中間エネルギーイオンビームによる物理　研究会
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原子核のＧＴ遷移と殻模型 殻構造の新局面

Gamov-Teller transitions and new aspects of shell model / shell structure of nuclei

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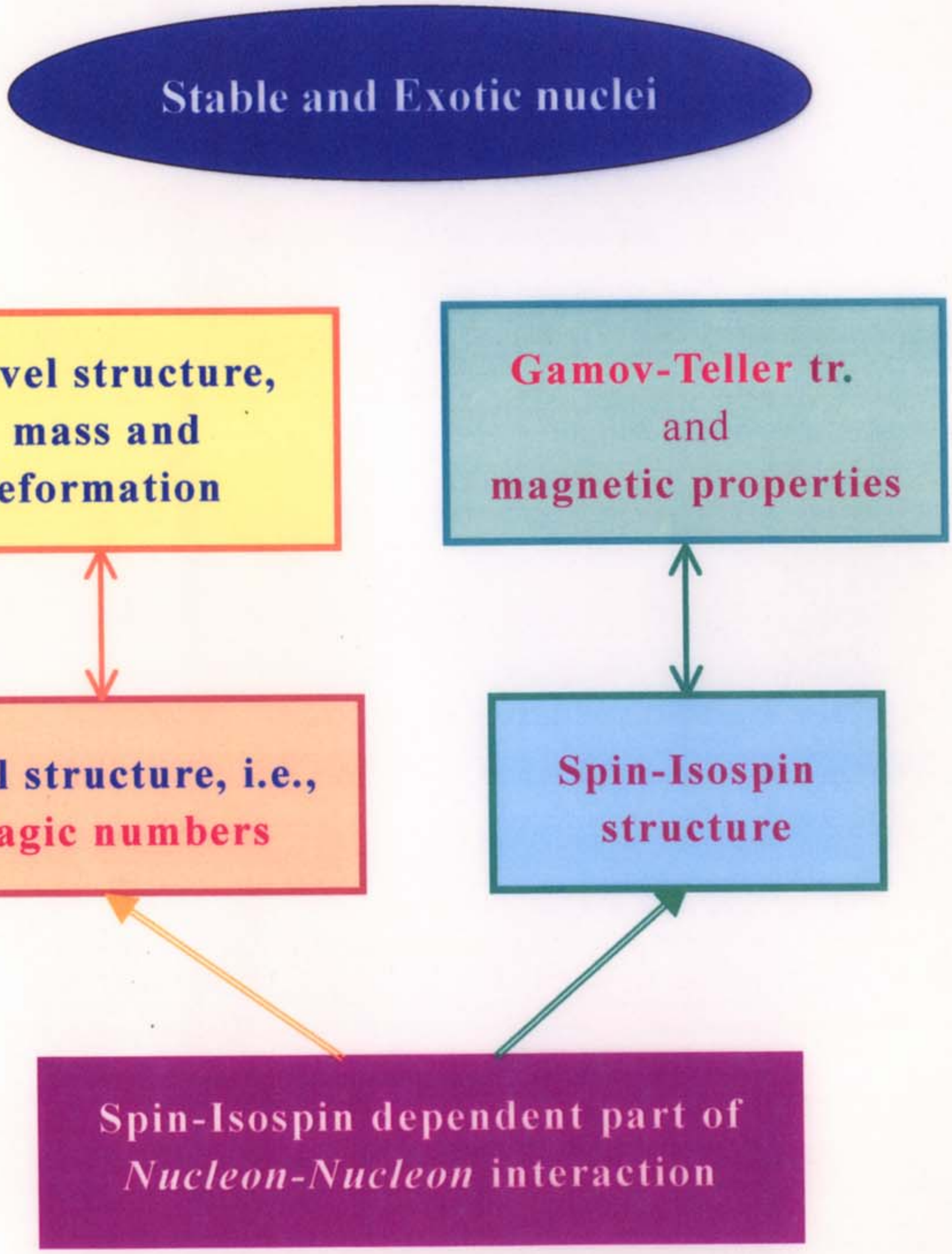
M. Honma	Univ. Aizu	*GT in pf shell*
T. Mizusaki	Senshu Univ.	*GT in pf shell*
B.A. Brown	MSU	
Y. Utsuno	JAERI	

