Schiffer Fest
Argonne
September 20-22, 2006

Structure of Exotic Nuclei and the Nuclear Force

Takaharu Otsuka University of Tokyo / RIKEN

I met John for the first time in 1976 or 77 in Tokyo.
We walked together in the Ueno park in an evening.
I was a Ph.D. student in Tokyo, but courageous enough to asked to produce more 2-body matrix elements.

The effective interaction between nucleons deduced from nuclear spectra*

John P. Schiffer

Argonne National Laboratory, Argonne, Illinois 60439 and University of Chicago, Chicago, Illinois 60637

William W. True

University of California, Davis, California 95616

Two-body matrix elements of the residual nucleon–nucleon interaction are extracted from experimental data throughout the periodic table and are used to determine the ranges and well depths of various components of a local interaction. The $T = 1$ even and odd components of the central interaction both definitely require two wells with different ranges; a shorter-range attractive well with a longer-range repulsive one. The need for a tensor interaction and a two-body spin–orbit interaction is also explored and their inclusion improves the fit slightly.

Reviews of Modern Physics, Vol. 48, No. 2, Part I, April 1976

191

But, we did not communicate for a quarter century.

In the meantime, ...

New things have emerged
in nuclear physics.....

Let me discuss one of them,
shell structure of exotic nuclei.

Single particle motion in the nucleus

- is determined basically by a potential like a Woods-Saxon with a spin-orbit splitting term,

- has magic numbers 2, 8, 20, 28, 50, 82 ,…., as Mayer and Jensen have proposed,

- can be basically reproduced by theories (Skyrme or Gogny) consisting of central (finite-range and density-dependent) and 2-body *LS* forces.

→ The relative locations among single-particle orbits do not change much.

The magic numbers are common for all nuclei, stable or unstable (exotic), while can be broken by deformation occasionally.

This has been widely conceived for half a century.

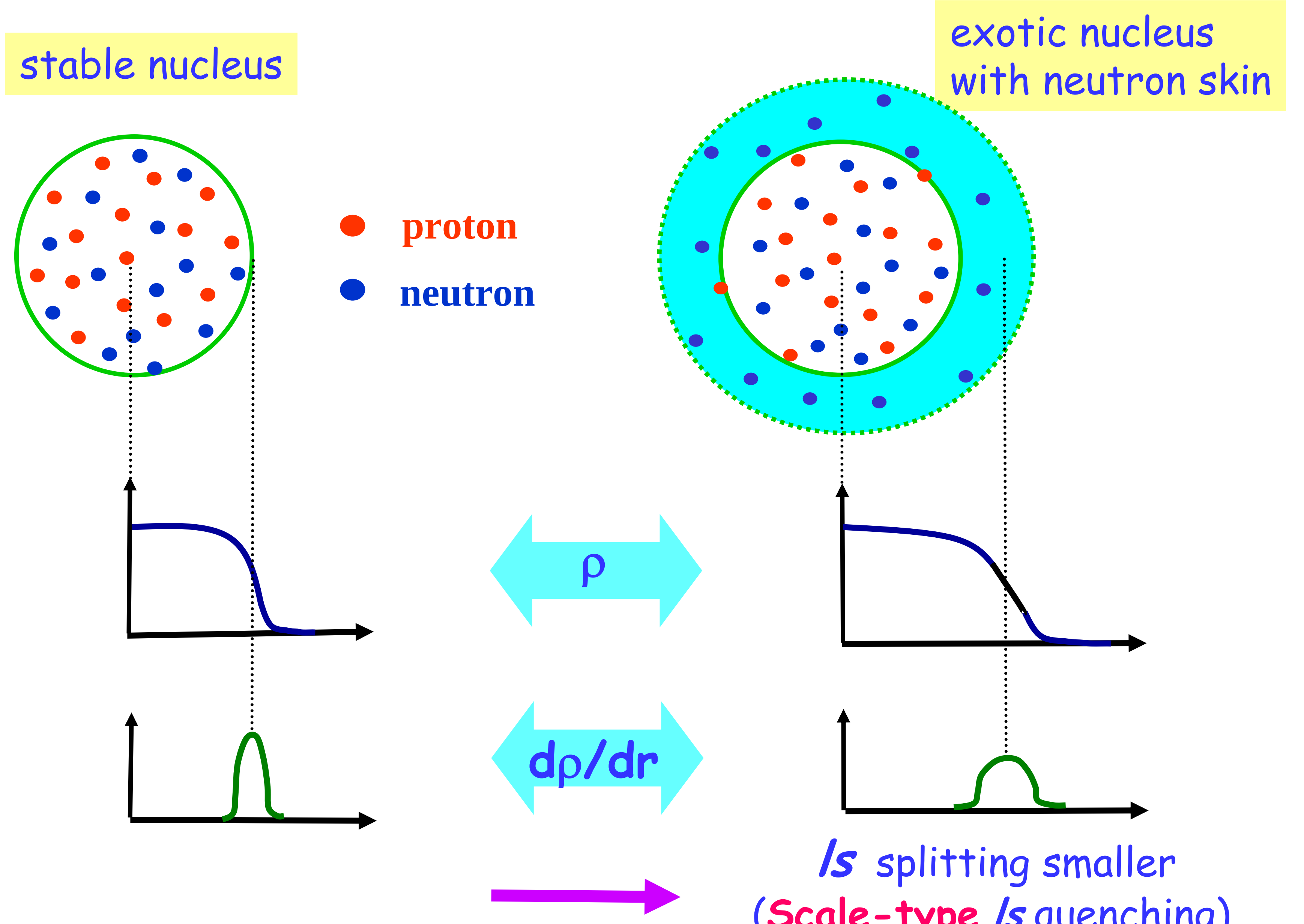
In 1990's, extensive studies on exotic nuclei have started.

A generally conceived idea or hope :

Excess neutrons in halo or skin have more diffuse surface.

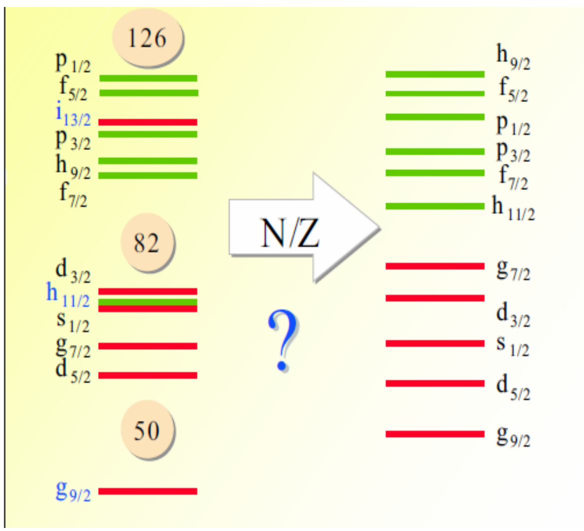
See next 2 pages (*LS* cartoon)

Conventional image of *ls* splitting change



ls splitting smaller
(Scale-type *ls* quenching)

From RIA Physics White Paper



shell structure. The bunching of the energy levels that is endemic to shell structure depends on the form and the shape of the average mean field potential in which the hadrons are moving. With a diffuse surface region, the spin-orbit force may be weakened. Some

In 1990's, extensive studies on exotic nuclei have started.

A generally conceived idea or hope :

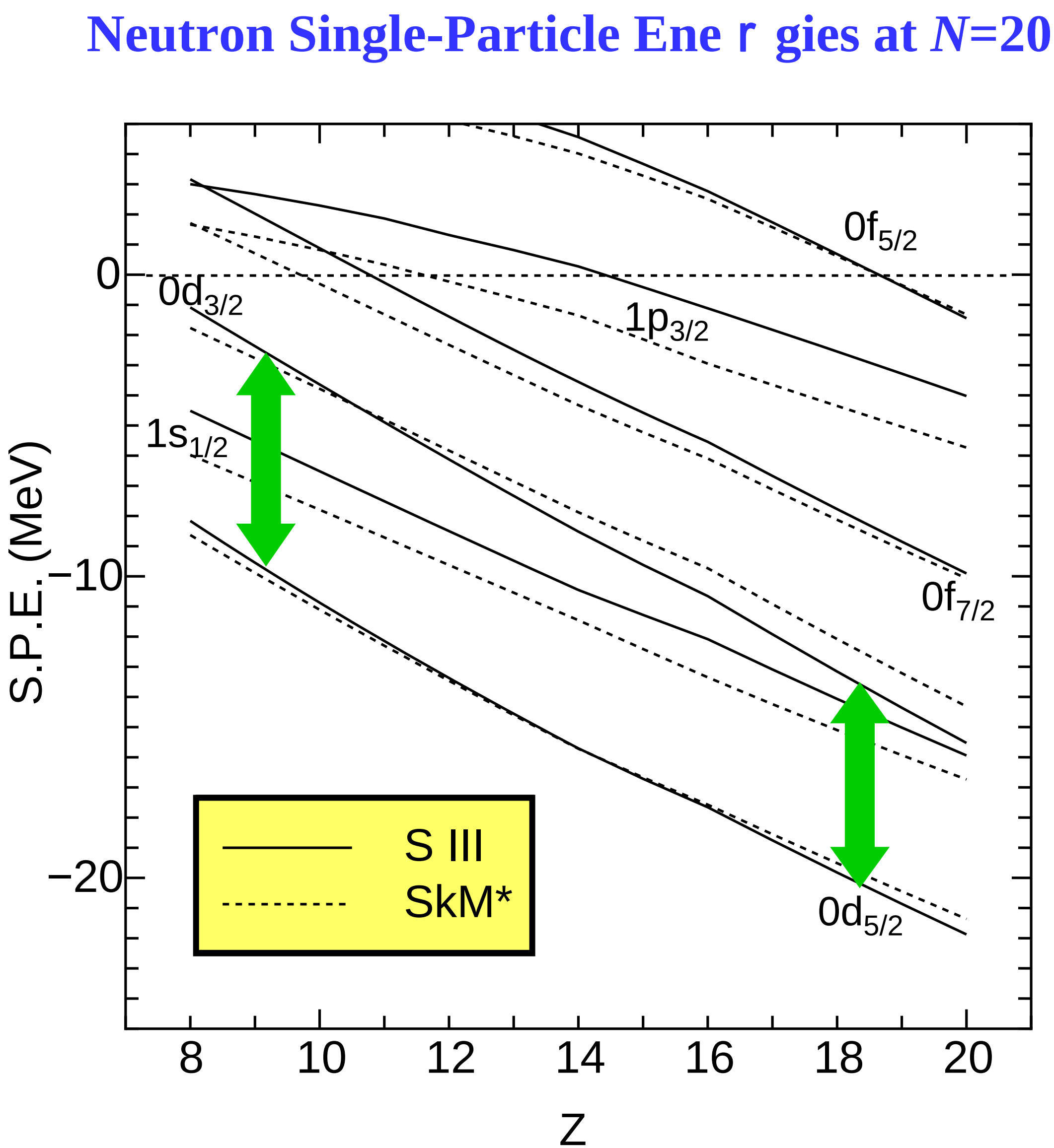
Excess neutrons in halo or skin have more diffuse surface.

See next 2 pages (*LS* cartoon)

This mechanism was expected to be a major driving force.

But, in exotic nuclei studied actually, → HF results

Hartree-Fock energies by Skyrme Hartree-Fock



The shell structure remain rather unchanged

-- orbitals shifting together

-- change of potential depth

~ Woods-Saxon.

In 1990's, extensive studies on exotic nuclei have started.

A generally conceived idea or hope :

Excess neutrons in halo or skin have more diffuse surface.

See next 2 pages (*LS* cartoon)

This mechanism was expected to be a major driving force.

But, in exotic nuclei studied actually, → HF results

Nothing particular would happen between stability line and dripline ?

Too sad

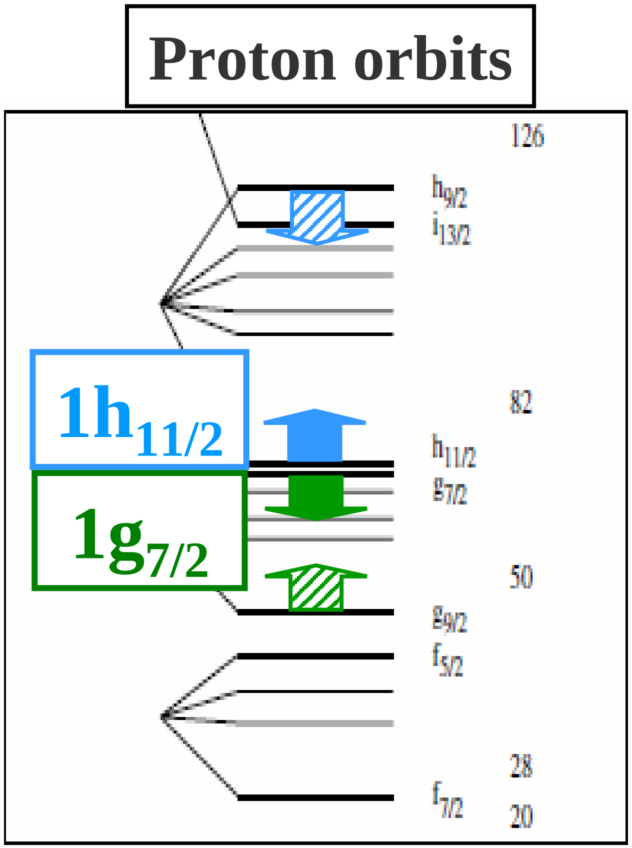
Ozawa, Tanihata et al. "discovered" that neutron separation energies shows strange behavior, and tried to explain it in connection to neutron halo (PRL 84, 5493 (2000)). But, it happens without halo.

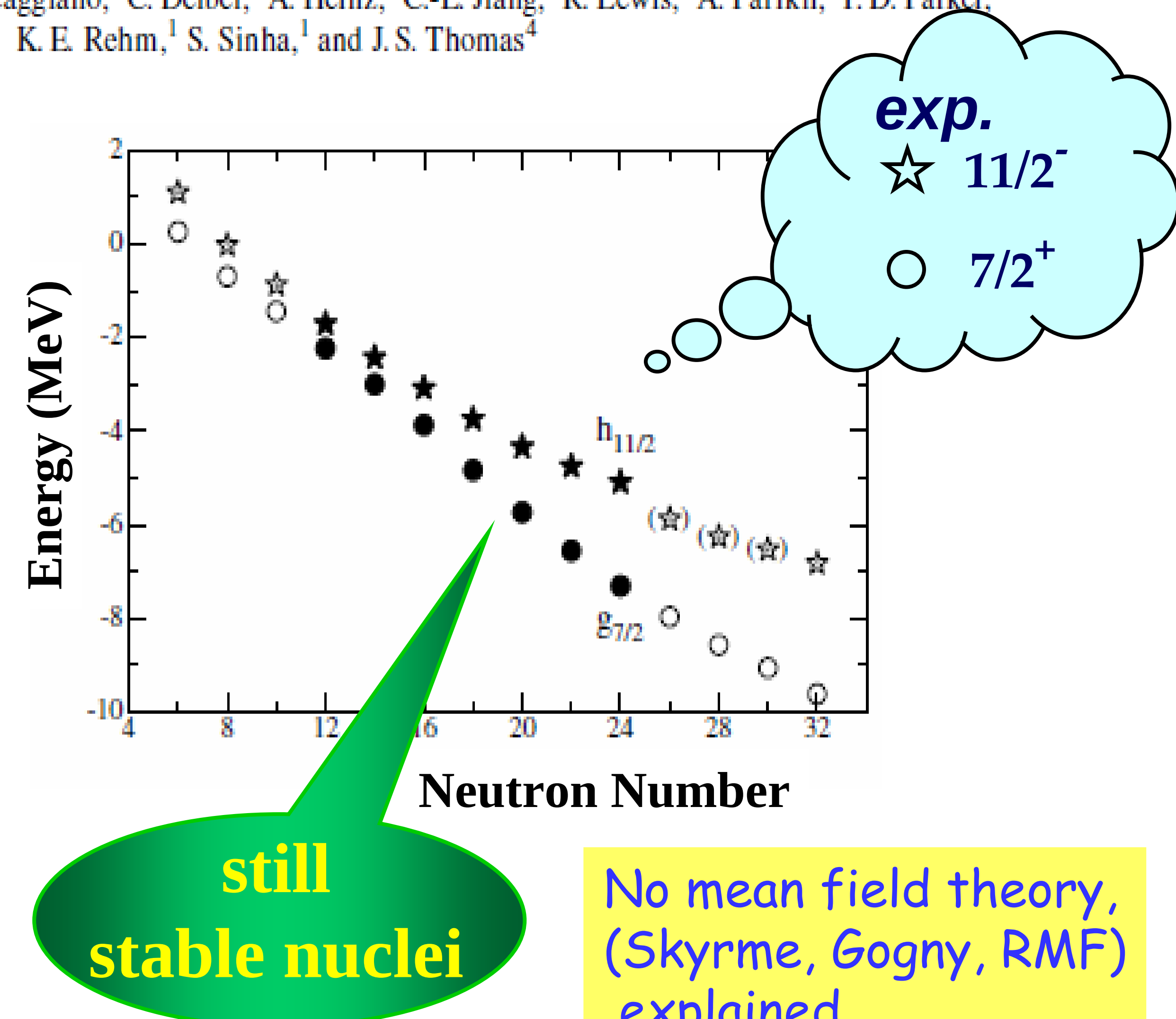
A few years later,
the quenching of spin-orbit
splitting was studied
by John and his company
with John's favorite toy,
transfer reaction.

VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

J. P. Schiffer,[1] S. J. Freeman,[1,2] J. A. Caggiano,[3] C. Deibel,[3] A. Heinz,[3] C.-L. Jiang,[1] R. Lewis,[3] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] S. Sinha,[1] and J. S. Thomas[4]





No mean field theory, (Skyrme, Gogny, RMF) explained.

Independently,
I was trying to see whether or not
the shell structure can be changed
by the *NN* interaction
even if the dripline is still far away,
and if so, how it occurs.

Finally, the key is found to be the tensor force.

Let me jump to this point,
skipping some history.

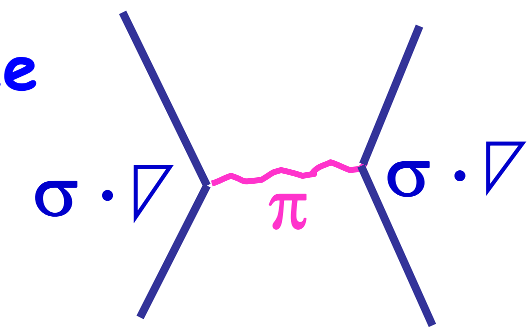
Tensor Interaction

$$V_T = (\tau_1 \tau_2)\,(\,[\sigma_1 \sigma_2]^{(2)}\, Y^{(2)}(\Omega)\,)\, Z(r)$$

contributes only to **S=1** states

relative motion

π meson : primary source



ρ meson (~ π+π) : minor (~1/4) cancellation

Ref: Osterfeld, Rev. Mod. Phys. 64, 491 (92)

Equivalent expressions of tensor force

The standard expression of tensor force may be

$$V_T = (\vec{\tau}_1 \cdot \vec{\tau}_2)\, S_{12}\, V(r)$$

$$S_{12} = 3\,(\vec{s}_1 \cdot \vec{r}/r)\,(\vec{s}_2 \cdot \vec{r}/r) - (\vec{s}_1 \cdot \vec{s}_2)$$

$$= 3\,(\,[\vec{s}_1 \times \vec{s}_2]^{(2)} \cdot [\vec{r} \times \vec{r}]^{(2)}/r^2)$$

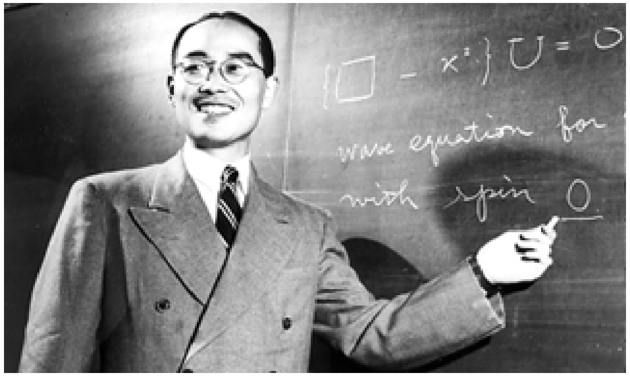
By using $[\vec{r} \times \vec{r}]^{(2)}/r^2 = \sqrt{8\pi/15}\; Y^{(2)}$, **we get**

$$S_{12} = \sqrt{24\pi/5}\,(\,[\vec{s}_1 \times \vec{s}_2]^{(2)} \cdot Y^{(2)})$$

We thus obtain an equivalent expression

$$V_T = \sqrt{24\pi/5}\,(\vec{\tau}_1 \cdot \vec{\tau}_2)\,(\,[\vec{s}_1 \times \vec{s}_2]^{(2)} \cdot Y^{(2)})V(r)$$

The atomic nucleus is bound due to meson exchange.
(Yukawa 1935)



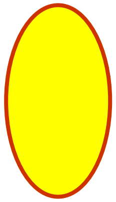
Multiple pion exchanges
→ strong effective central forces in *NN* interaction (as represented by σ meson, *etc.*)
→ nuclear binding

Where can we see one pion exchange ?

One pion exchange ~ Tensor force

First-order tensor force effect in spectroscopy
→ manifestation of pions in nuclei

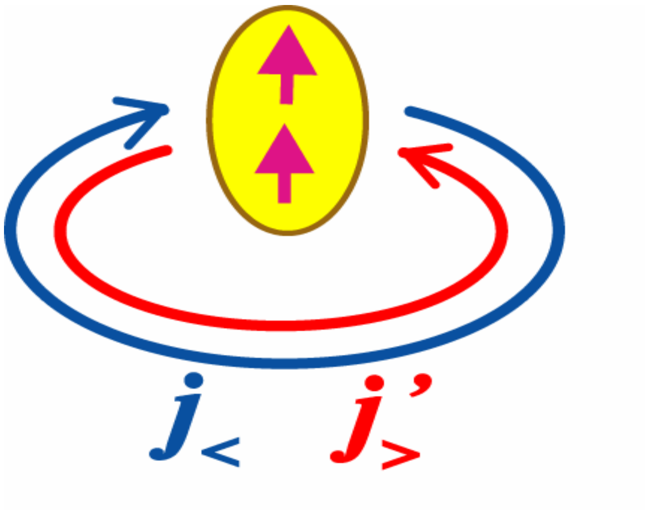
Intuitive Picture

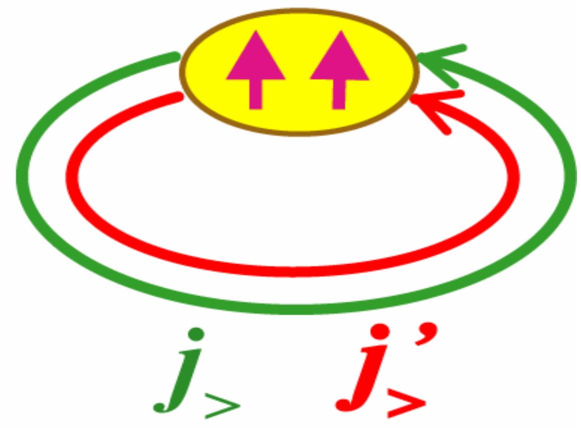


wave function of relative motion

spin of nucleon

large relative momentum **small relative momentum**



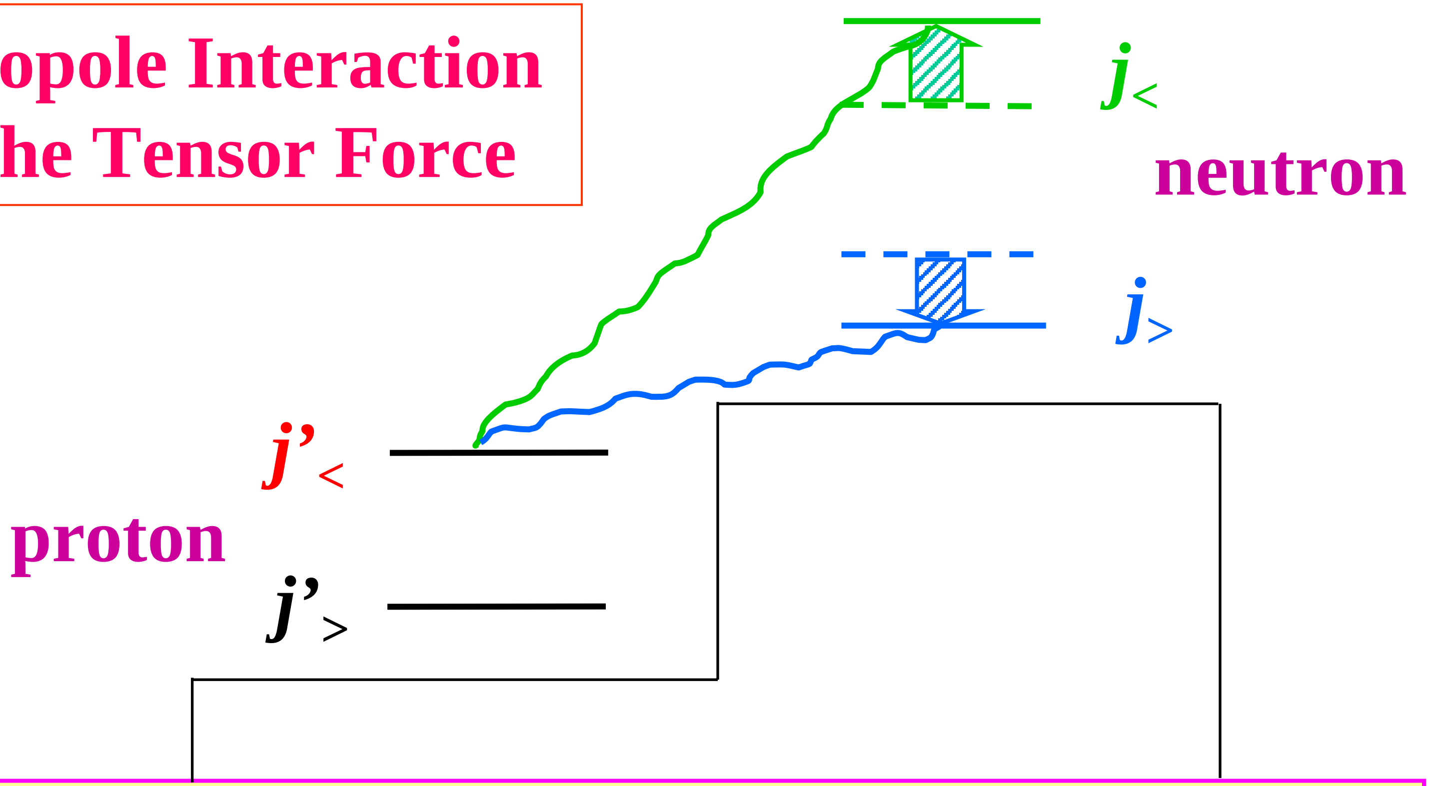


deuteron ⇨ attractive **repulsive**

TO *et al.*, Phys. Rev. Lett. 95, 232502 (2005)

TO *et al.*, Phys. Rev. Lett. 95, 232502 (2005)

Monopole Interaction of the Tensor Force



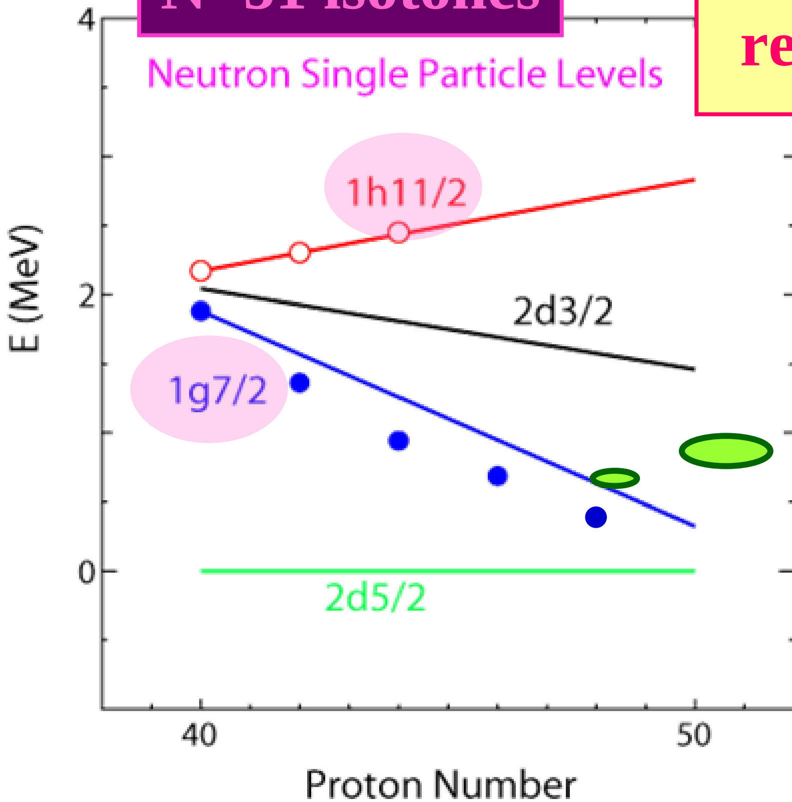
Identity for tensor monopole interaction

$$(2j_> + 1)\ v_{m,T}^{(j' j_>)} + (2j_< + 1)\ v_{m,T}^{(j' j_<)} = 0$$

$v_{m,T}$: monopole strength for isospin T

Changes of N=51 neutron effective single-particle energies from Zr to Sn

N=51 isotones



repulsion between $g_{7/2}$ and $h_{11/2}$

Federman-Pittel mechanism

Lines : $\pi + \rho$ meson tensor

Points : exp. level

protons in $g_{9/2}$

Zr → Sn

shown relative to $d_{5/2}$

Reduction of the Spin-Orbit Splittings at the $N = 28$ Shell Closure

L. Gaudefroy,[1,2] O. Sorlin,[2,1] D. Beaumel,[1] Y. Blumenfeld,[1] Z. Dombrádi,[3] S. Fortier,[1] S. Franchoo,[1] M. Gélin,[2] J. Gibelin,[1] S. Grévy,[2] F. Hammache,[1] F. Ibrahim,[1] K. W. Kemper,[4] K.-L. Kratz,[5,6] S. M. Lukyanov,[7] C. Monrozeau,[1] L. Nalpas,[8] F. Nowacki,[9] A. N. Ostrowski,[5,6] T. Otsuka,[10] Yu.-E. Penionzhkevich,[7] J. Piekarewicz,[4] E. C. Pollacco,[8] P. Roussel-Chomaz,[2] E. Rich,[1] J. A. Scarpaci,[1] M. G. St. Laurent,[2] D. Sohler,[11] M. Stanoiu,[12] T. Suzuki,[13] E. Tryggestad,[1] and D. Verney[1]

Neutron single-particle energies

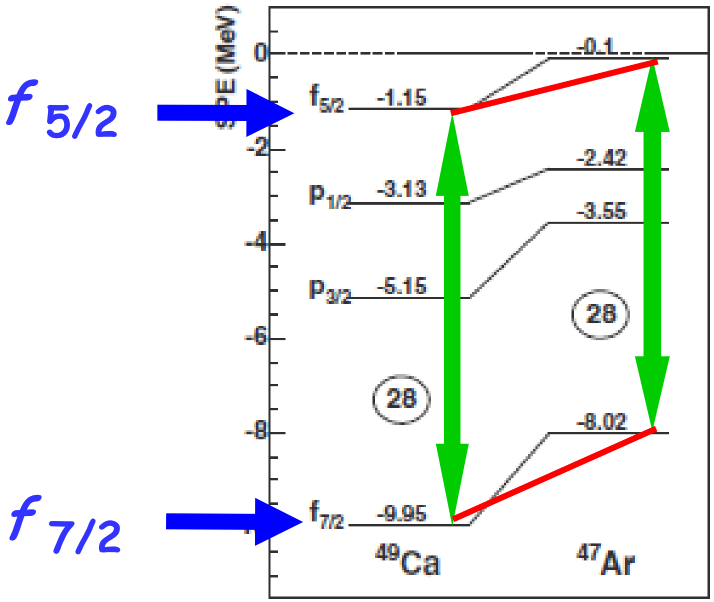


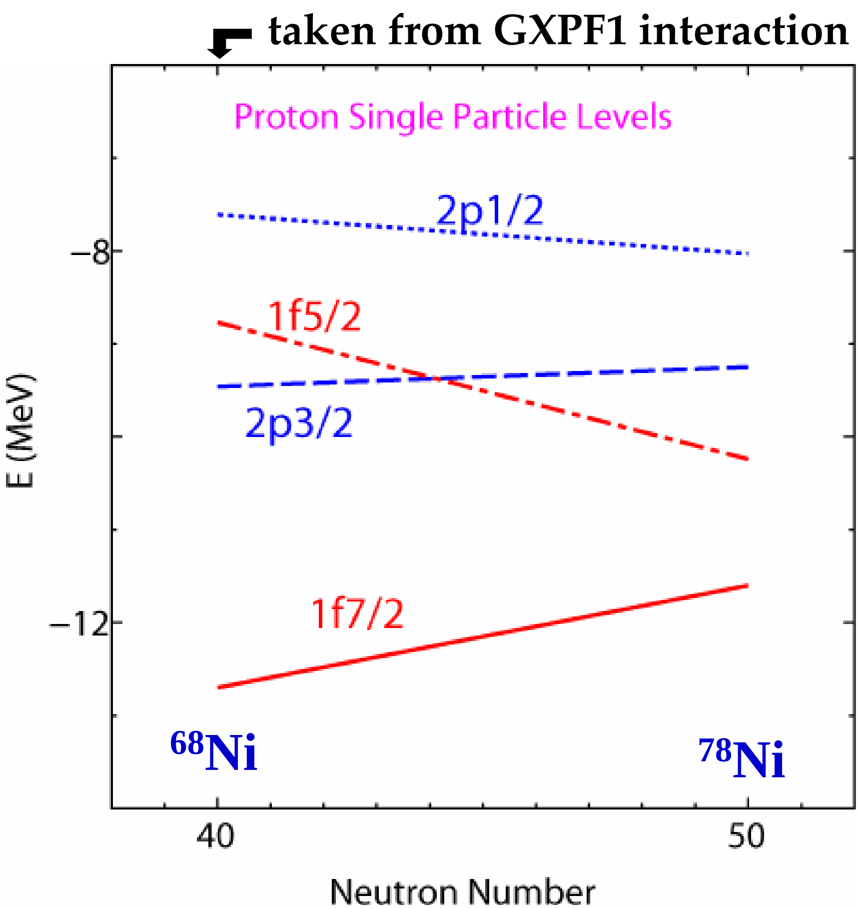
FIG. 3. Neutron single-particle energies (SPE) of the fp orbitals for the $^{47}Ar_{29}$ and $^{49}Ca_{29}$ nuclei (see text for details).

