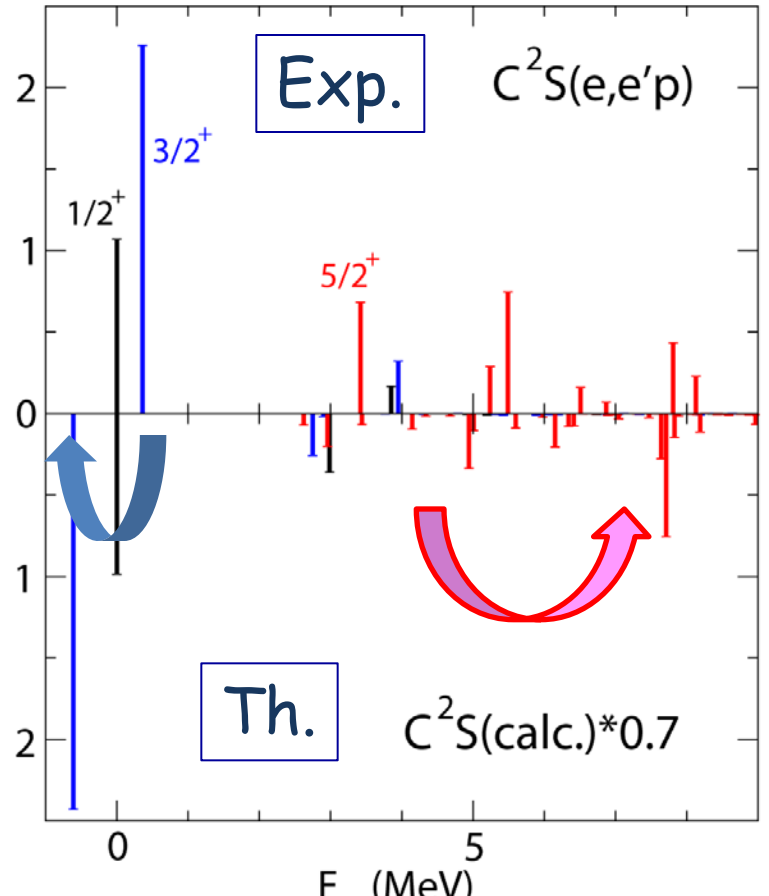
What happens, if the tensor force is taken away ?



with full tensor force



no tensor in the cross shell part



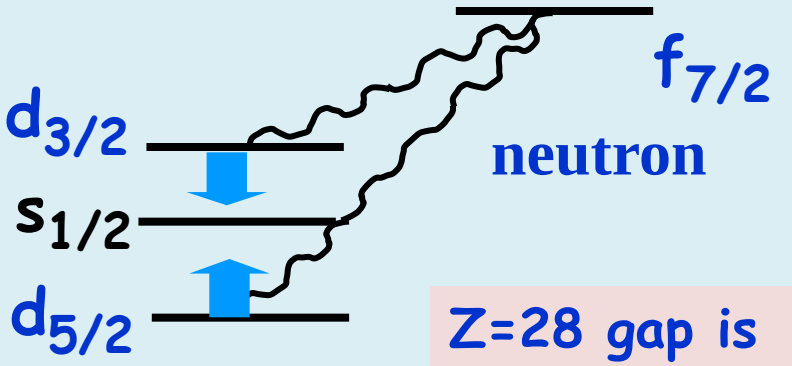
Let's use the same interaction* to see

spectroscopic properties of Si isotopes

* - microscopically sound basis

- tested by (e,e'p)