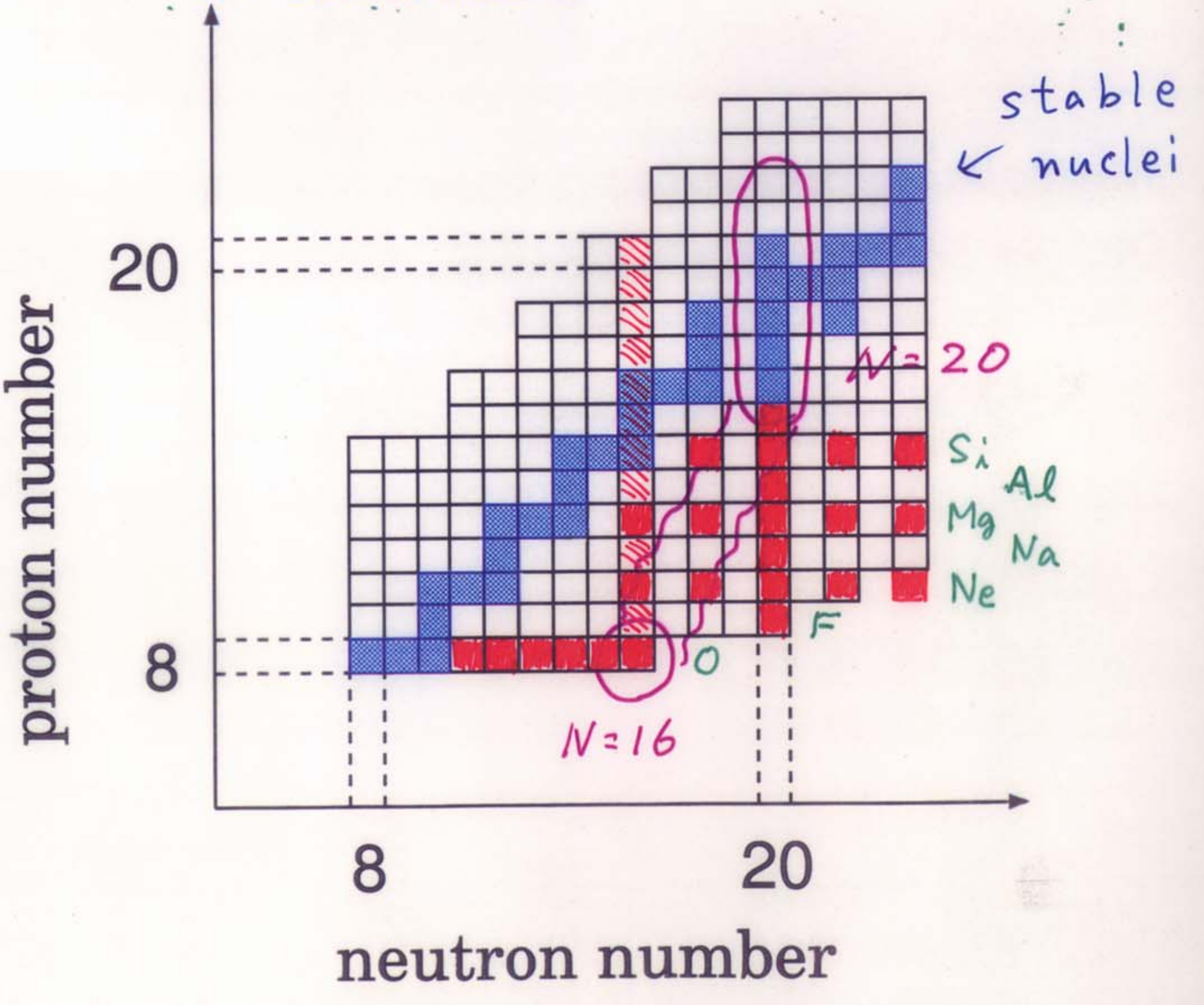
outline


Stable and Exotic nuclei
Level structure, mass and deformation
Gamov-Teller tr. and magnetic properties
Shell structure, i.e., Magic numbers
Spin-Isospin structure
Spin-Isospin dependent part of *Nucleon-Nucleon* interaction

* See also Dlouhý et al. (2001) submitted

N = 16 : a magic number ?