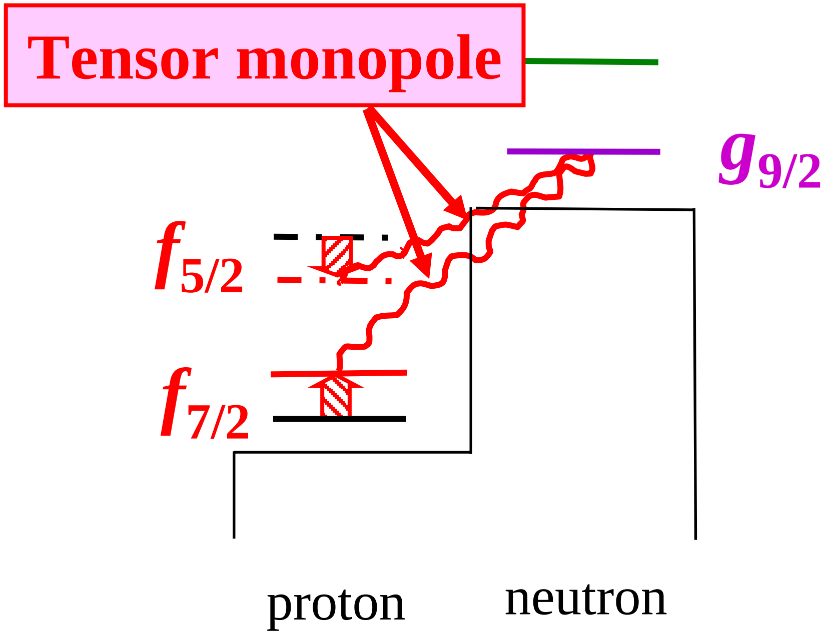
Mean-field models (Skyrme or Gogny) do not reproduce this reduction.

Tensor force effect due to vacancies of proton $d_{3/2}$ in $^{47}_{18}Ar_{29}$: 650 (keV) by $\pi+\rho$ meson exchange.

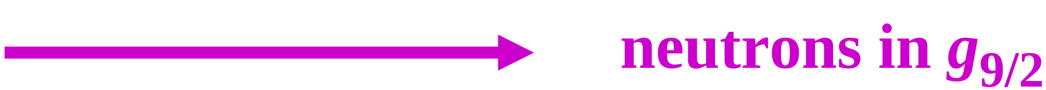
Change of proton single-particle energies due to the tensor force (π + ρ meson exchange)

calculation only

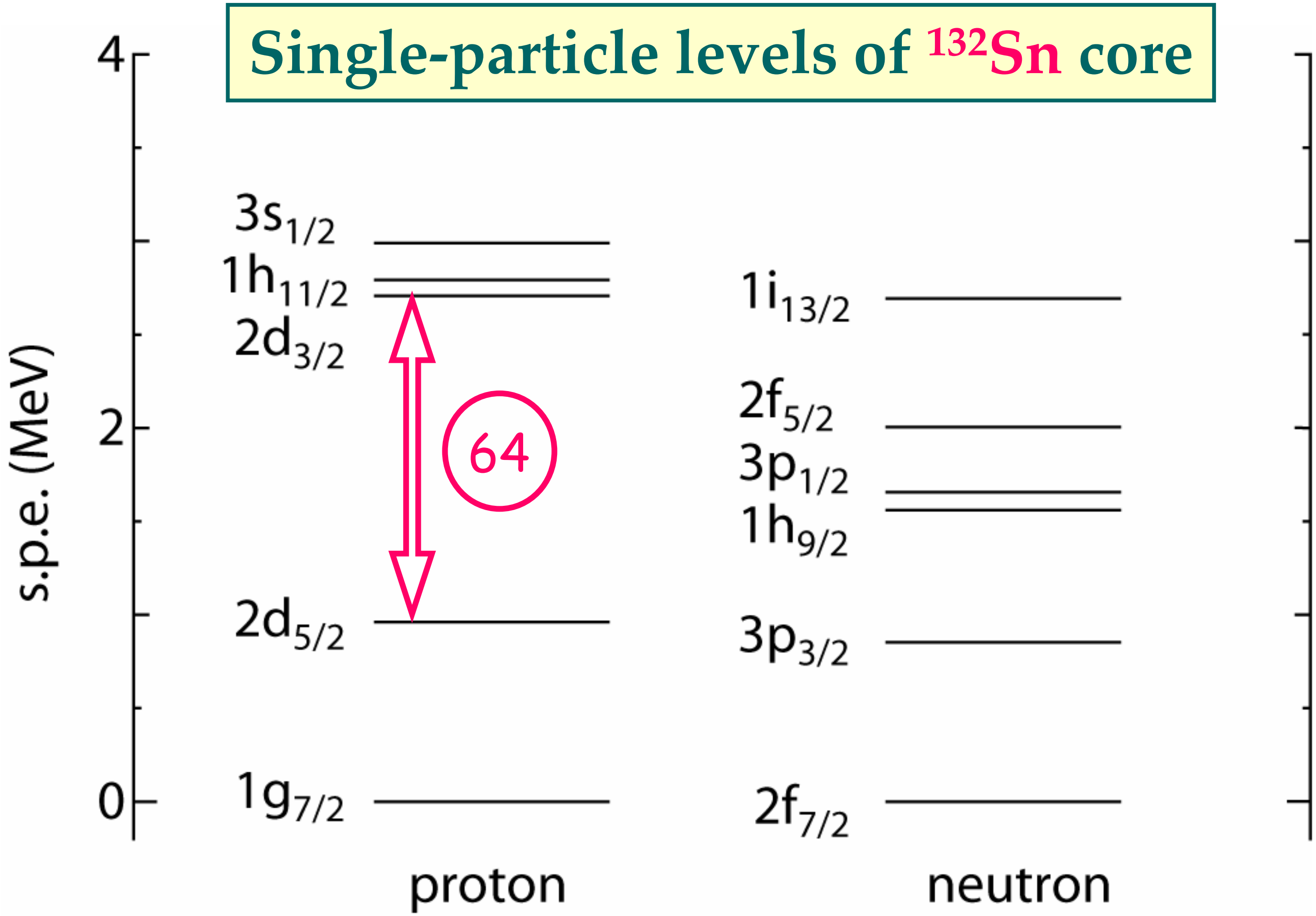




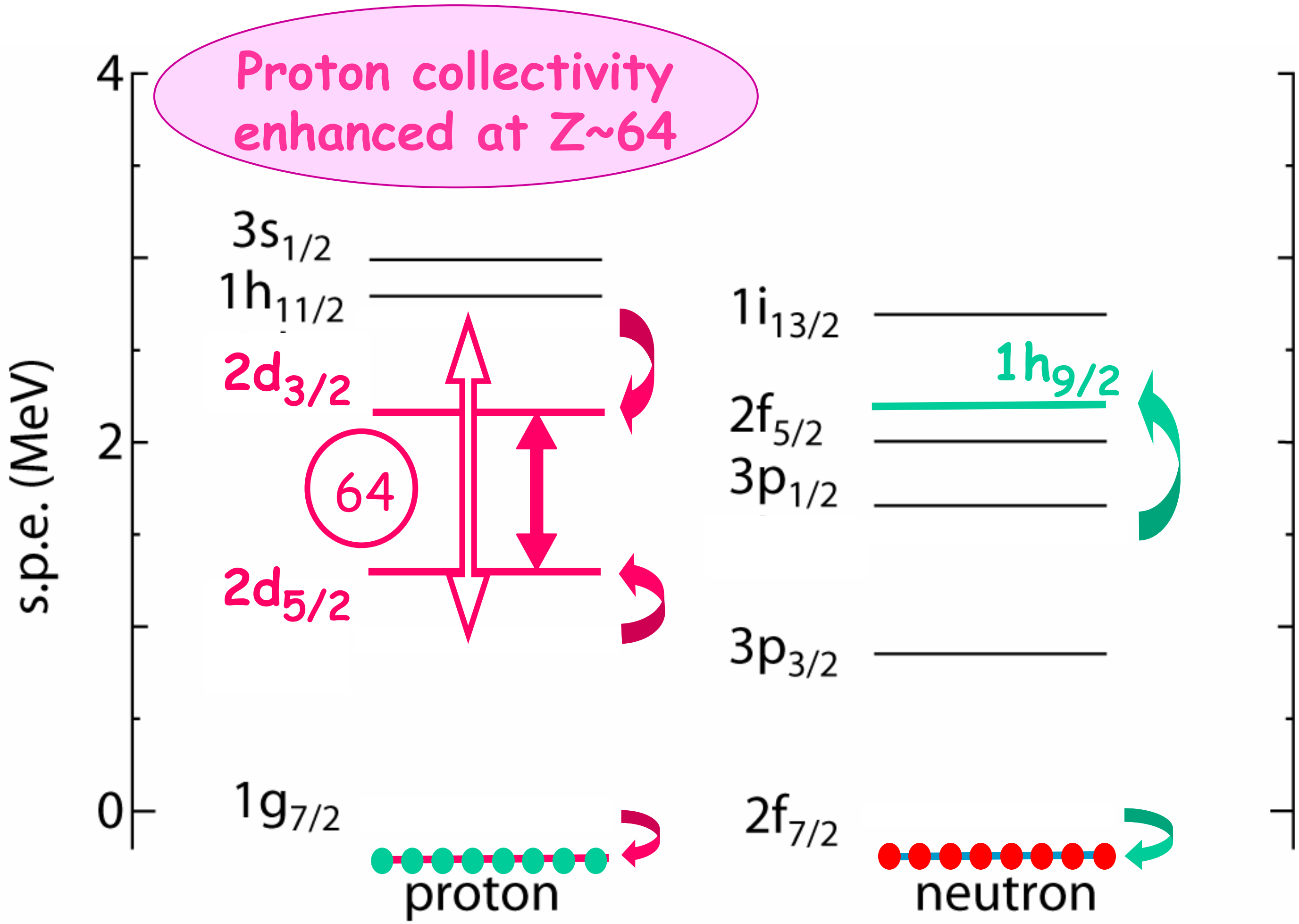
➡ **Low-lying 2^+ levels in Ni,**
M. Sawicka et al.,
Phys. Rev. C68, 044304 (03)



Weakening of Z=64 submagic structure for N~90



Weakening of Z=64 submagic structure for N~90



8 protons in $1g_{7/2}$ pushes up $1h_{9/2}$ by ~1 MeV

8 neutrons in $2f_{7/2}$ reduces the Z=64 gap to the half value

Implementation of tensor interaction into mean field calculations

Gogny interaction (J. Decharge and D. Gogny, 1980)

(1+σσ+ττ+σσττ) (Gauss1 + Gauss2) + Density Dep.

finite range **zero range**

Successful descriptions of various properties with D1S interaction (J.F. Berger et al., Nucl. Phys. A428, 23c (84))

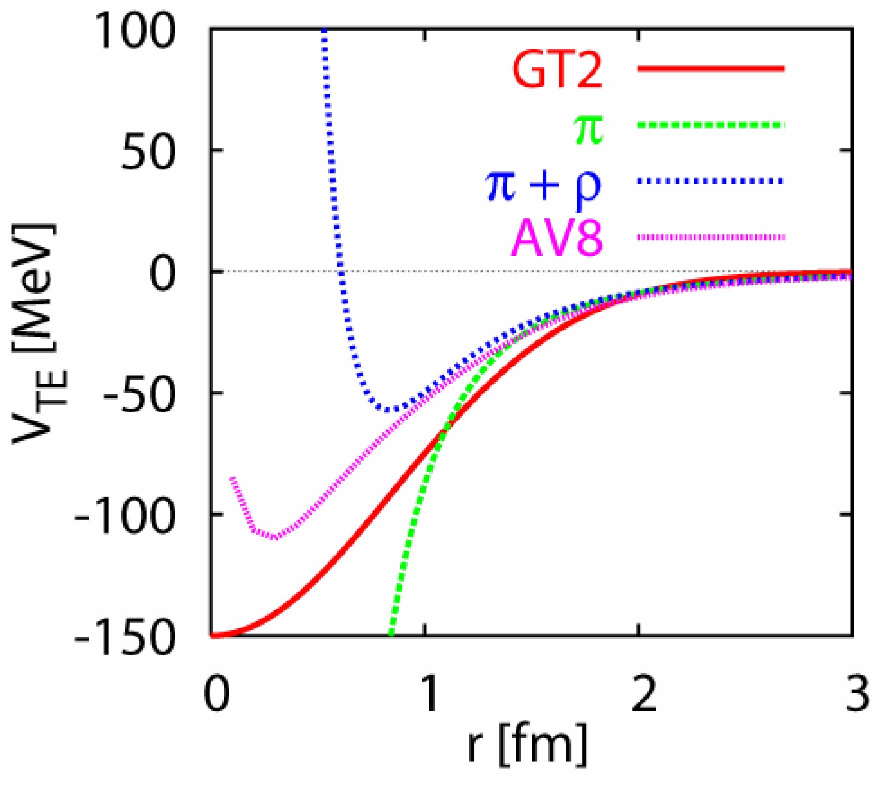
Tensor interaction is added

All parameters are readjusted

Nuclear matter properties reproduced with improvement of imcompressibility

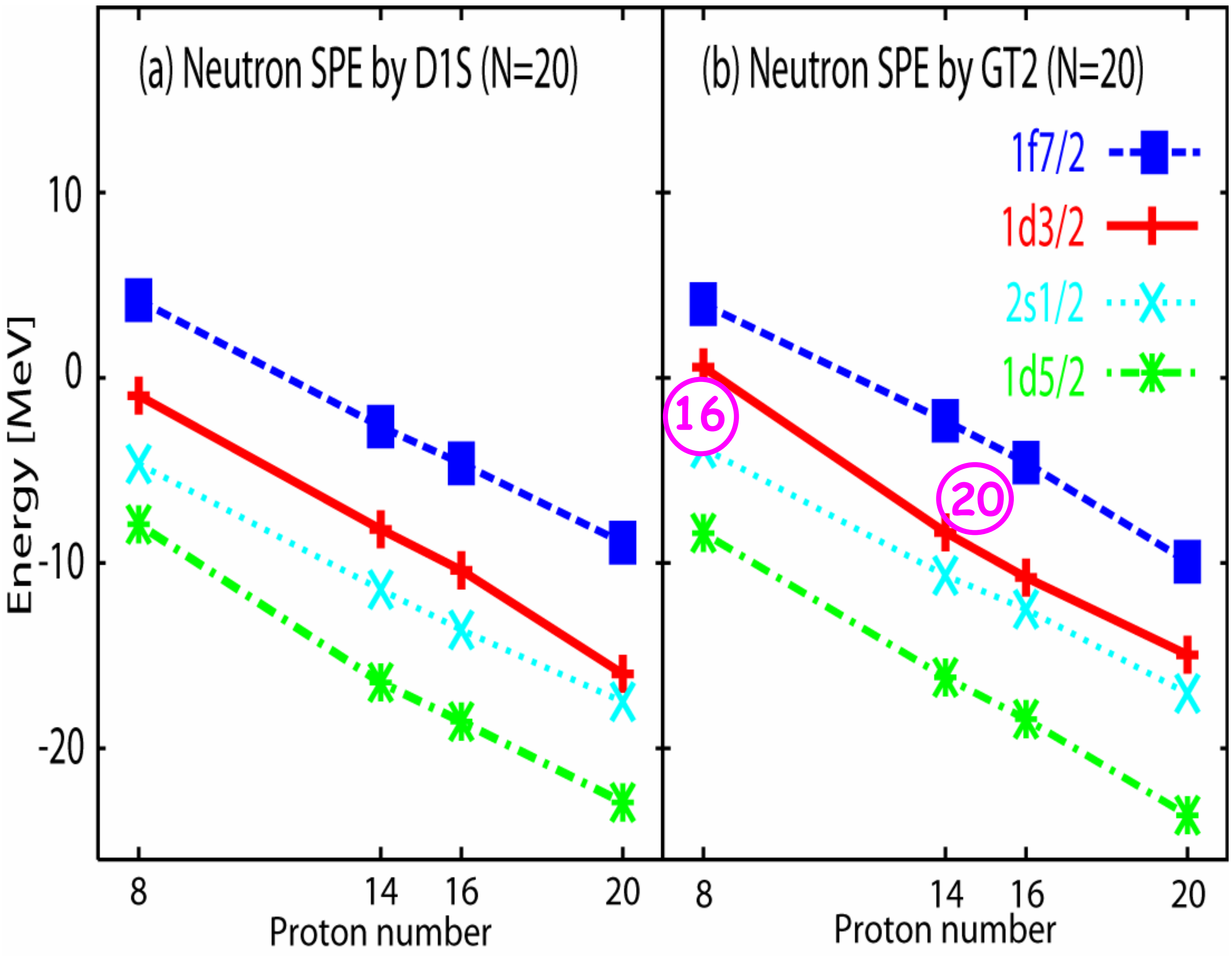
Gogny-Tokyo interaction - 2 (GT2)