Utsuno, O, Shimizu, Suzuki, Honma, Y. Tsunoda

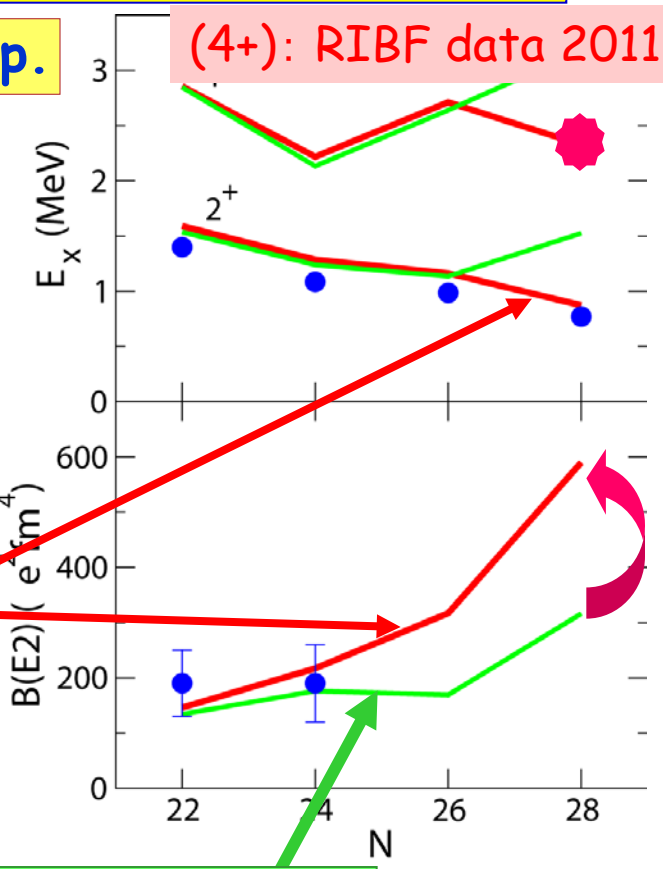


Z=28 gap is reduced also

Si isotopes
SM calc. by Utsuno et al.

● exp.

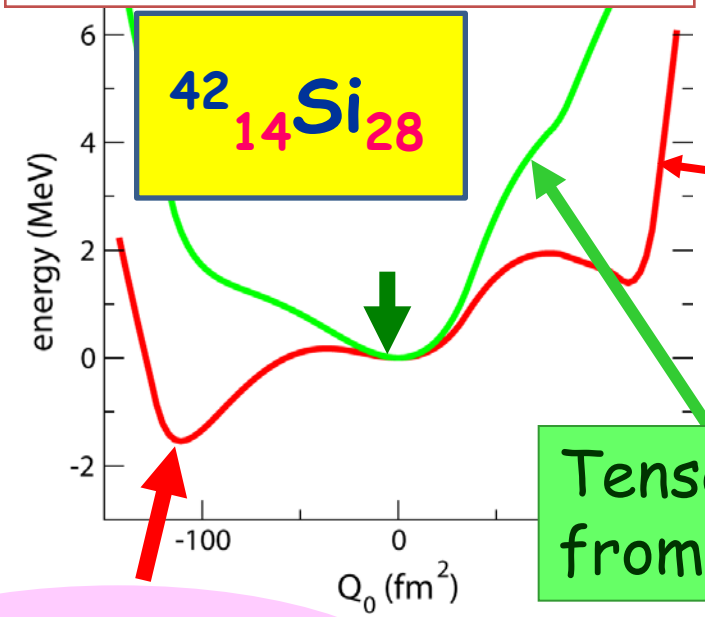
(4+): RIBF data 2011



^{42}Si

Potential Energy Surface

$^{42}_{14}Si_{28}$



full

Tensor force removed from cross-shell interaction

Strong oblate Deformation ?

Other calculations (RMF, Gogny) show oblate shape.

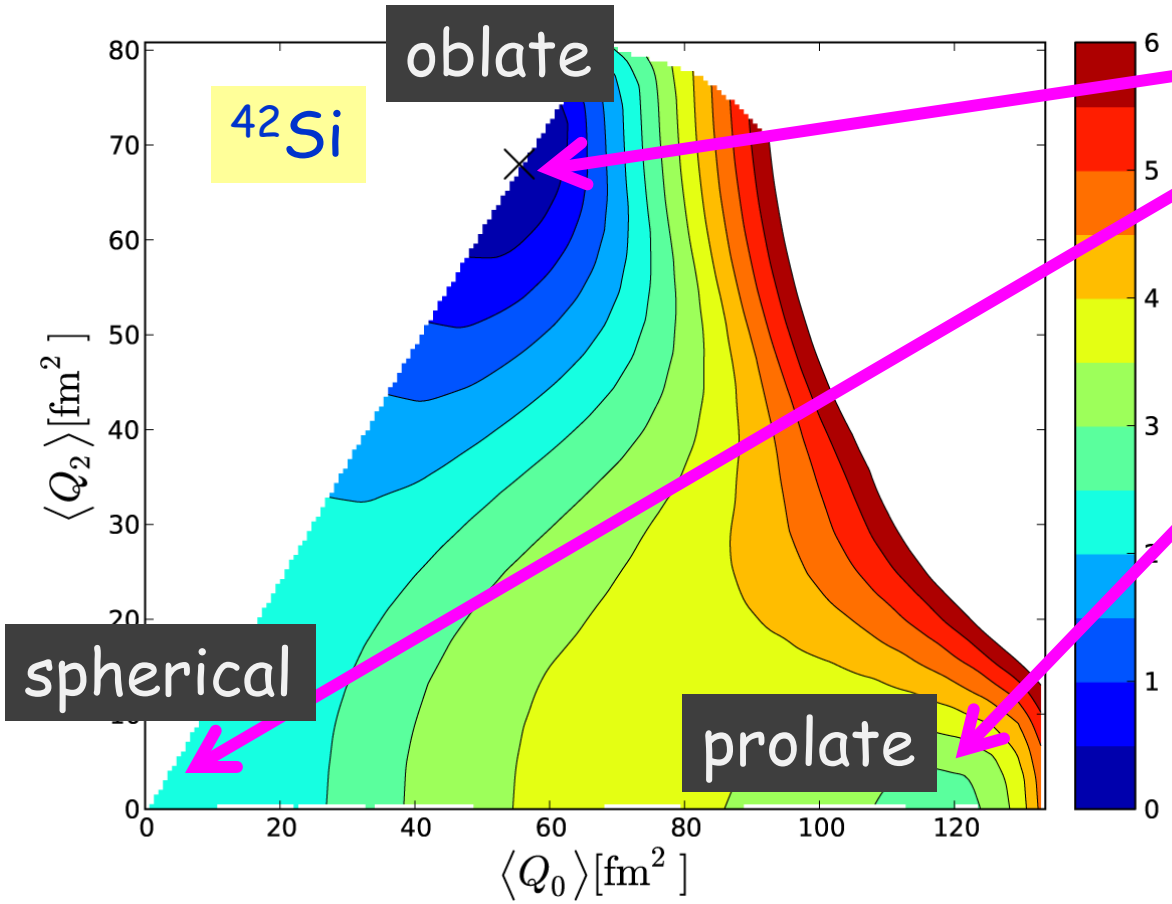
Otsuka, Suzuki and Utsuno, Nucl. Phys. A805, 127c (2008)