- Ozawa et al. PRL 84 (2000) 5493
  anomalies in separation-energy systematics for N ~ 16 *
- 2^+_1 of ^{24}O and $\frac{3}{2}^+_1$ of ^{25}O in continuum

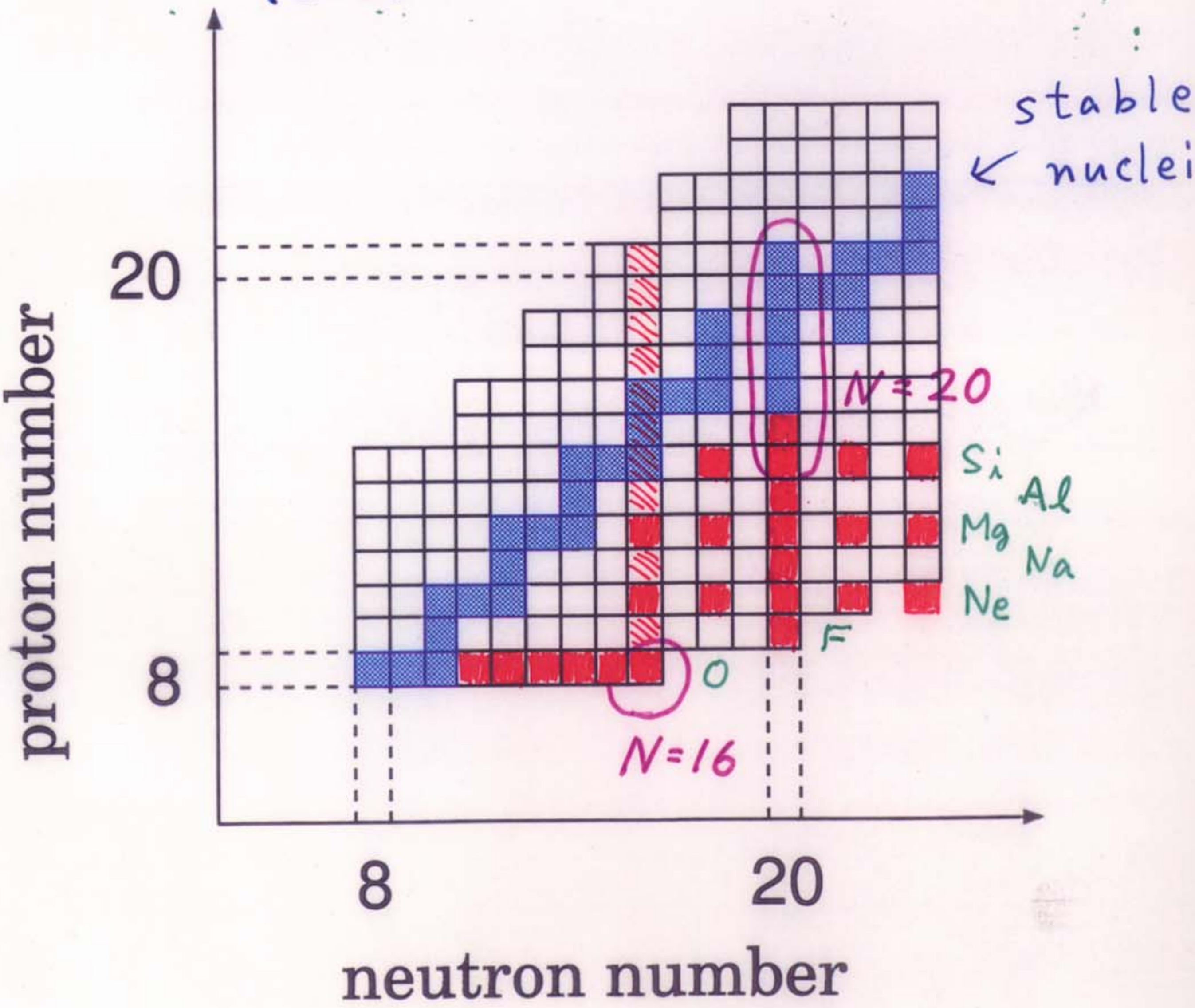


Transition between