Triplet-Even potential due to the Tensor force



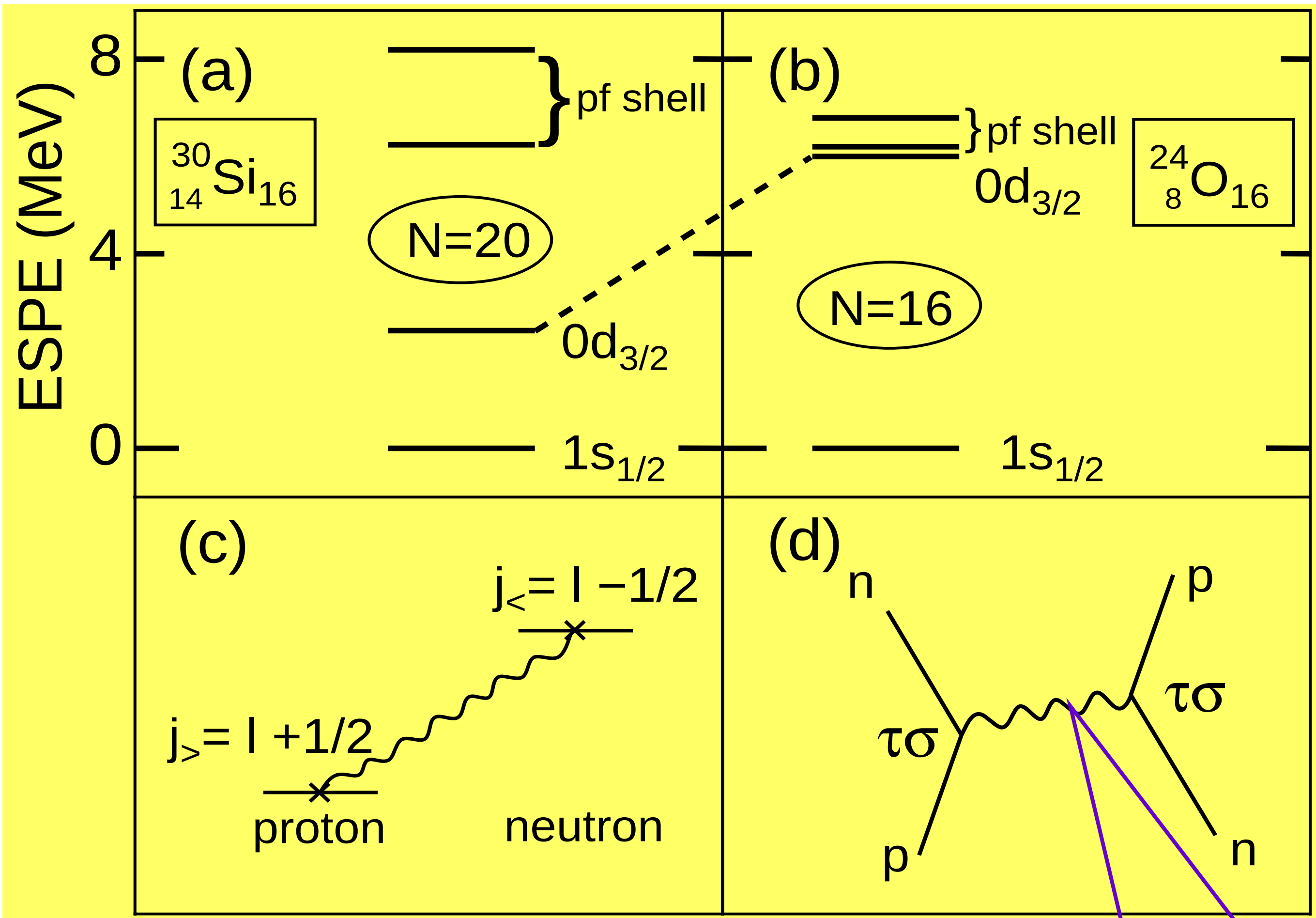
Two Gogny(-type) interactions : D1S and GT2

w/o tensor | with tensor



The same change as in the shell model with SDPF-M int.

Tensor interaction is the primary origin of the p-n $j_>$-$j_<$ coupling.

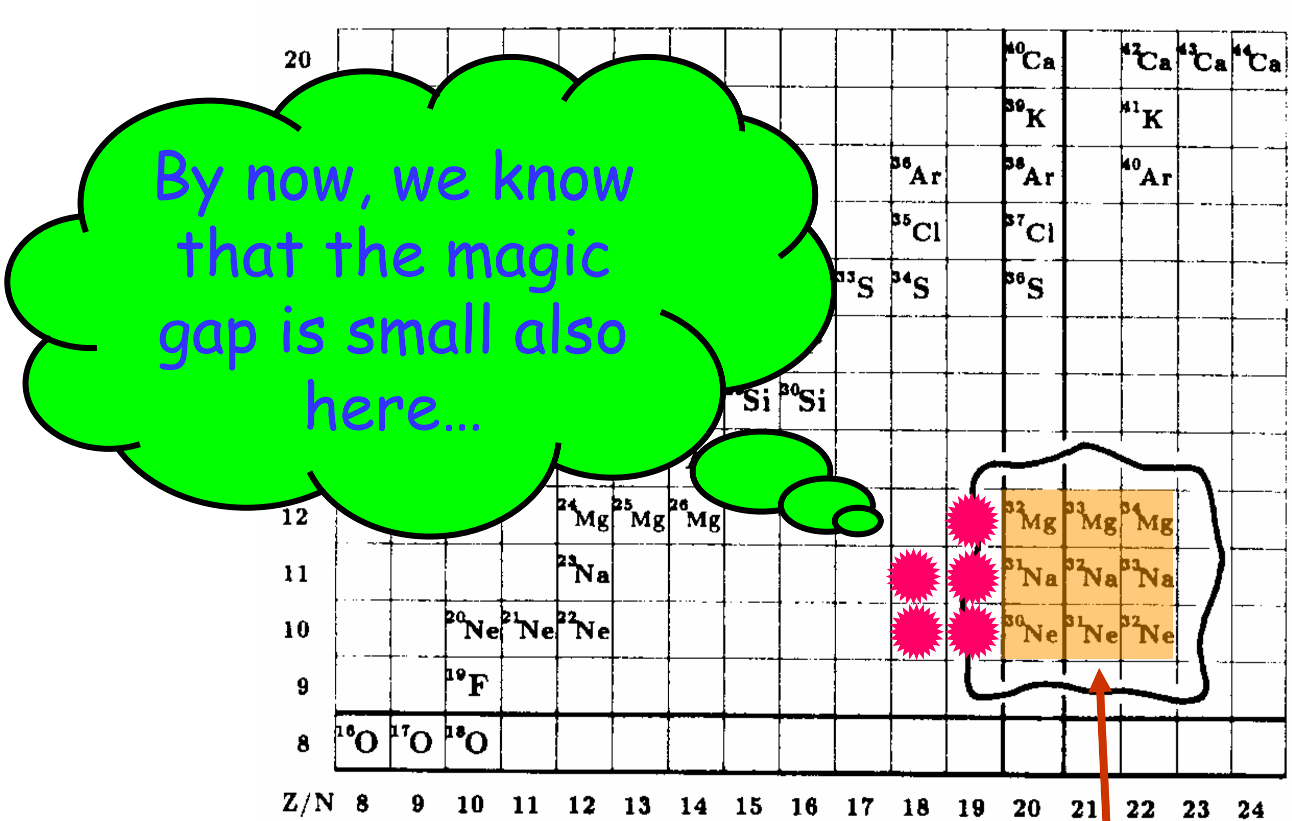


σστ τ central

Tensor

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

Island of Inversion is being changed …



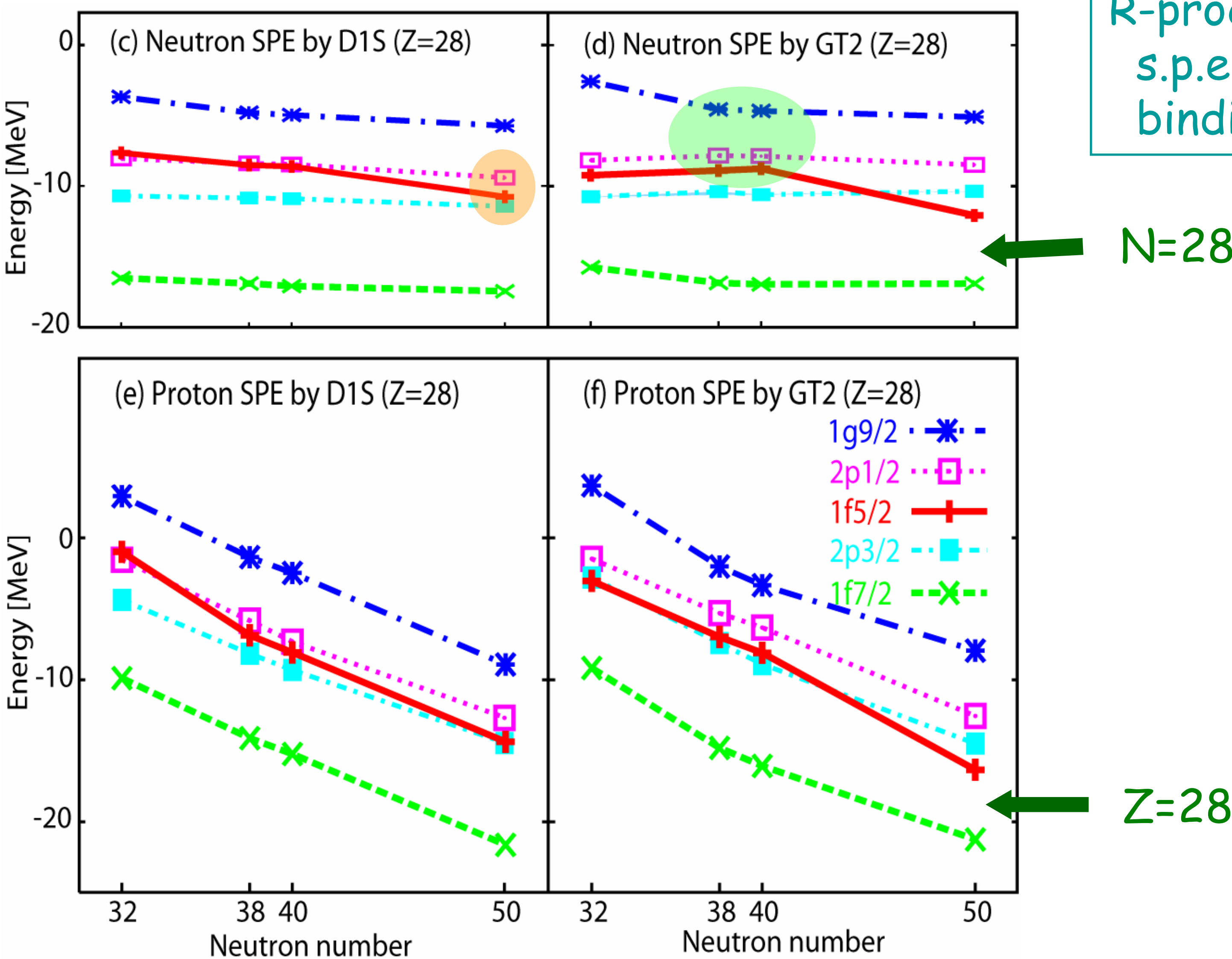
Island of Inversion :
region of intruder ground states

Only 9 nuclei in the original model (1990)

Phys. Rev. C 41, 1147 (1990), Warburton, Brown and Becker

Single-particle energies of exotic Ni isotopes

w/o tensor | with tensor



relevance to R-process
- s.p.e.'s
- binding energies

TO, Matsuo, Abe, Phys. Rev. Lett. *in press* (2006)

2-body *LS* force

$$V_{\mathrm{LS}} = V_{\mathrm{LS}}(r)\boldsymbol{L}_{12}\cdot(\boldsymbol{s}_1+\boldsymbol{s}_2)$$
$$\simeq iW_0(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\overleftarrow{\boldsymbol{k}}\times\delta(\boldsymbol{r})\overrightarrow{\boldsymbol{k}}$$

Vautherin - Brink

One-body mean potential

Proton

$$U_{\mathrm{p}} \propto \frac{d}{dr}(\rho_{\mathrm{n}}+2\rho_{\mathrm{p}})$$

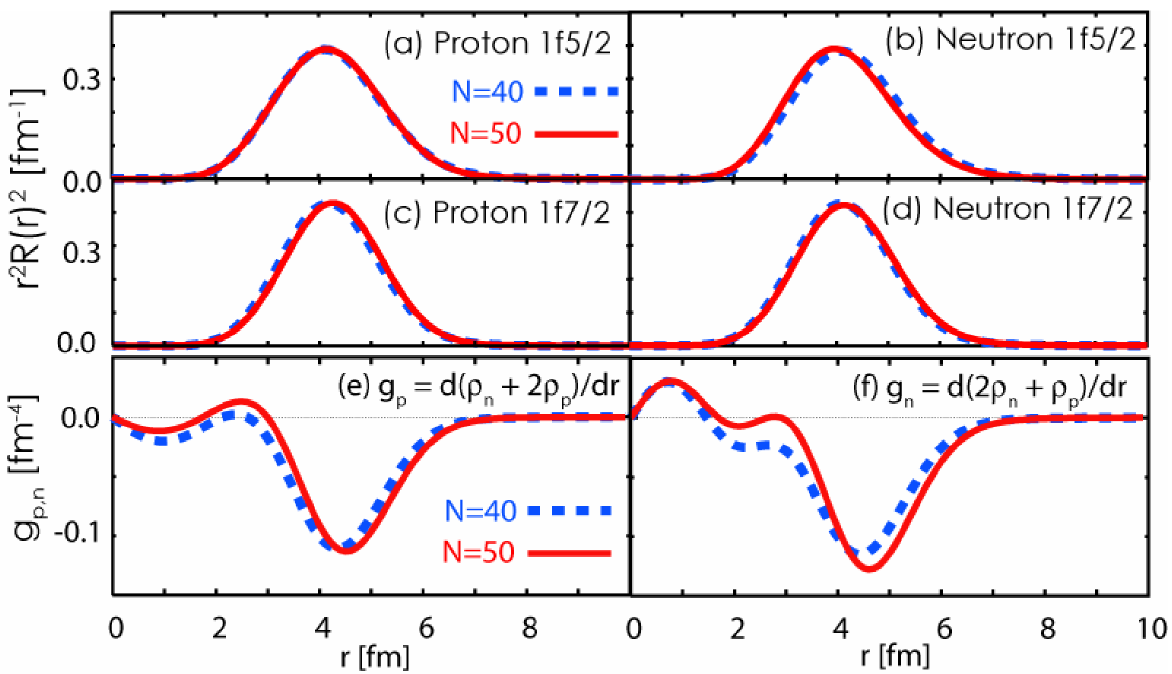
Neutron

$$U_{\mathrm{n}} \propto \frac{d}{dr}(2\rho_{\mathrm{n}}+\rho_{\mathrm{p}})$$

Wave functions of f7/2 and f5/2 and derivatives of densities

N=40 (dashed)
N=50 (solid)

proton neutron



f5/2

f7/2

derivatives of densities

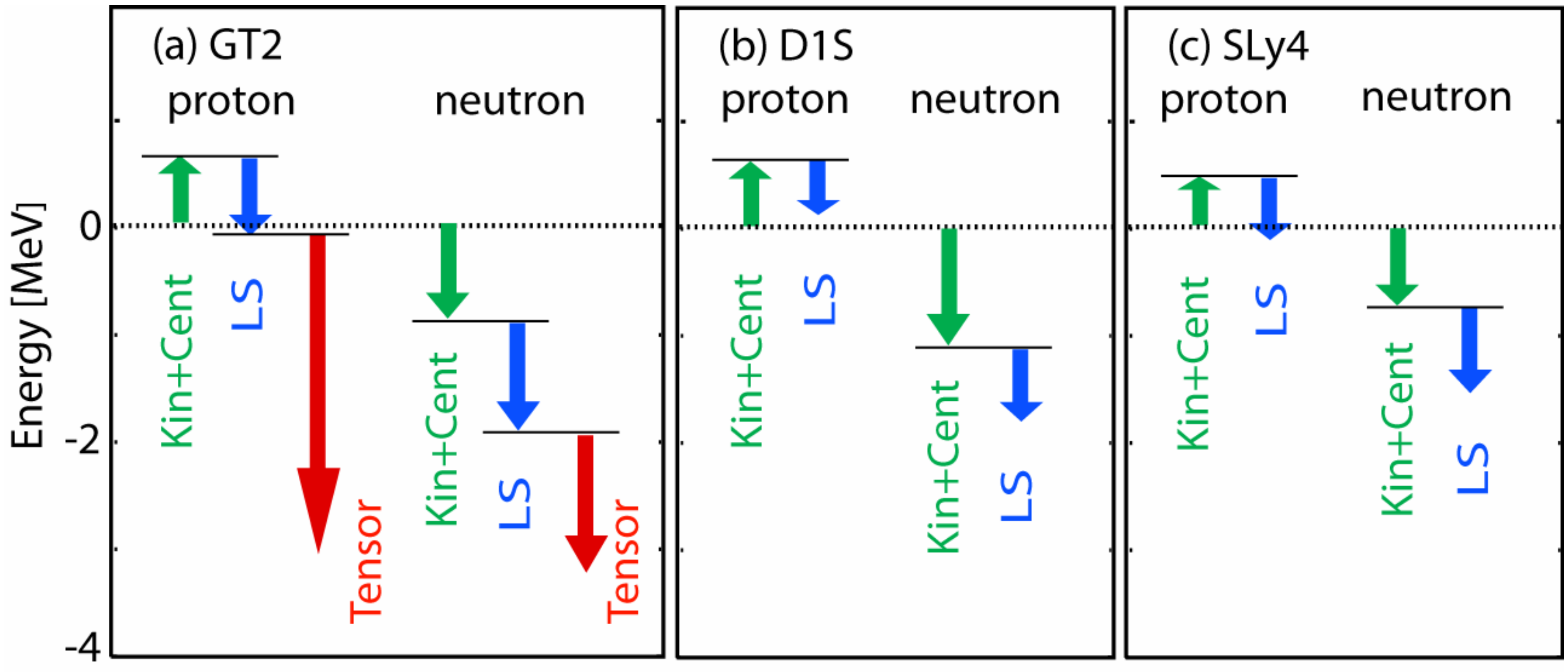
Peaks of derivatives do not get lower, but move outwards.