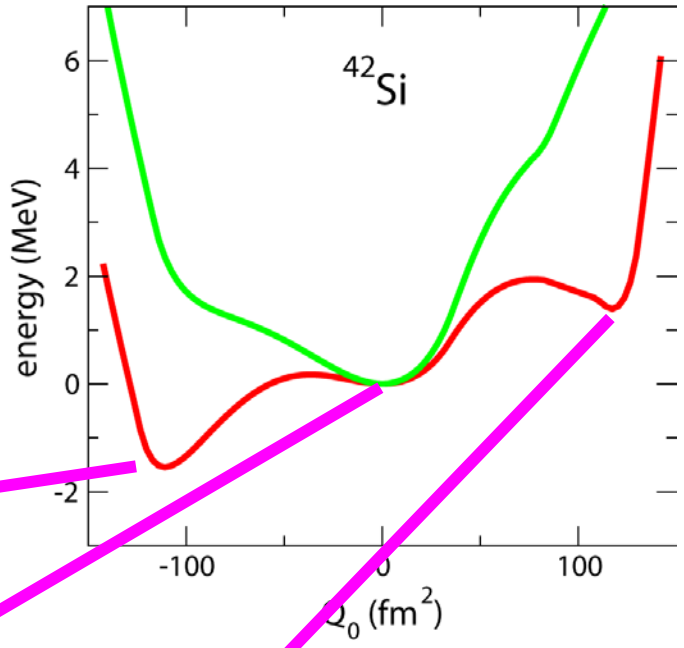
^{42}Si 2+: *B. Bastin, S. Grévy et al., PRL 99 (2007) 022503*

PES of ^{42}Si

Tensor force included

(as global V_{MU})