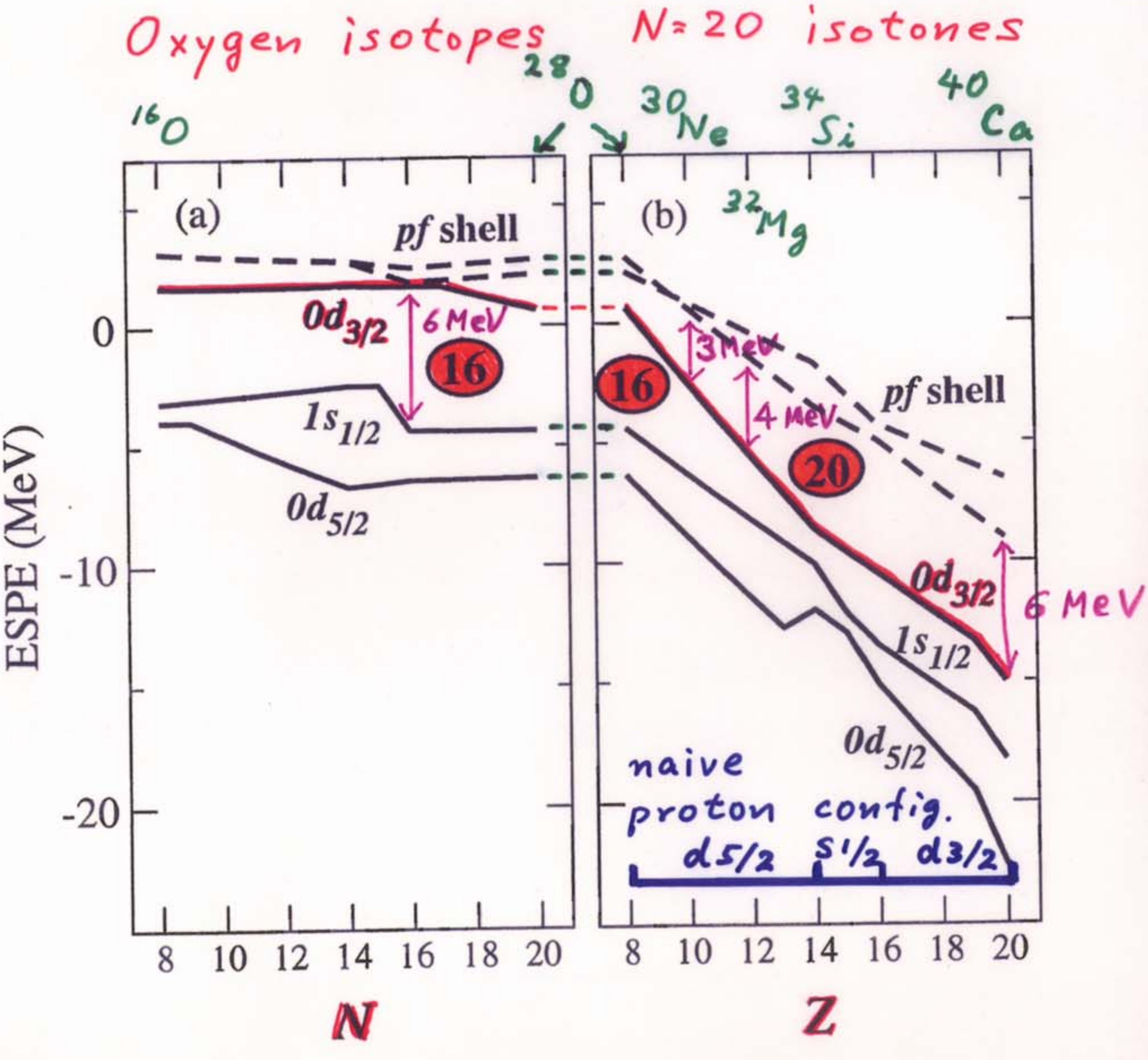
N = 16 and N = 20

magic schemes

Oxygen isotopes : $^{24}_{8}O_{16}$ is heaviest
(Z = 8)



Effective single-particle energies of neutrons



Interaction : sd shell USD (1984)