Position-type *ls* quenching

Scale-type *ls* quenching

TO, Matsuo, Abe, Phys. Rev. Lett. *in press* (2006)

Contributions of Kinetic+Central, 2-body LS, and Tensor components to the change of f7/2 - f5/2 gap in going from N=40 to N=50 (g9/2 occupancy)

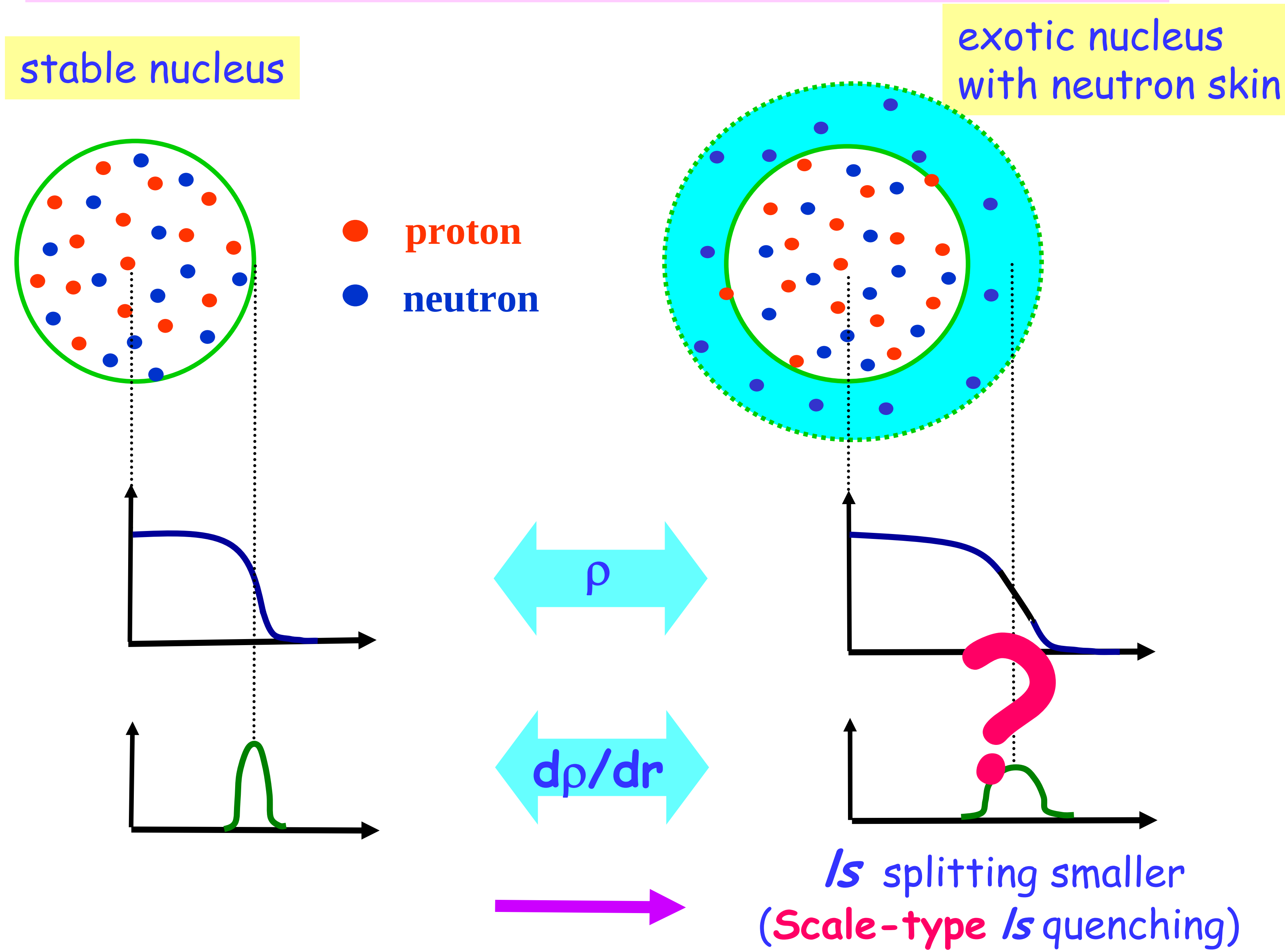


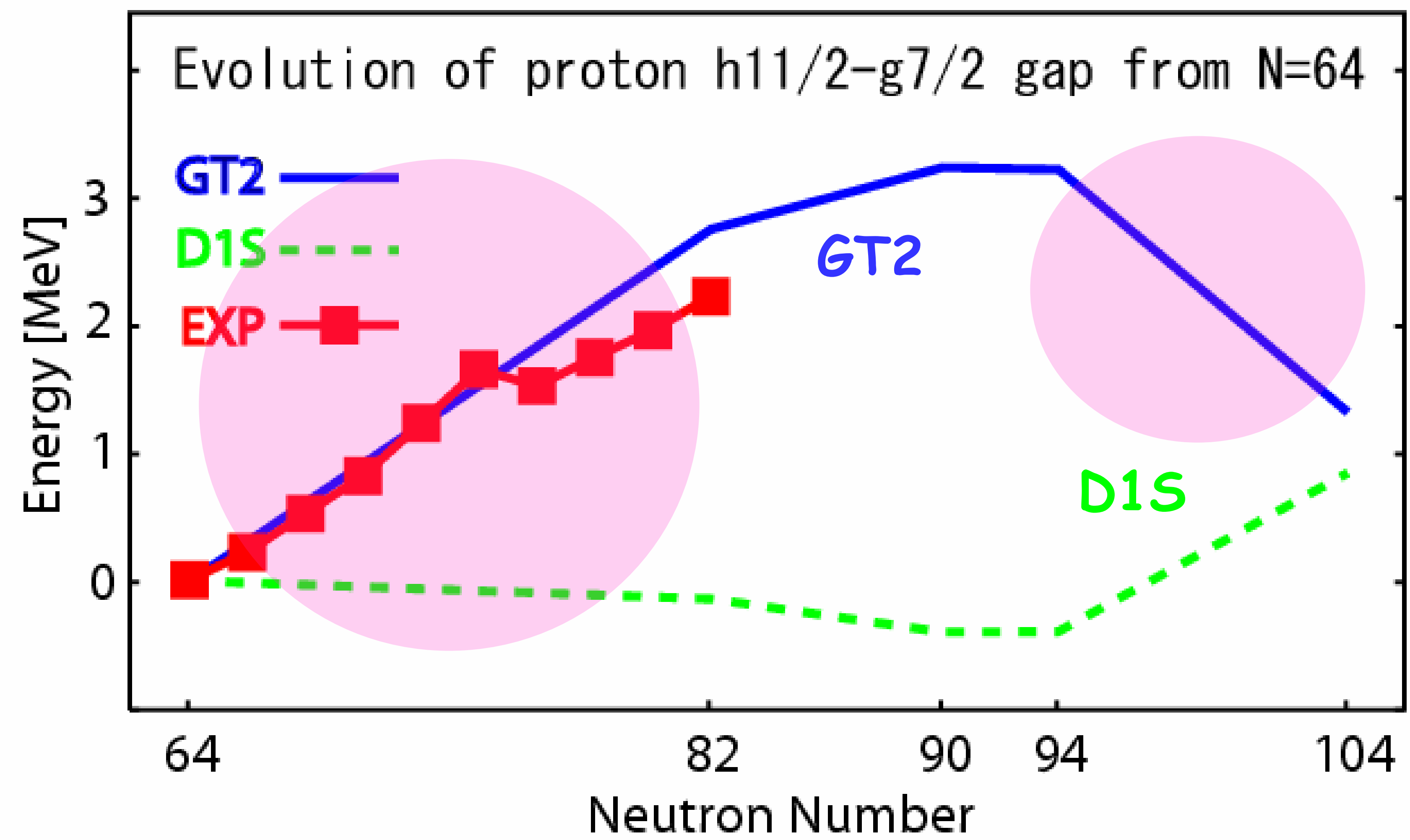
Kin+Cent and LS : almost the same among three calculations

Tensor : largest effect

TO, Matsuo, Abe, Phys. Rev. Lett. *in press* (2006)

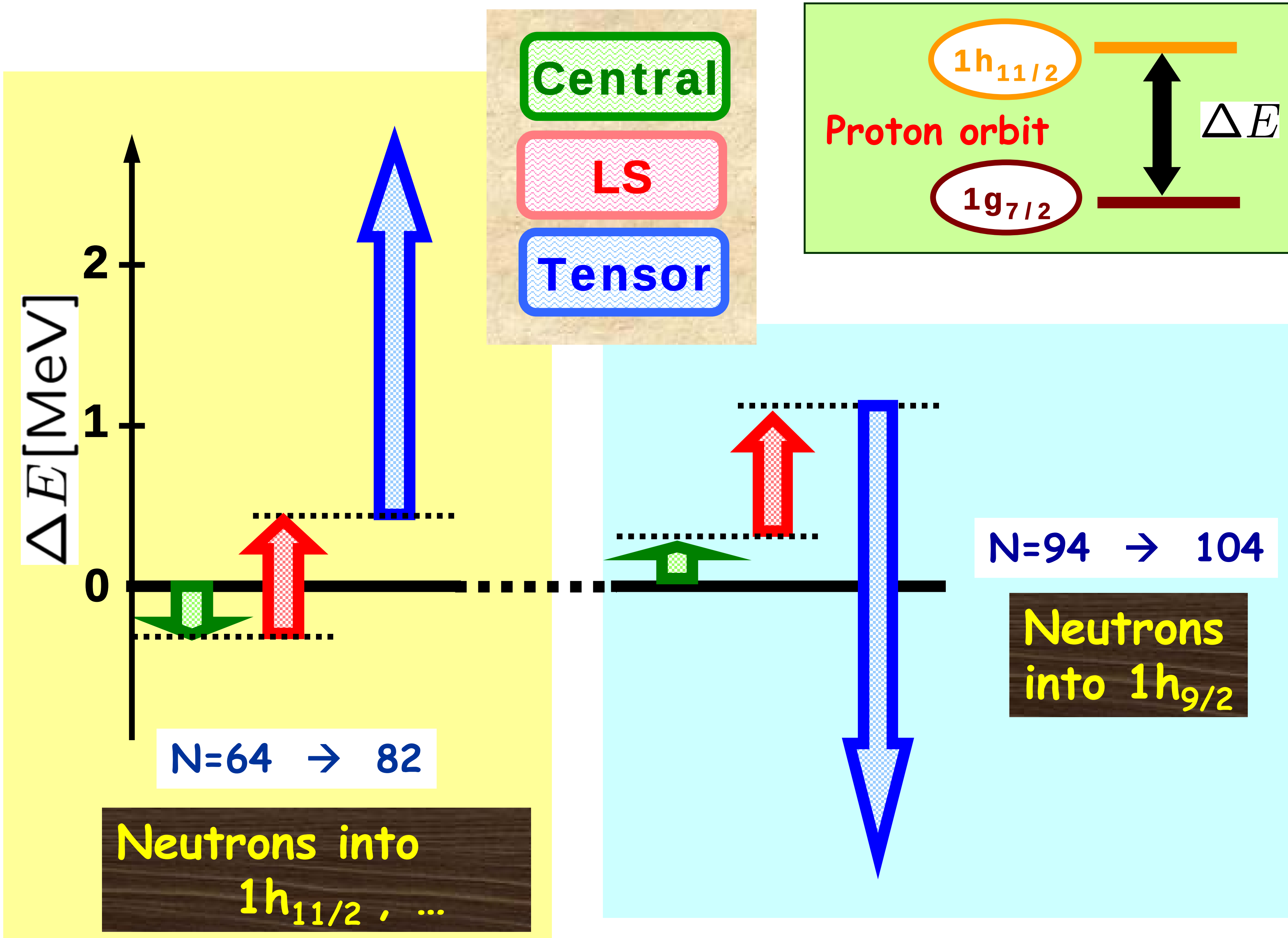
Conventional image of *ls* splitting change





RIBF region

post-RIBF region



Central
LS
Tensor
$1h_{11/2}$
Proton orbit
$1g_{7/2}$
ΔE
ΔE[MeV]
2
1
0
N=64 → 82
Neutrons into $1h_{11/2}$, ...
N=94 → 104
Neutrons into $1h_{9/2}$

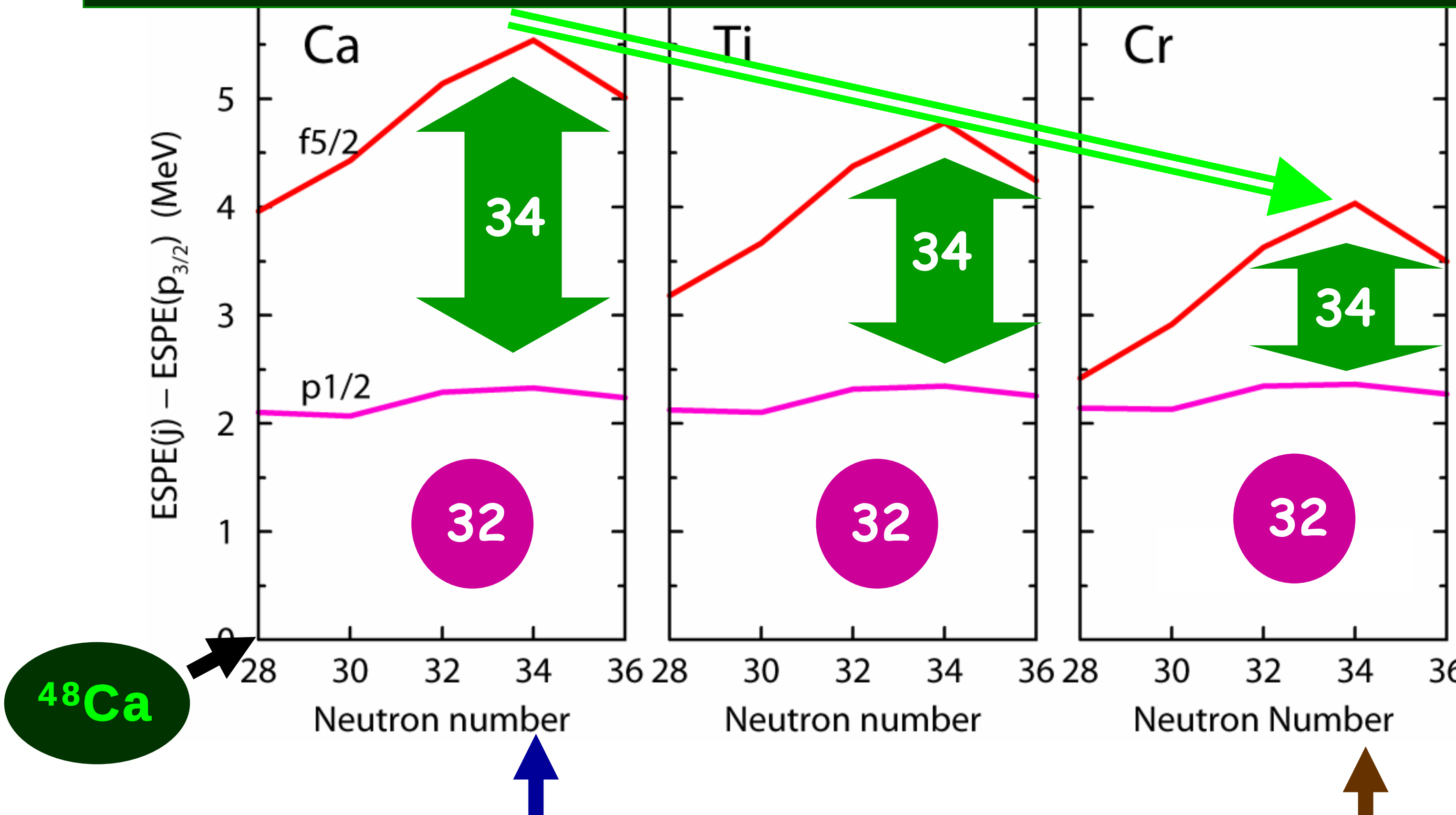
New magic numbers N=32 and 34 :