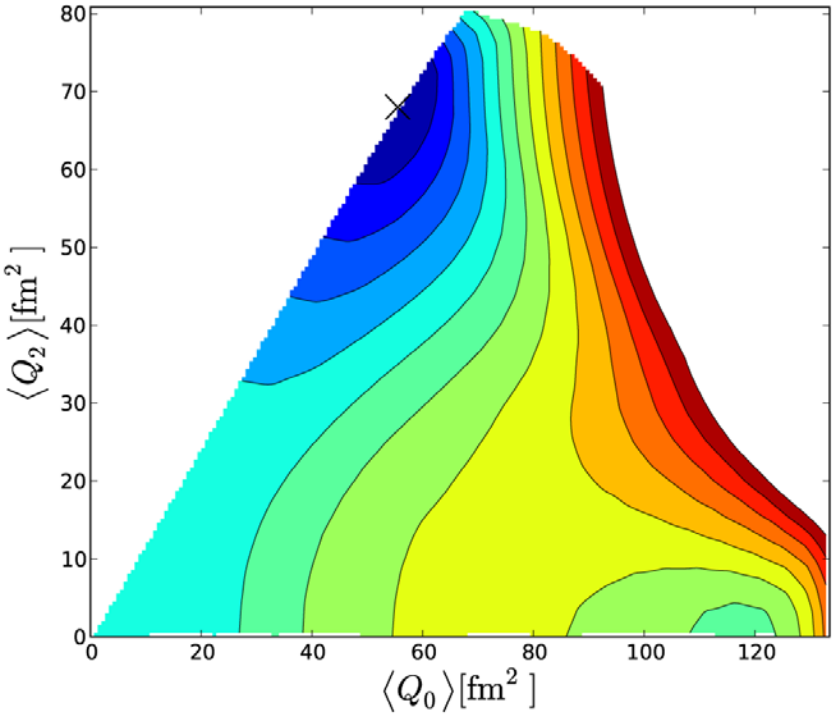


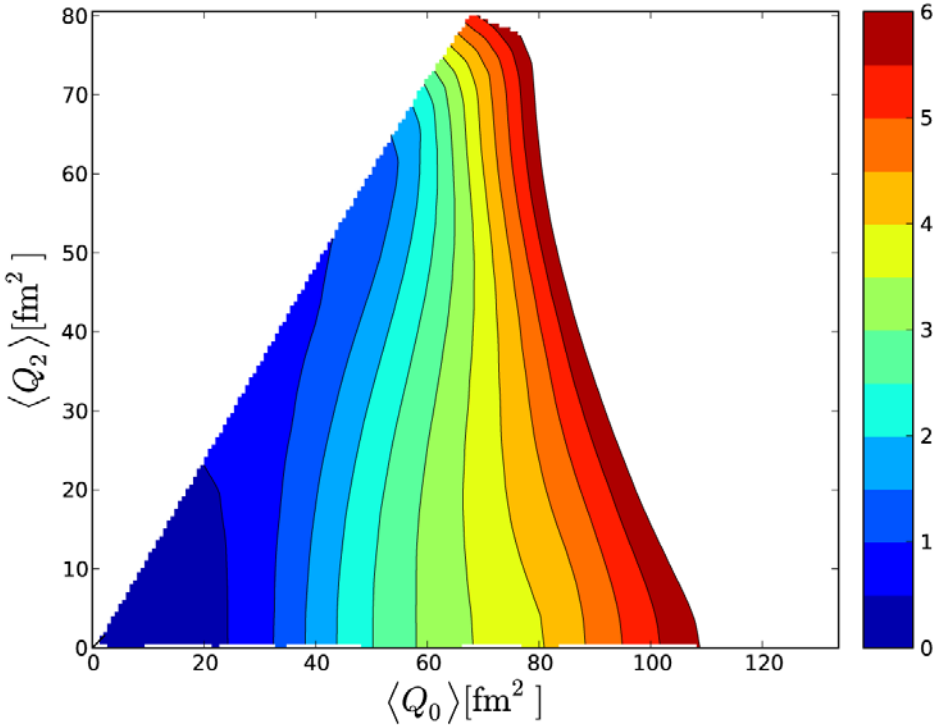
^{42}Si PES

tensor force between sd and pf shells

ON **OFF**

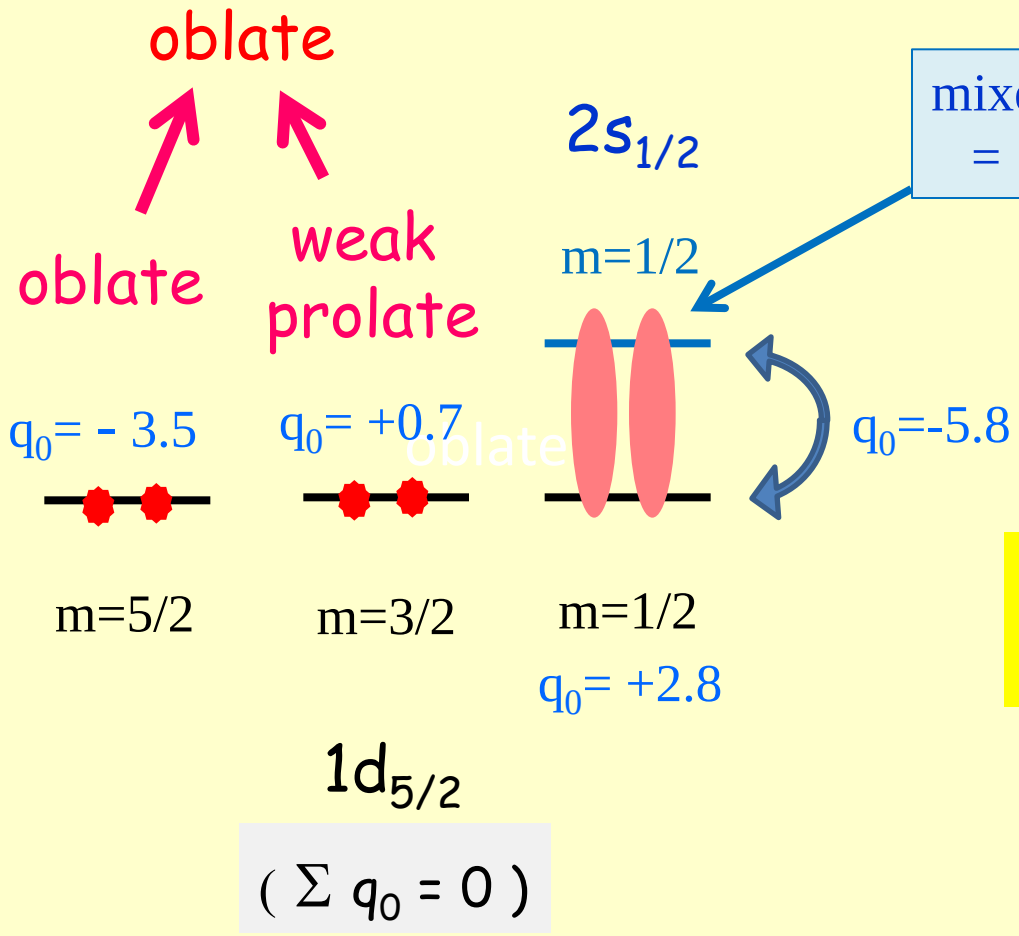
consistent with (e,e'p)