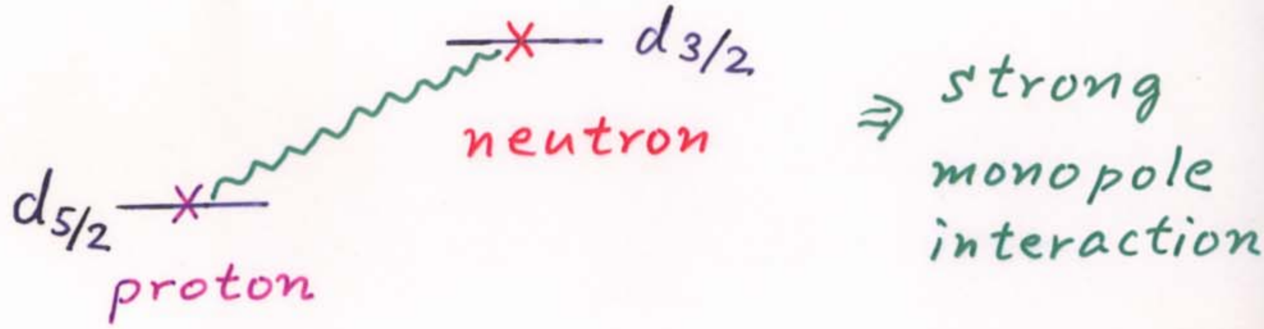
pf shell Kuo (1968)

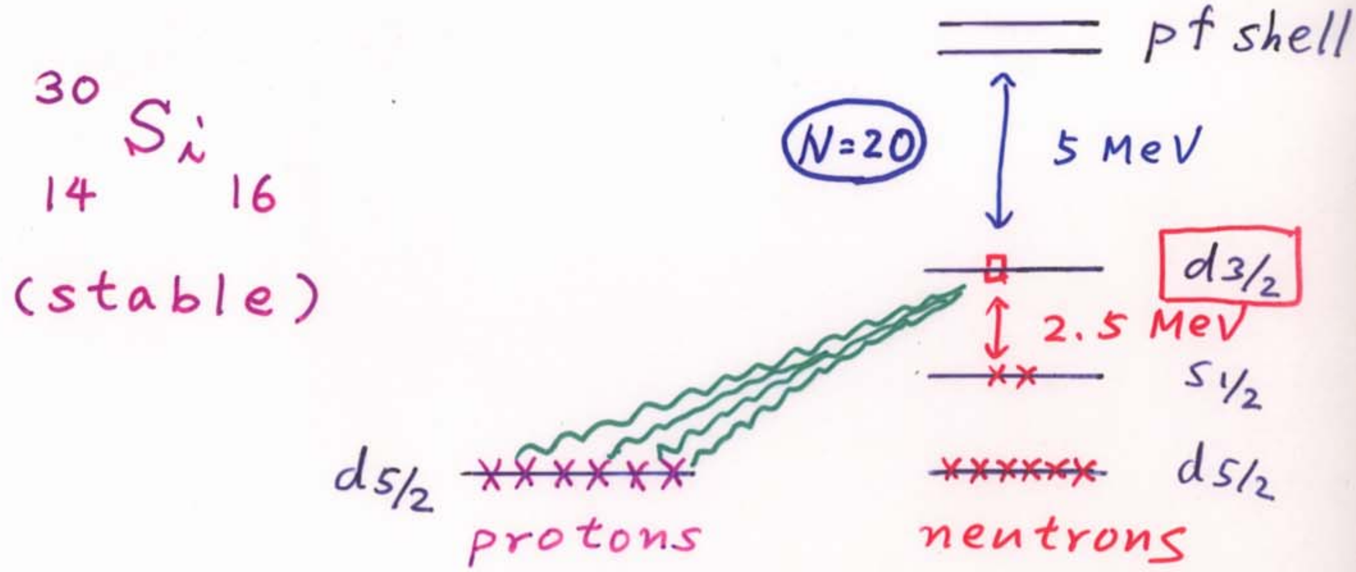
sd-pf MK′ (1975)