Their appearance and disappearance

Frontier of RI-beam experiments
(currently impossible)

Effective single-particle energies of Ca, Ti and Cr isotopes calculated by GXPF1B interaction

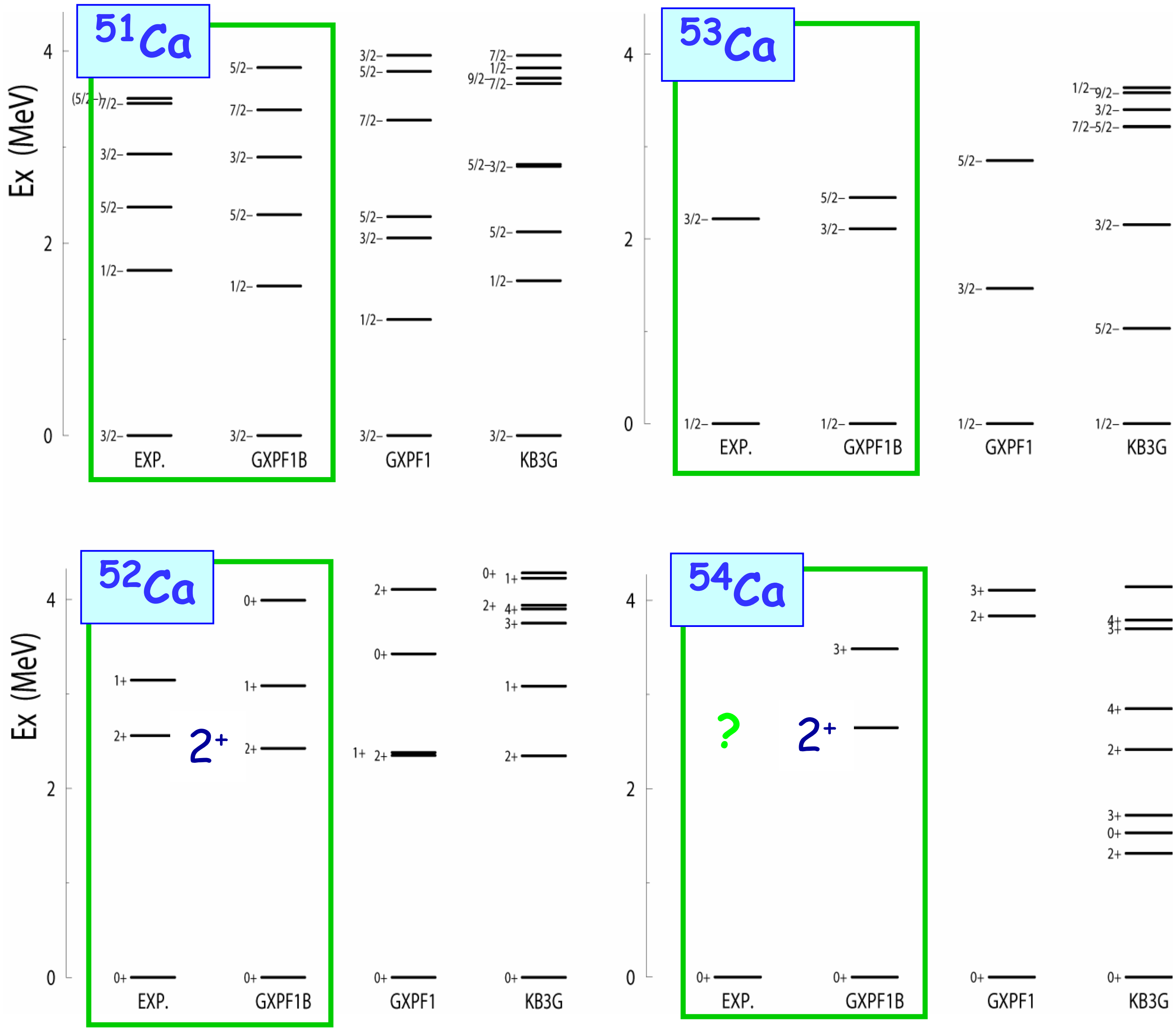
Monopole effect of tensor force (f7/2 occupancy)



Gap = 2 MeV at N=32 and 3 MeV at N=34

Gap = 2 MeV at N=32 and 1.5 MeV at N=34

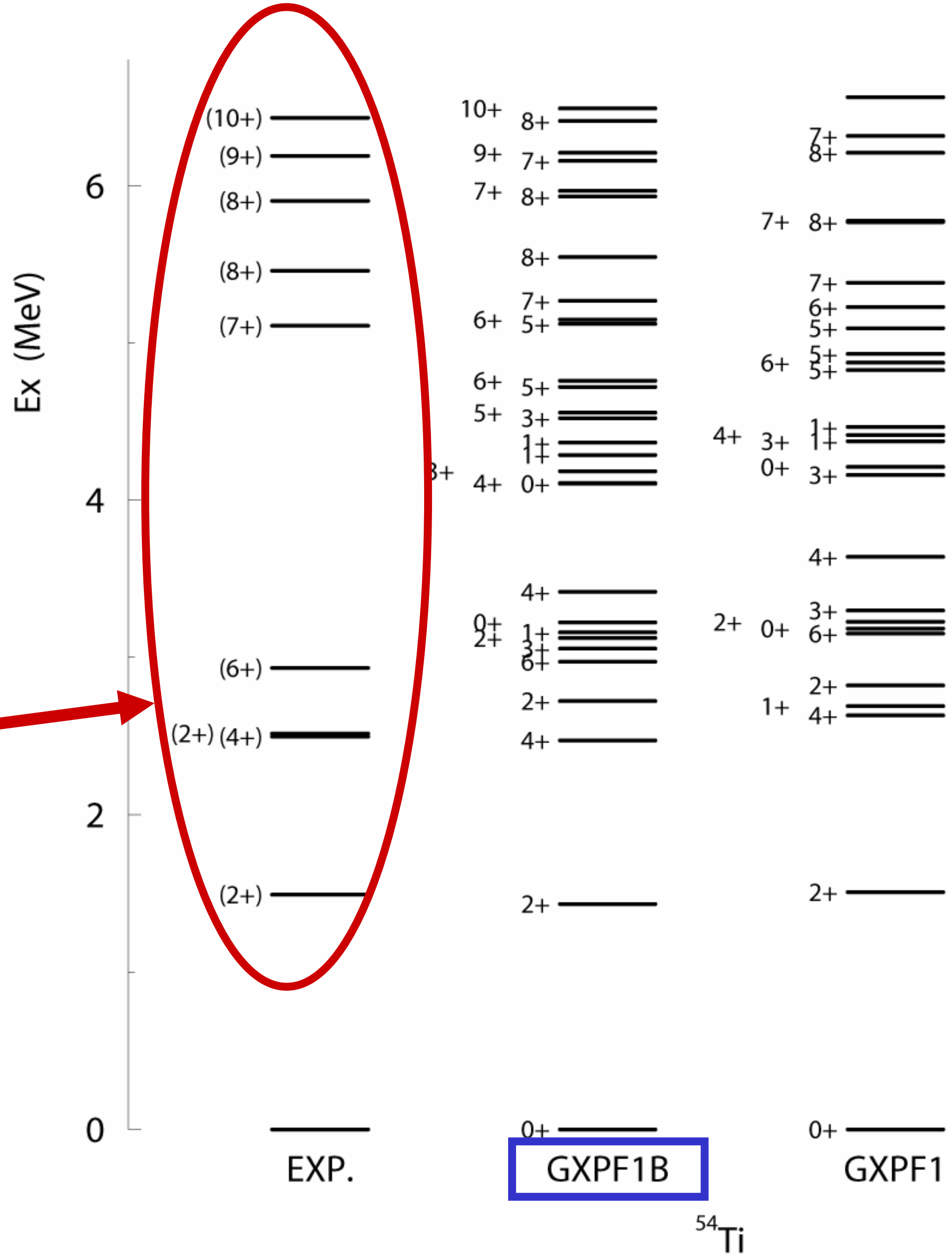
Exotic Ca Isotopes : N = 32 and 34 magic numbers ?



GXPF1B int.: p3/2-p1/2 part refined from GXPF1 int. (G-matrix problem)

Some exp. levels : priv. com.

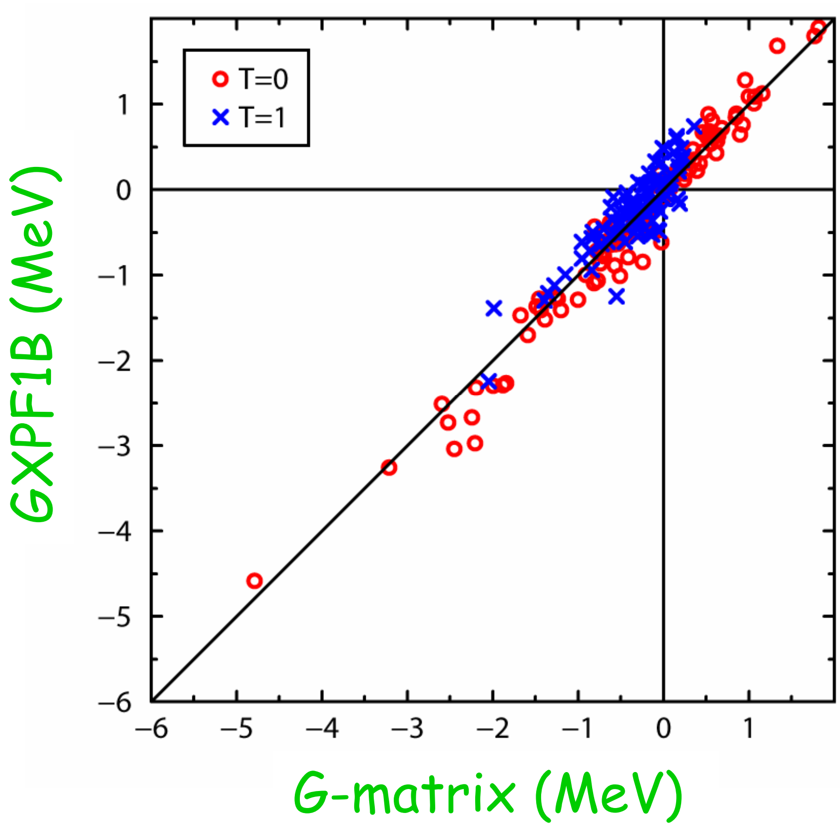
^{54}Ti



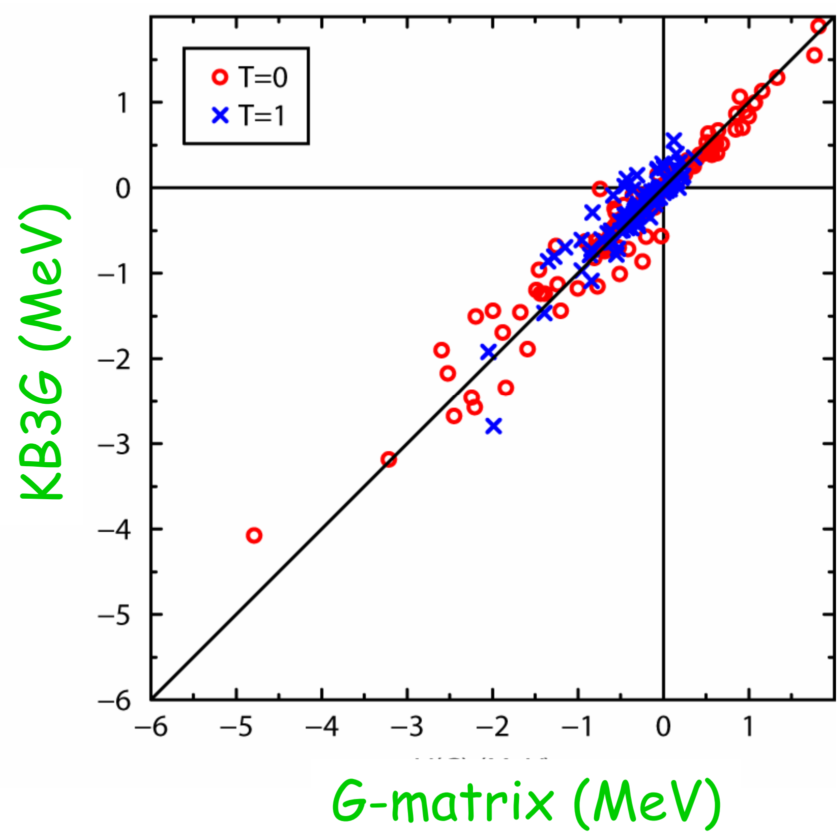
R.V.F. Janssens et al. PLB546 (2002) 55

Comparison with G-matrix + polarization correction

GXPF1B vs. G-matrix (Bonn-C)



KB3G vs. G-matrix (Bonn-C)



each point = a 2-body matrix element

Summary

Nuclear shell evolves in unique ways as compared to other physical systems, particularly in exotic nuclei (note that ΔN must be >10 to see this → **RNB !**).

Shell evolution due to tensor interactions

-drives $j_>$ or $j_<$ levels in a specific and robust way

intuitive picture → many cases expected from p-shell to superheavies

- is the dominant origin of shell evolution

John's Sb (Sn) experiment → first test excluding other possibilities

connection to exp. in RIBF, …., hopefully "RIA"

Shell evolution due to 2-body LS interactions

Naïve picture (scale-type) may not be relevant

Real phenomena may be of position-type → *ls* splitting decreases

Remark on forces

Central forces : basic binding
Complex origins : Multiple meson exchange,
hard core (quarks, QCD may be needed)
3-body forces

Tensor force : amusing changes in single particle properties
Simpler origin
dominated by one pion exchange (of course ρ, higher order …)

←→ consistent with Chiral Perturbation (Weinberg)

Physics opened by upcoming **RNB** machines
can be connected to QCD

New principle for further shell-model and mean-field studies

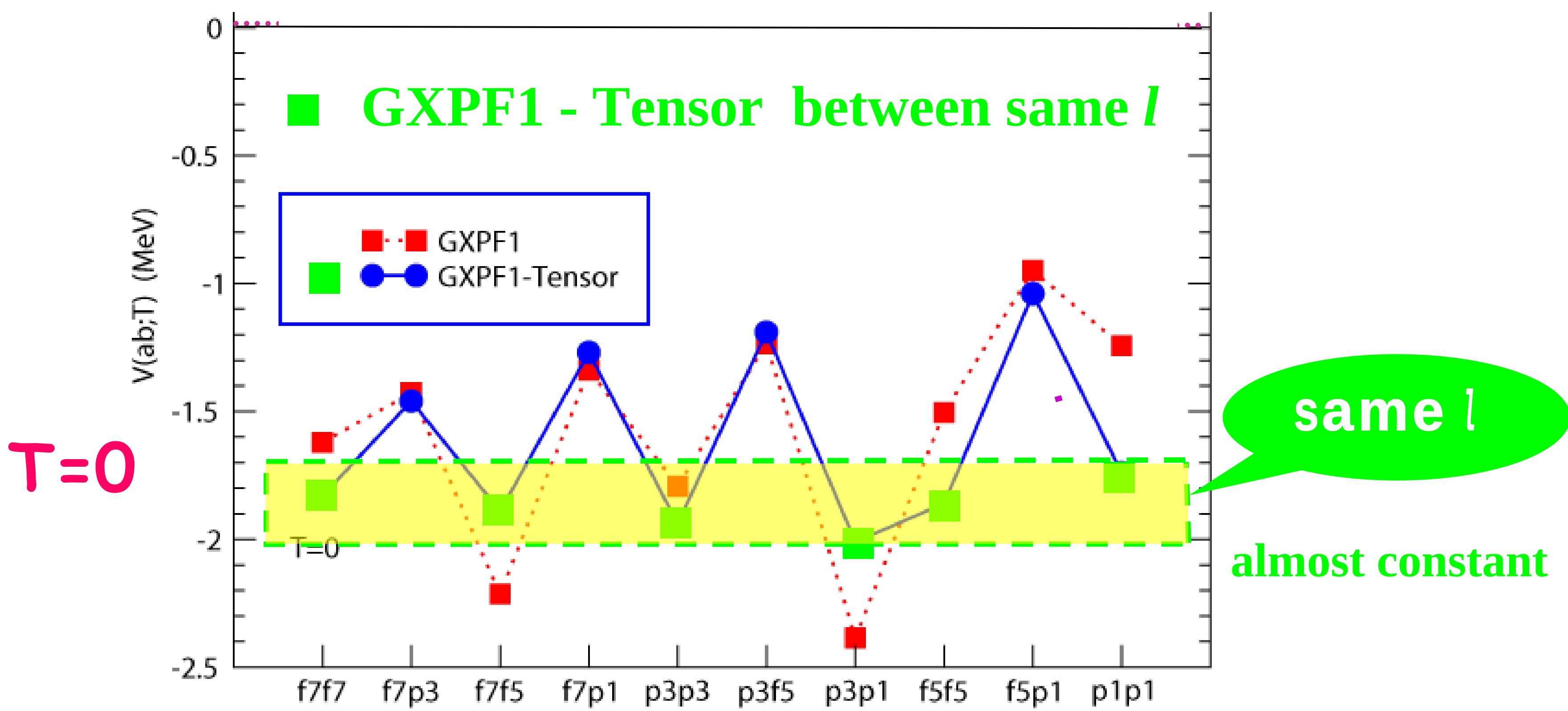
Collaborators

D. Abe	Tokyo
T. Matsuo	Hitachi Ltd.
T. Suzuki	Nihon U.
R. Fujimoto	U. Tokyo
M. Honma	U. Aizu
H. Grawe	GSI
Y. Akaishi	KEK

END

Monopole interaction
after subtraction of tensor part

GXPF1 = shell model interaction for pf-shell
(G-matrix + fit)