Why oblate deformation in ^{42}Si ground state ?

Proton wave function of intrinsic state with axial symmetry



mixed state
= α |2s1/2> + β |1d5/2, m=1/2>

mixed by Q_0 field

mixing occurs so as to have maximum $|q_0|$

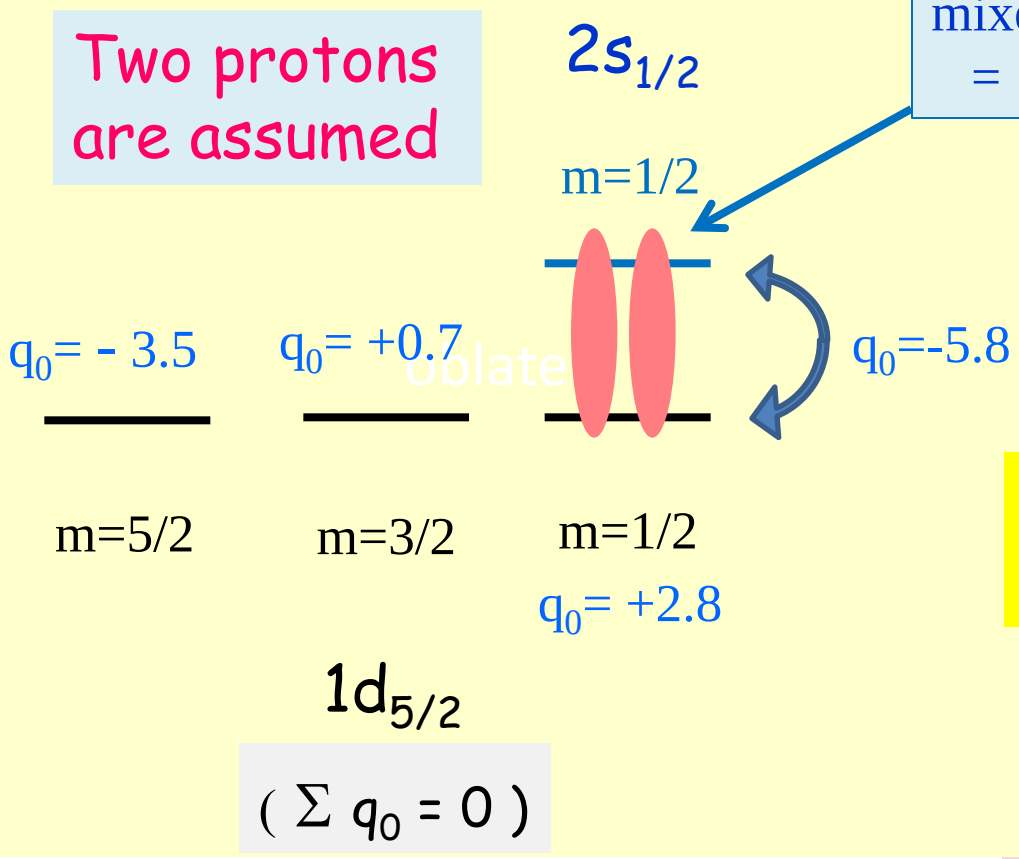
oblate
in this case
due to oblate
shape by m=5/2, 3/2

(*$1d_{3/2}$ is omitted for simplicity*)

Why prolate deformation at the beginning of the shell ?

Proton wave function of intrinsic state with axial symmetry

Two protons are assumed



mixed state
$= \alpha\,|2s1/2> + \beta\,|1d5/2, m=1/2>$

mixed by Q_0 field

mixing occurs so as to have maximum $|q_0|$

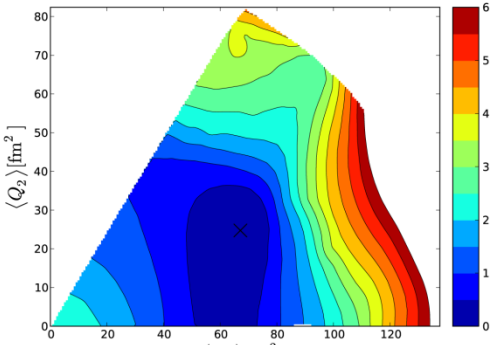
prolate
in this case
due to absence of
other occupied substates