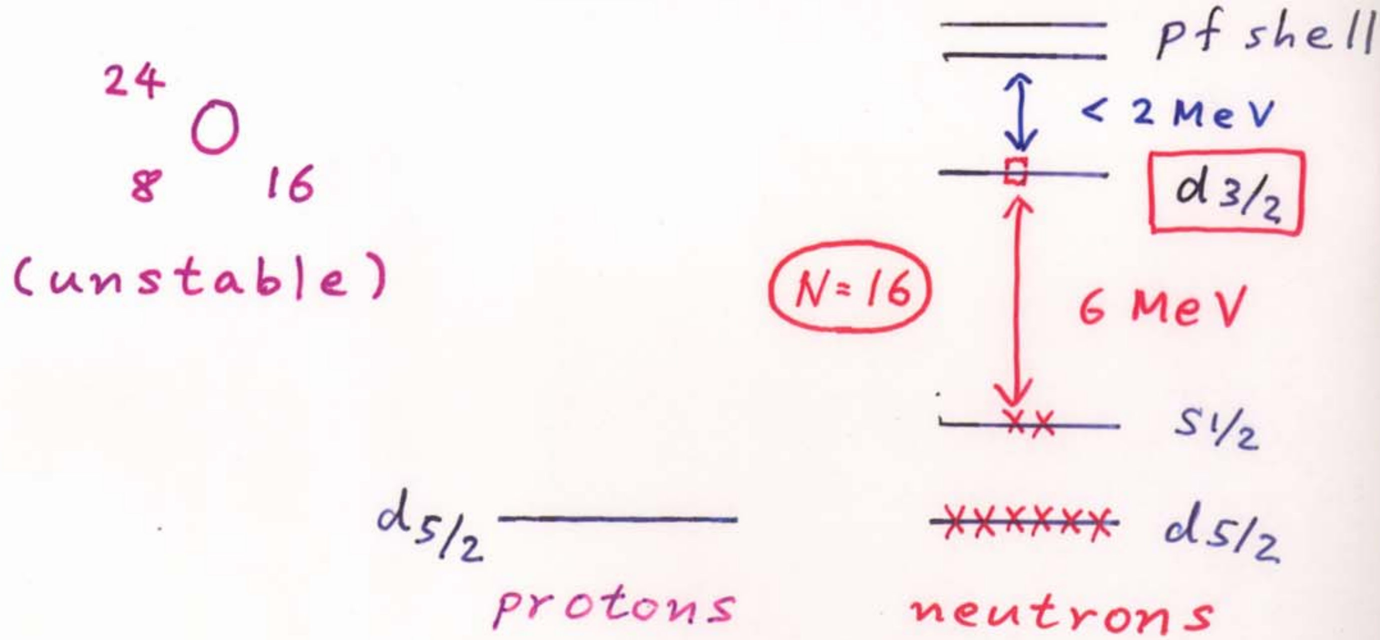
+ Warburton et al (1986)

+ fine tuning Utsuno et al. (1999)

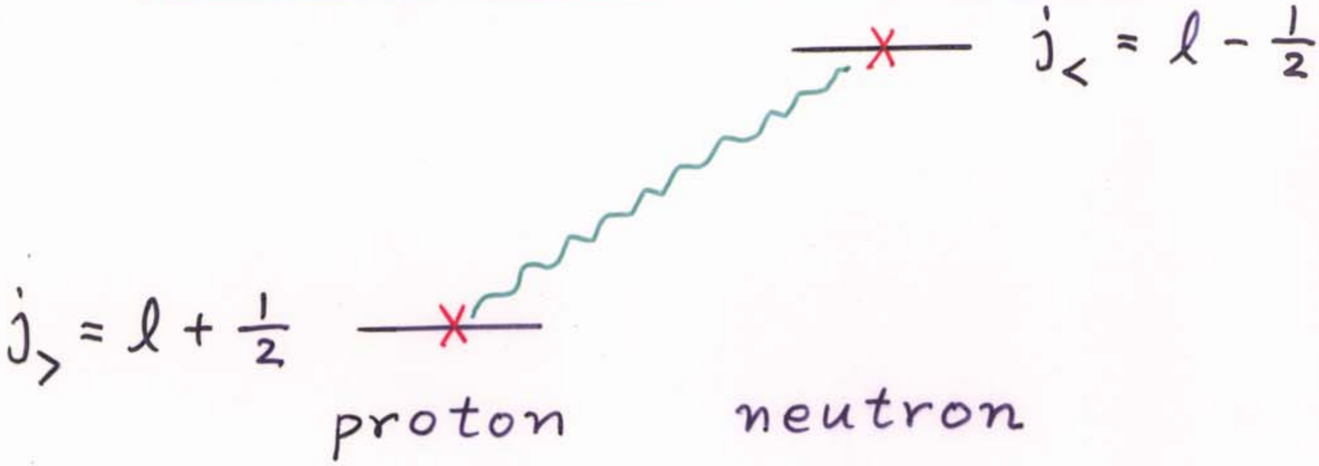
- Strong T=0 attraction in $d_{5/2}$ - $d_{3/2}$ configuration







A more general picture



- Strong attractive interaction in T=0 channel for $j_> \otimes j_<$ configuration in general

  Ex : $\langle d_{5/2}\, d_{3/2} | V | d_{5/2}, d_{3/2} \rangle_{J,\, T=0}$

  $p_{3/2}$ $p_{1/2}$ $p_{3/2}$ $p_{1/2}$

- This interaction contains strong attractive monopole component in general.