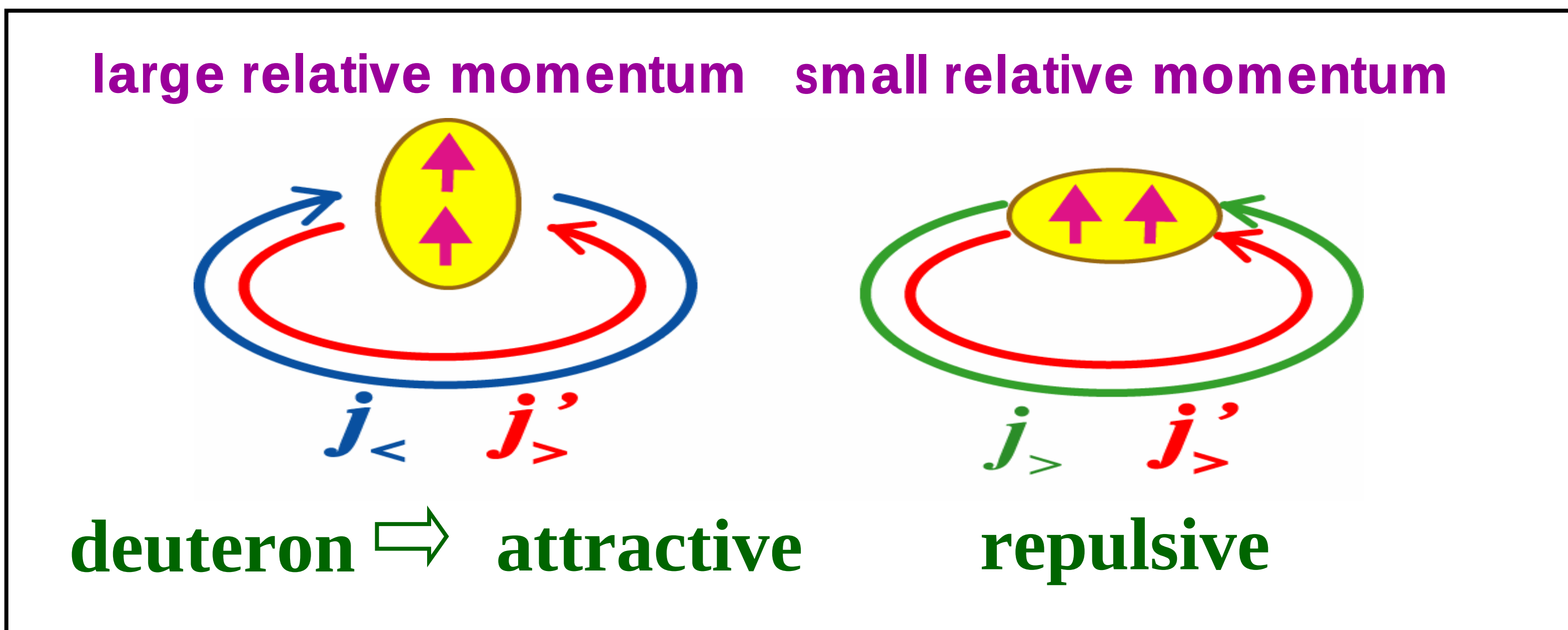


Stancu, Brink and Flocard, Phys. Lett. 68B, 108 (1977)

Zero-range spin-momentum tensor coupling term

$$
\begin{aligned}
v_{\mathrm{T}} = \tfrac{1}{2} T \{ & [(\boldsymbol{\sigma}_1 \cdot \boldsymbol{k}')(\boldsymbol{\sigma}_2 \cdot \boldsymbol{k}') - \tfrac{1}{3}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) k'^2] \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2) \\
& + \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)[(\boldsymbol{\sigma}_1 \cdot \boldsymbol{k})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{k}) - \tfrac{1}{3}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) k^2] \} \\
& + U \{ (\boldsymbol{\sigma}_1 \cdot \boldsymbol{k}') \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{k}) \\
& - \tfrac{1}{3}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)[\boldsymbol{k}' \cdot \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2) \boldsymbol{k}] \}, \qquad (1)
\end{aligned}
$$

This is not be a good approximation to the tensor force itself, but may simulate the monopole effect of the tensor shown below, picking up differences in relative momenta.



$^{31}Mg_{19}$

Phys. Rev. Lett. 94, 022501 (2005), G. Neyens, et al.

Outside the ***original*** Island of Inversion

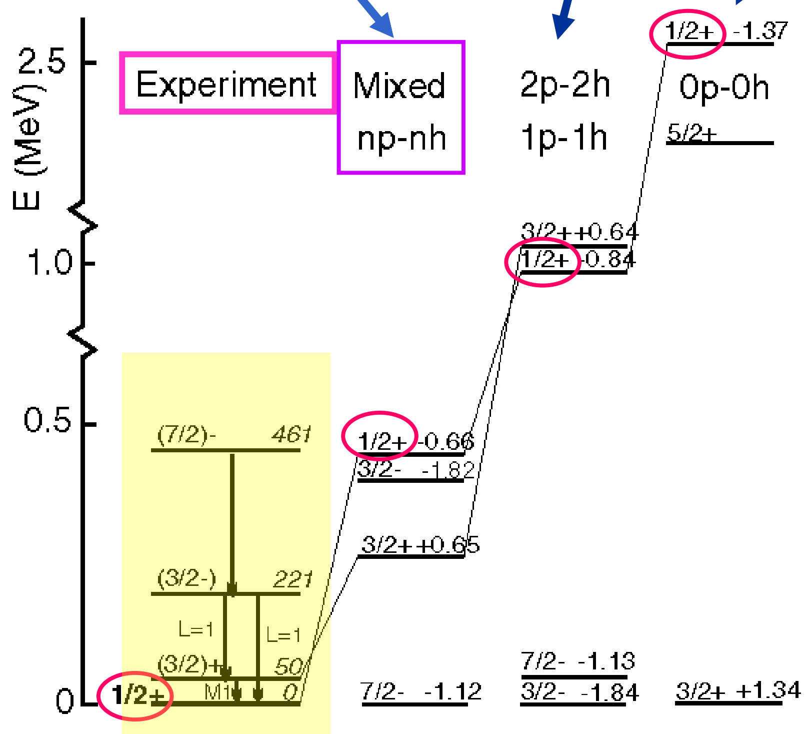
Tokyo MCSM

Strasbourg unmixed

USD (only sd shell)

2.5 MeV

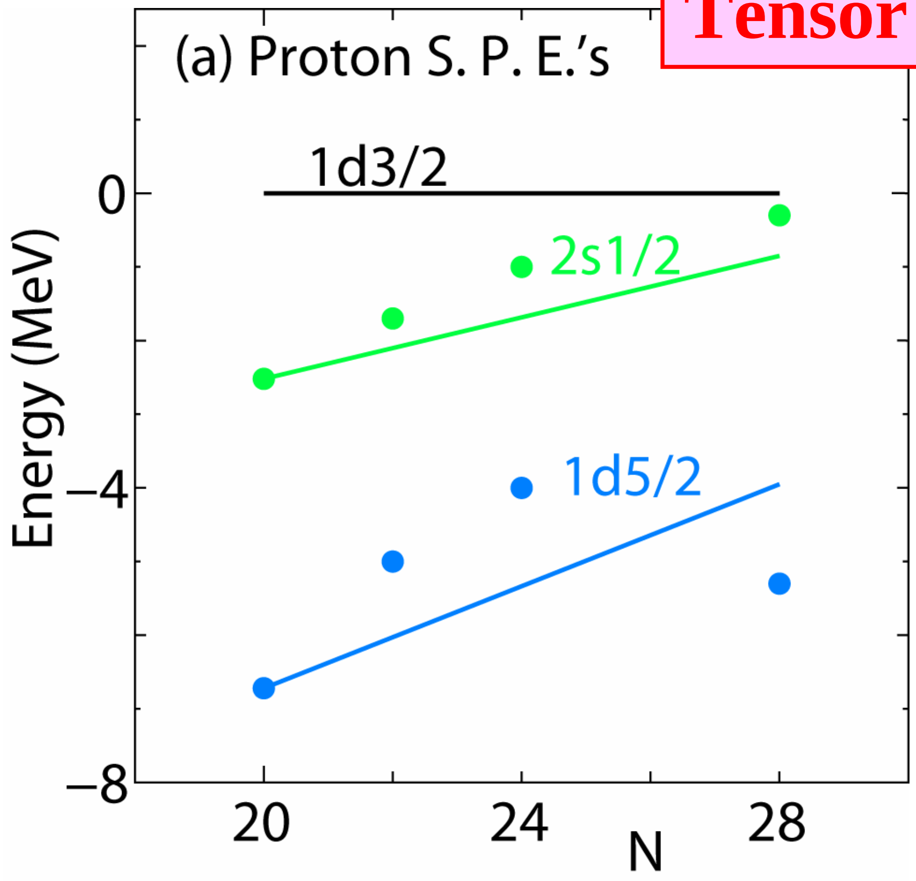
0.5 MeV



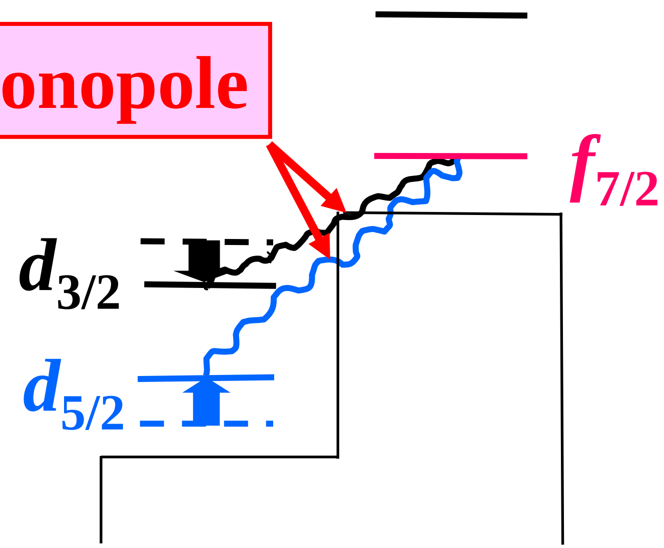
1/2$^+$ state comes down by 2 MeV from USD result by strong mixing between *sd* and *pf* shell configurations due to **narrower *N*=20 gap**

→ fine details to be refined (odd-A nuclei are difficult)

Proton effective single-particle levels (relative to $d_{3/2}$)



Tensor monopole



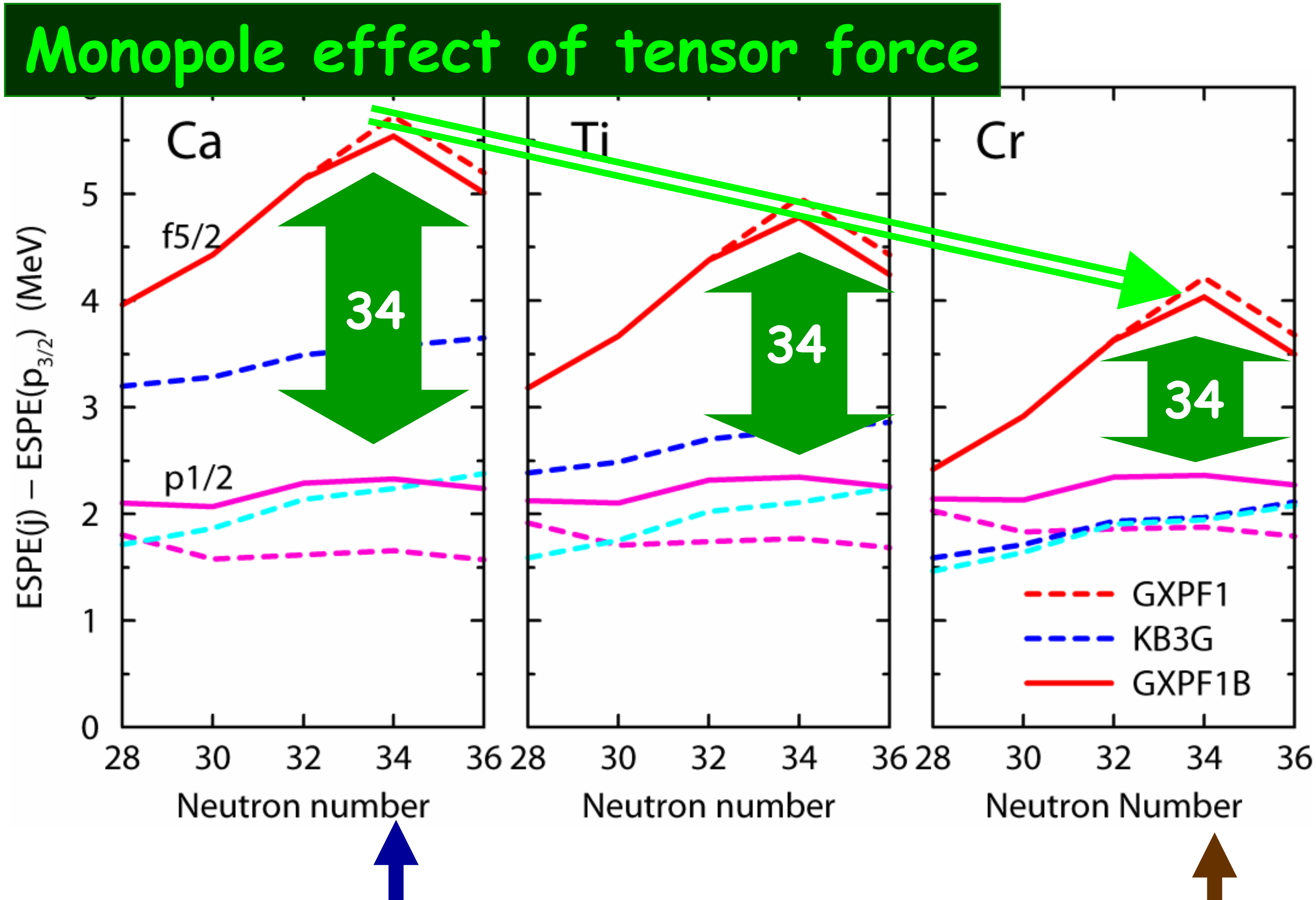
$\pi + \rho$ **meson tensor**

exp.

Cottle and Kemper, Phys. Rev. C58, 3761 (98)

neutrons in $f_{7/2}$

Effective single-particle energies of Ca, Ti and Cr isotopes



Gap = 2 MeV at N=32 and 3 MeV at N=34

Gap = 2 MeV at N=32 and 1.5 MeV at N=34

The shell structure is the basis of quantum many-body systems and also reflects the underlying mechanism to make the system bound.

If the shell is created by the potential source at the Center (like Coulomb potential of Hydrogen-like atoms), the shell structure does not change much.

However, if the shell structure is made by the particles themselves, the shell may evolve lively as the number of particles changes. Is this the case with exotic nuclei ?

But, the most relevant point today is that John Schiffer likes single-particle motion.

Among many possible issues, e.g. loose binding effect, on the shell evolution, I would like to focus on the following two points.

- As N increases from the β stability line, the spin-orbit splitting becomes smaller due to the change of the density distribution.

  Is this true ? If so, how does it happen ?

- More recently, variations of the shell structure off the β stability line but still far away from the drip line have emerged due to the **tensor force**.