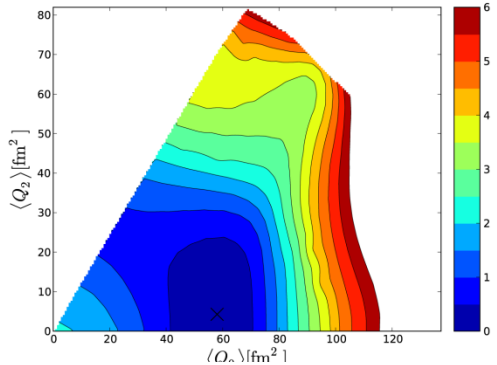
(*$1d_{3/2}$ is omitted for simplicity*)

with tensor

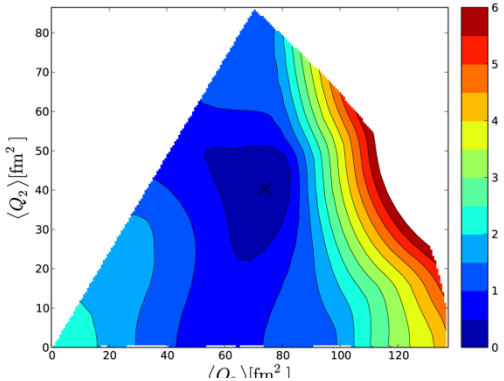
without tensor

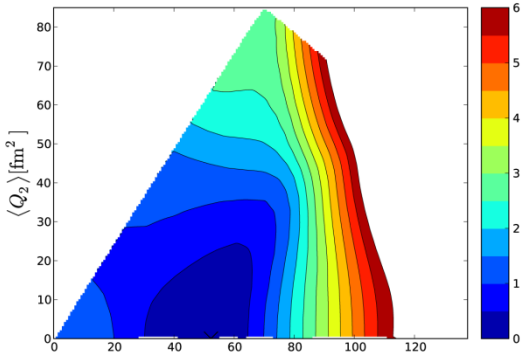
38 Si



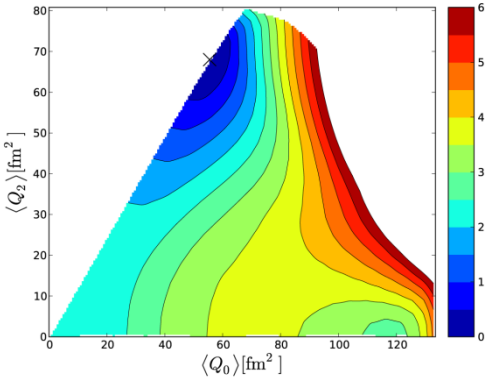


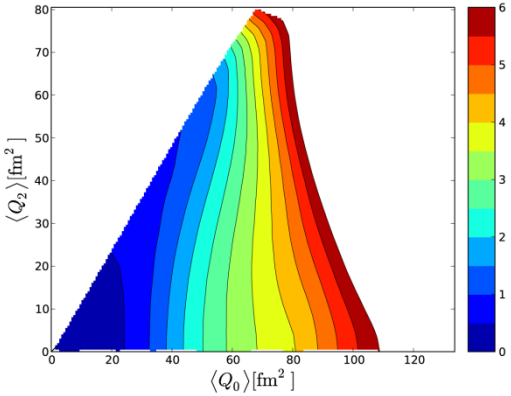
40 Si





42 Si

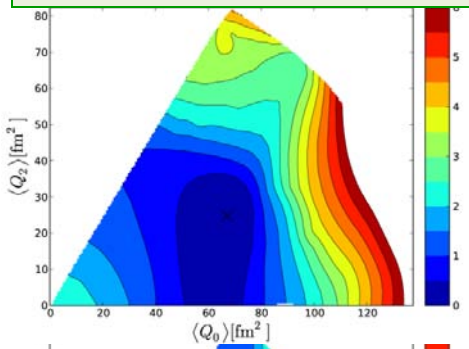


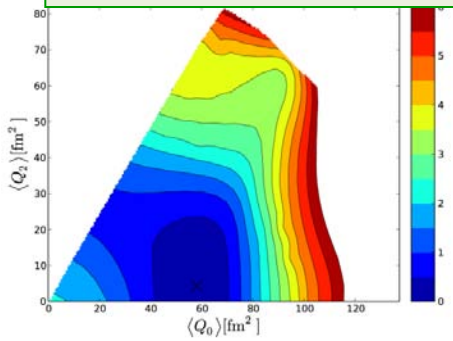


with tensor in sd-pf

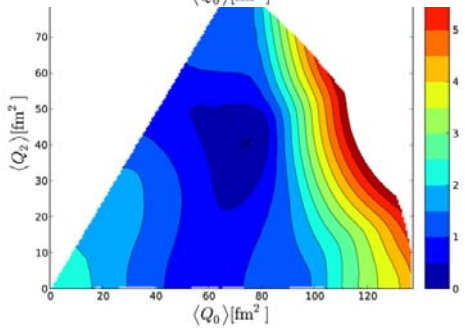
without tensor in sd-pf

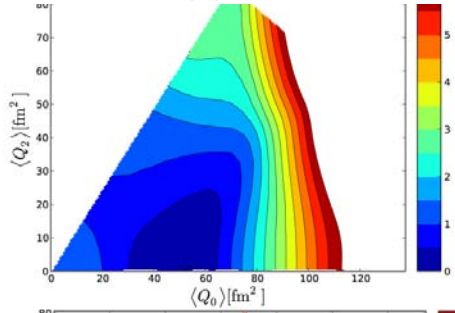
38 Si