  Strongest in one major shell

  - G-matrix p, sd, pf shells
  - USD, GXPF1/2

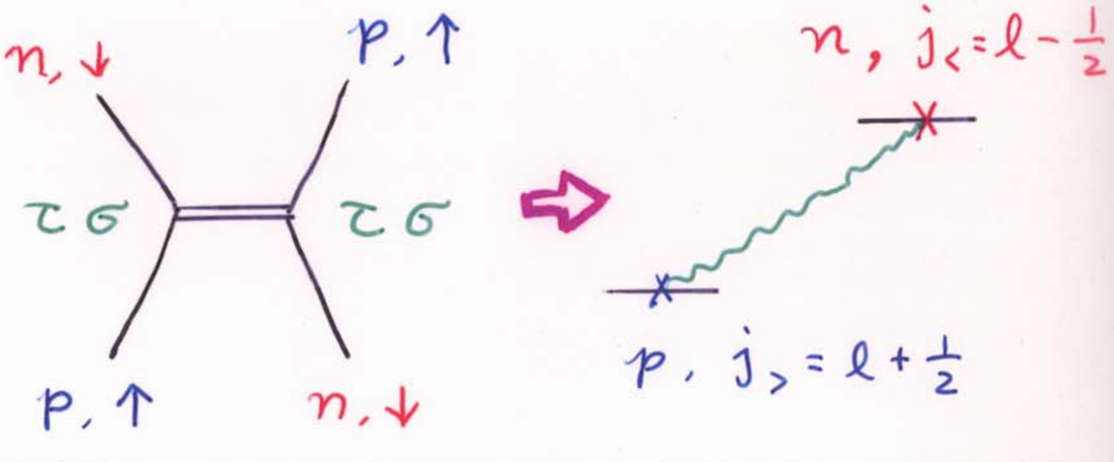
A major mechanism producing this $j_> - j_<$ coupling

$$V_{\tau\sigma} = (\tau \cdot \tau)(\sigma \cdot \sigma) f_{\tau\sigma}(\vec{r})$$

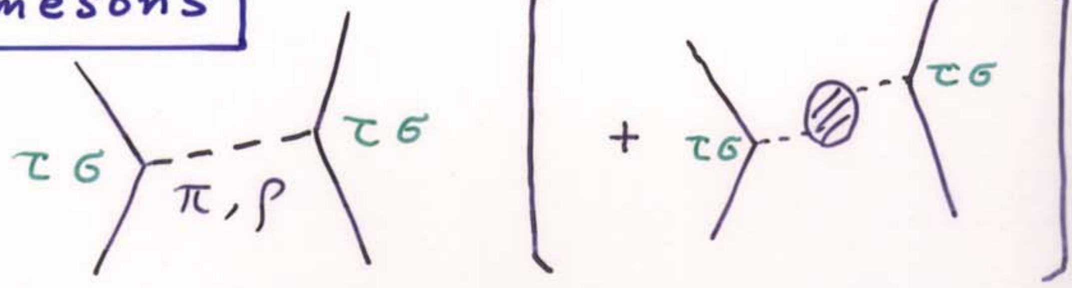
long range limit of $f_{\tau\sigma}(\vec{r})$

$\Rightarrow \overset{\circ}{V}_{\tau\sigma} \propto (\tau \cdot \tau)(\sigma \cdot \sigma)$