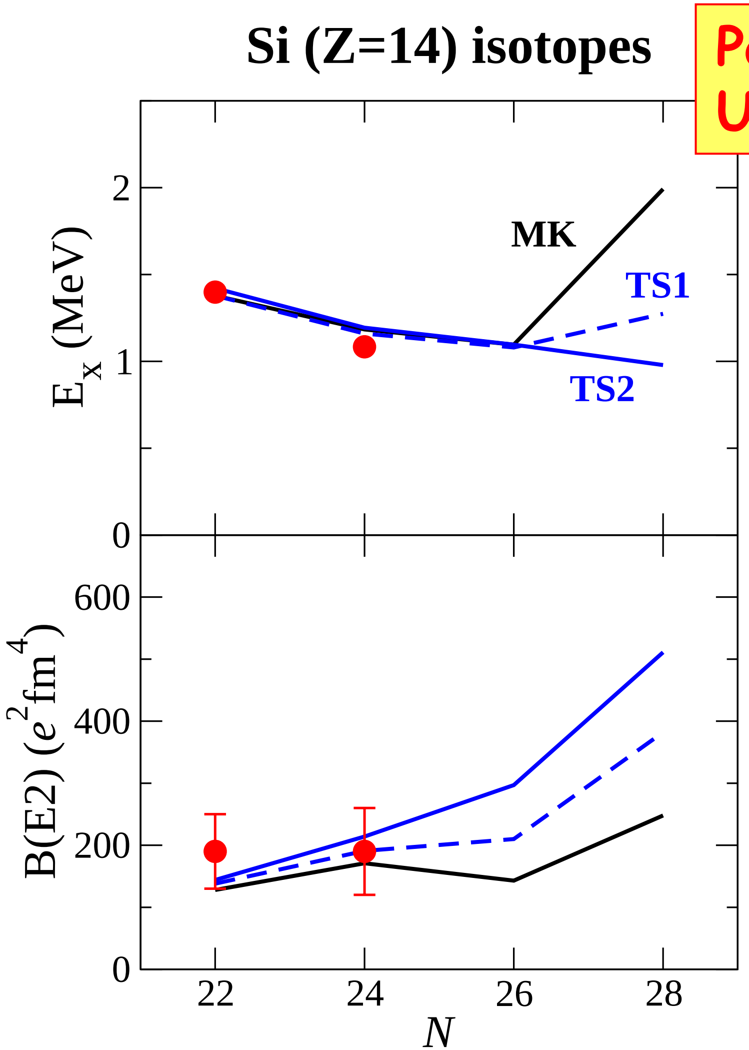
  How does the tensor force work in old and new problems ?

How do these two effects compare in their sizes ?

• Structure of neutron-rich Si isotopes

ı by the tensor force

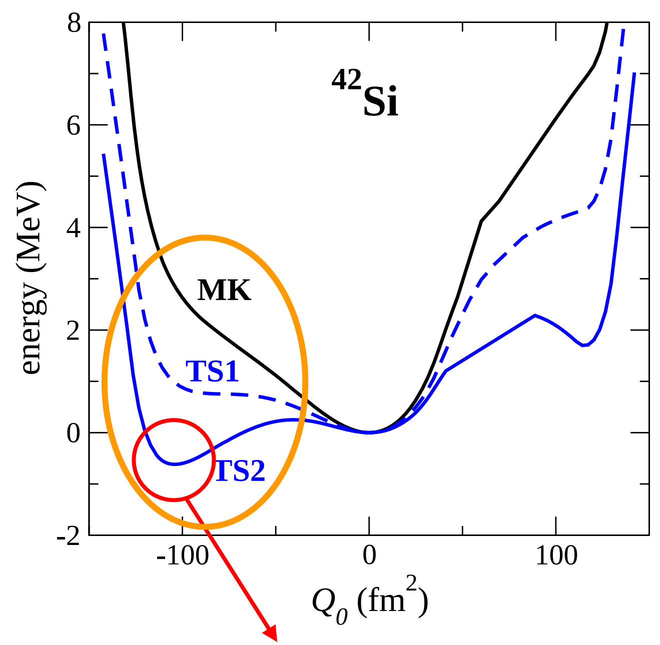
24 MeV (TS2) vs. 1.12 MeV (MK).



(e_p=1.2e,
e_n=0.45e)

Poster by
Utsuno et al.

Constrained HF calculation
in the shell-model space



About 1.5 **protons are excited**
across the Z=14 shell gap.

The following points were raised as new aspects of shell evolution in exotic nuclei :

- As *N* increases from the β stability line, mean potential has a more diffuse surface, and the spin-orbit splitting becomes smaller.

- In dripline nuclei, extremely loosely bound orbits, particularly s-orbit, remain bound by tunnel effect (neutron halo).

- Also near the drip line, coupling to continuum may produce new phenomena, e.g., those like BCS/BEC (pairing dynamics).

More recently, variations of the shell structure off the β stability line but still far away from the drip line have emerged.
Such variations appears to be due to the spin-isospin component of the NN interaction, particularly the **tensor**.

Phys. Rev. Lett. 94, 162501 (2005), V. Tripathi et al.

Lowest states are intruders (> 50%)

$^{29}Na_{18}$

3/2⁺, 5/2⁺ ? (from log *ft*)

zero BR

only state below 2.8 MeV by USD (large log *ft*)

4 additional states of intruder config. by SDPF-M int. (MCSM calc.)

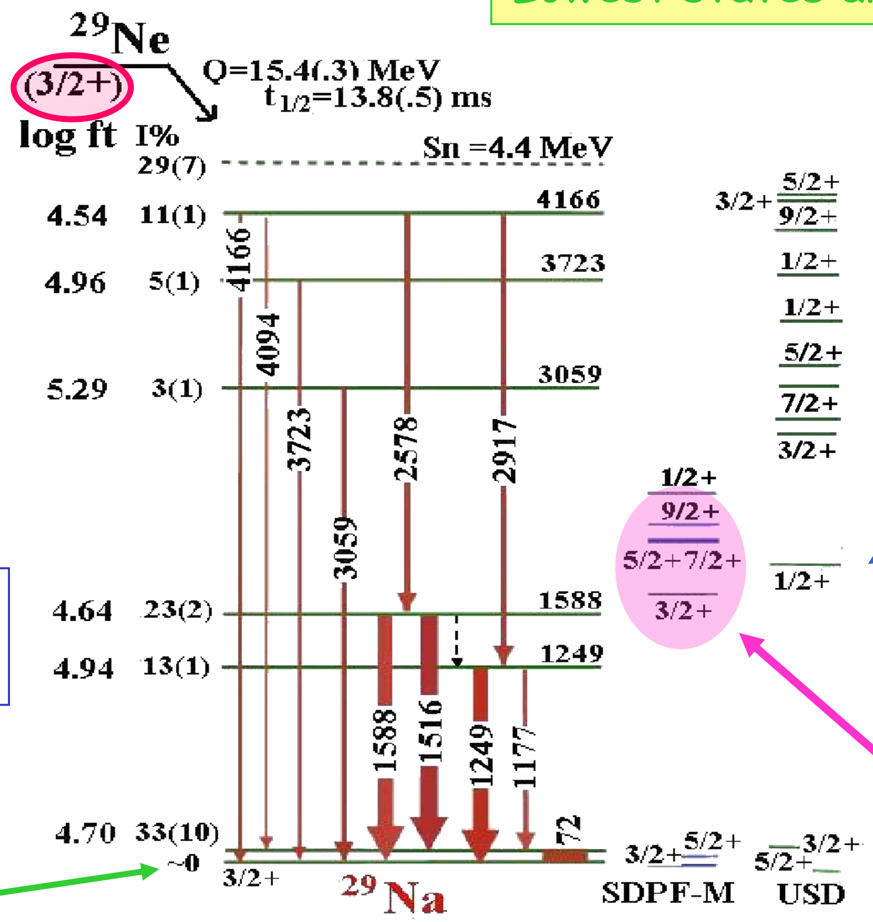


FIG. 2 (color online). Proposed level scheme for ^{29}Na populated following the β^- decay of ^{29}Ne. The absolute β-decay branching to each level per 100 decays is indicated along with the calculated logft values. Shown on the right are shell model calculations with the USD and SDPF-M interactions.

Level scheme of ^{28}Ne

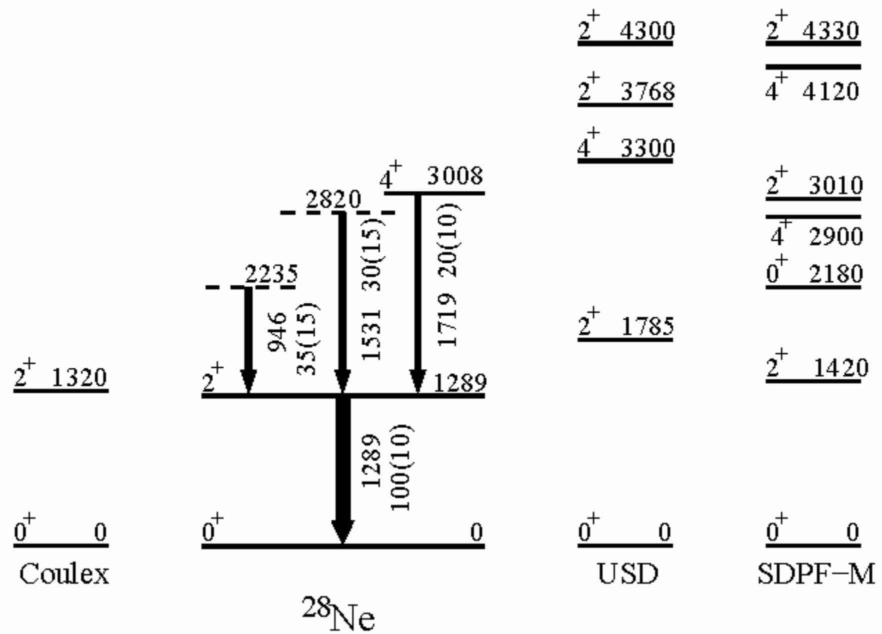


FIG. 9: Proposed level scheme of ^{28}Ne. The results of different shell model calculations [7, 22] are included in the right part of the figure. The energy of the first excited state observed in Coulomb excitation experiment is taken from Ref. [20]. The spin 4 assignment to the 3008 keV state is taken from Ref. [21].

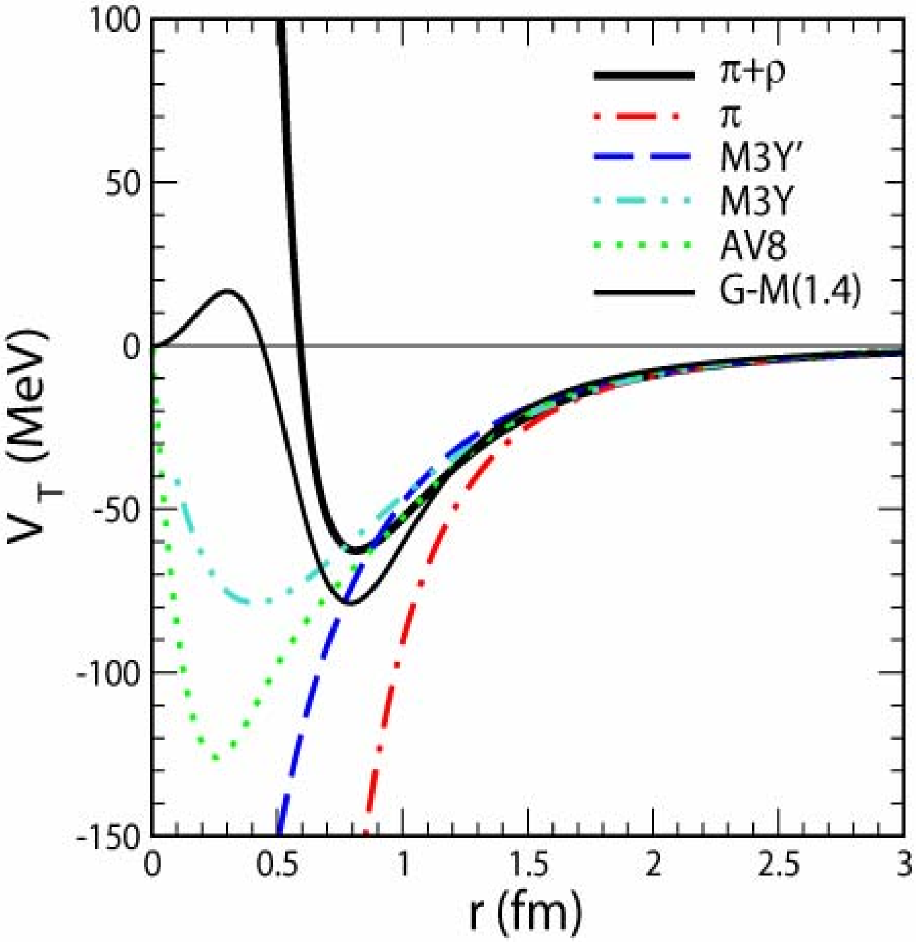
Federman and Pittel, Phys. Lett. B 69, 385 (1977)

- Overlap of radial wave functions is emphasized -

they can simultaneously fill the $1g_{9/2}$ proton and $1g_{7/2}$ neutron orbitals. The strong overlap of these spin-orbit-partner orbitals can lead to important n-p correlations in this region and thus to deformation.

At this point it is useful to generalize our earlier remarks as to when strong n-p correlations should occur. As noted earlier, the crucial criterion is that the neutrons and protons occupy orbitals with good overlap. It was pointed out long ago [8] that the overlap between two orbitals $(n_N\, l_N\, j_N)$ and $(n_P\, l_P\, j_P)$ is maximum if $n_N = n_P$ and $l_N \approx l_P$. So far, we have focussed on cases in which $n_N = n_P$ and $l_N = l_P$, although we have emphasized that j_N need not be the same as j_P.

Tensor potential



tensor

⇩

no s-wave to s-wave coupling

⇩

differences in short distance : irrelevant

Basic ideas to fix GT2 parameters

1. Include tensor
   follow meson exchange results
   but cut out singularity at short distance

2. Imcompressibility

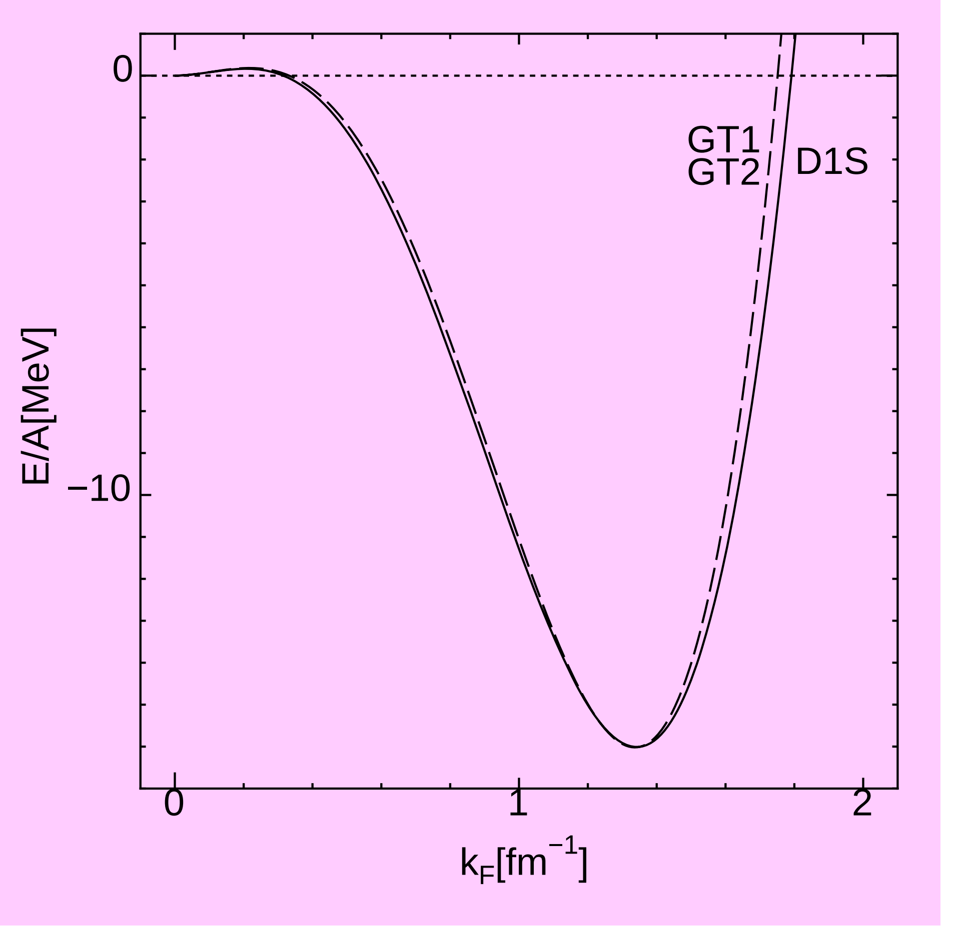
3. T=1 mean field is made more repulsive, while the pairing is made stronger
   See the result for oxygen isotopes

4. Parameters fitted by B.E.'s of ^{16}O, $^{40,48}Ca$, (^{56}Ni,) ^{132}Sn, ^{208}Pb, and by single-particle structure of neutron rich oxygen

Far from perfection, particularly in pairing correlation

Nuclear matter property

E/A



Parameters

D1S

i	1	2
μ	0.7	1.2
V^0	-512.94	-3.52
V^σ	300.60	-25.76
V^τ	557.37	-25.42
$V^{\sigma\tau}$	-349.40	55.98
W_0	130	
t_3	1390.6	
x_3	1	

GT2

i	1	2
μ	0.7	1.2
V^0	-210	-25
V^σ	-1040	129
V^τ	-781	120
$V^{\sigma\tau}$	700	-65
W_0	160	
t_3	1400	
x_3	1	

Potential in each spin-isospin channel