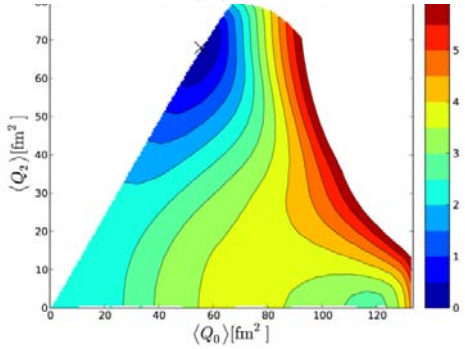


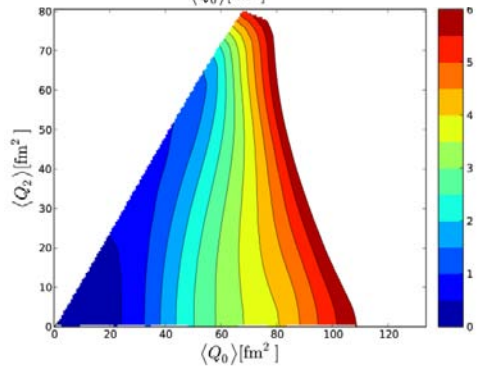
40 Si



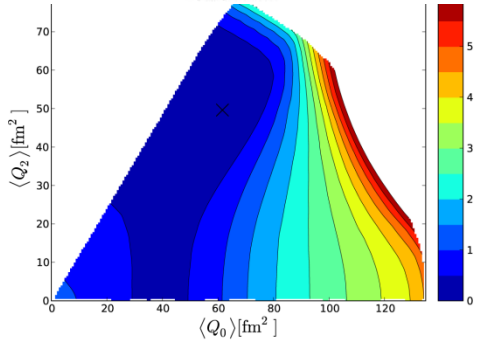


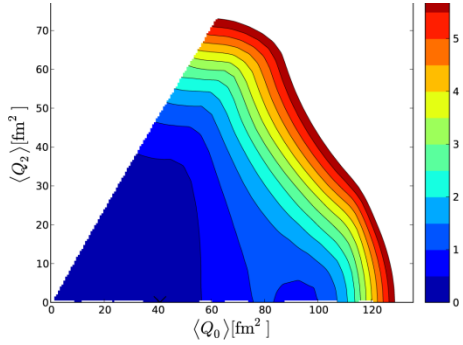
42 Si





44 Si





Summary

1. Monopole interactions : effects magnified in neutron-rich nuclei

   Nuclear deformation at low-excitation energy is a Jahn-Teller effect. Its description is closely connected to single-particle properties.

2. Tensor force combined with central force : a unified description particularly for proton-neutron monopole correlation.
   -> ^{42}Si

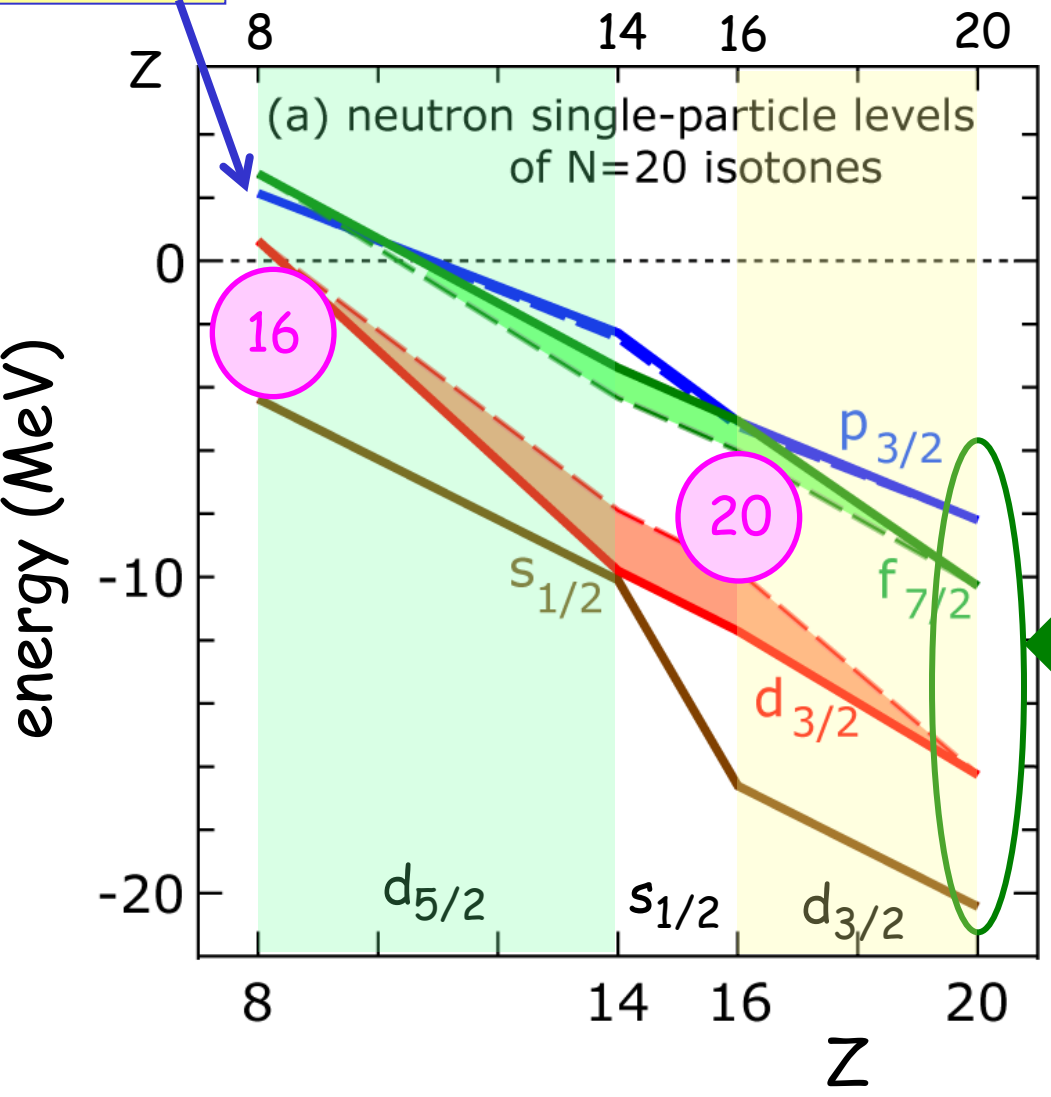
   Tensor force in nuclear medium is very similar to the bare one as formulated by Renormalization Persistency.
   The central force may be a challenge for microscopic theories.

   This tensor force works well for (e,e'p).

   Rapid shape transition within Si isotopes appears as a consequence of characteristic features of nuclear forces.

Neutron single-particle energies at N=20 for Z=8~20

$p_{3/2}$ low



solid line : full (central + tensor)

dashed line : central only

Tensor force makes changes more dramatic.

These single-particle energies are "normal"

$f_{7/2}$-$p_{3/2}$ 2~3 MeV
N=20 gap ~ 6 MeV

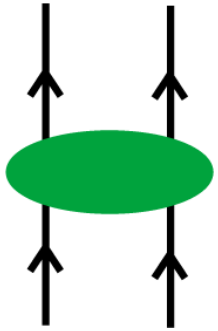
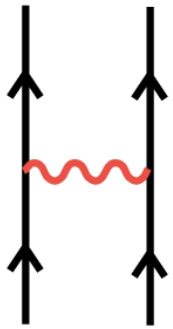
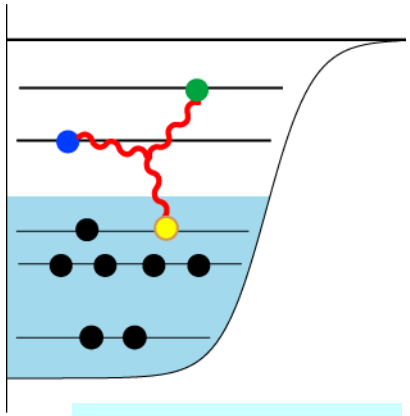
Quick Summary

Dominant monopole forces are due to

(a) central force :
Gaussian
(strongly renormalized)

(b) tensor force :
π + ρ meson
exchange

FM 3NF

V =  +  +  +

μ=1 fm

basic binding

variation of
shell structure

Renormalization
Persistency

limit of
existence

Repulsive T=1
Monopole
in SM eff. int.

END

O, Suzuki, Holt, O, Schwenk, Akaishi, PRL 105 (2010)

Ground-state energies of oxygen isotopes

NN force + *3N*-induced *NN* force

(Fujita-Miyazawa force)