This favors



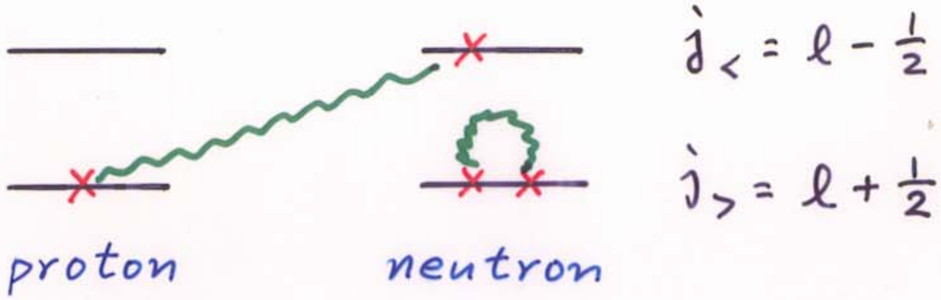
origin in mesons



$$V_{OBEP} \propto (\tau \cdot \tau)\{(\sigma \cdot \sigma) + \cdots\} f(r)$$

π : longest range

$$\mathring{V}_{\tau\sigma} = (\tau \cdot \tau)\,(\sigma \cdot \sigma)$$



Monopole interaction for $\mathring{V}_{\tau\sigma}$

$$\frac{\sum_J (2J+1) \langle j j' ; JT | \mathring{V}_{\tau\sigma} | j j' ; JT \rangle}{\sum_J (2J+1)}$$

j	j'	$T=0$	$T=1$
$l+\frac{1}{2}$	$l+\frac{1}{2}$	$-\frac{3}{2l+1}$	$-\frac{2l+3}{(2l+1)^2}$
$l+\frac{1}{2}$	$l-\frac{1}{2}$	$-\frac{6}{2l+1}$	$-\frac{2}{2l+1}$
$l-\frac{1}{2}$	$l-\frac{1}{2}$	$-\frac{3(2l-1)}{(2l+1)^2}$	$-\frac{1}{2l+1}$

Relative magnitude for $l \gg 1$

j	j'	pn	nn, pp
$l+\frac{1}{2}$	$l+\frac{1}{2}$	-2	-1
$l+\frac{1}{2}$	$l-\frac{1}{2}$	-4	-2
$l-\frac{1}{2}$	$l-\frac{1}{2}$	-2	-1

• $1/N_c$ expansion of QCD

Kaplan and Manohar
PR C56, 76 (97)

order N_c (= 3)

$\mathbb{1} \cdot f_0(r)$

$(\tau\cdot\tau)(\sigma\cdot\sigma)\ f_{\tau\sigma}(r)$

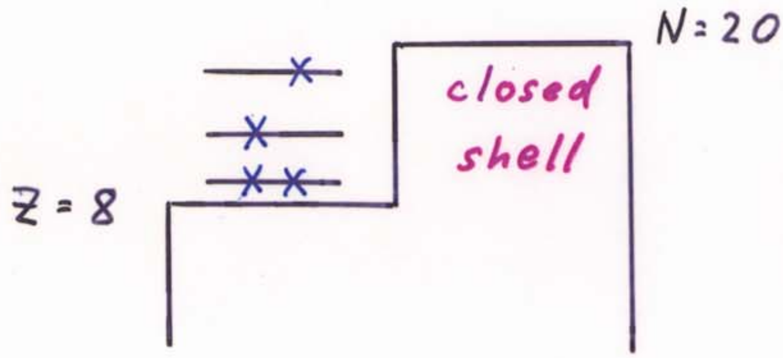
tensor

others $\frac{1}{N_c}$ $(=\frac{1}{3})$ or less

⇒ Long-range part of
NN interaction

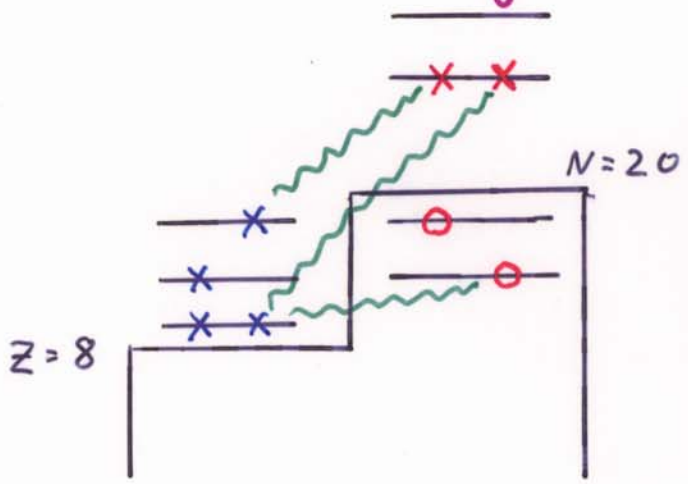
N = 20 isotones

normal configuration



They do mix!

intruder configuration



$\Delta\varepsilon_{gap}(Z,N)\big|_{N=20}$

↑ changes

proton-neutron quadrupole correlation energy

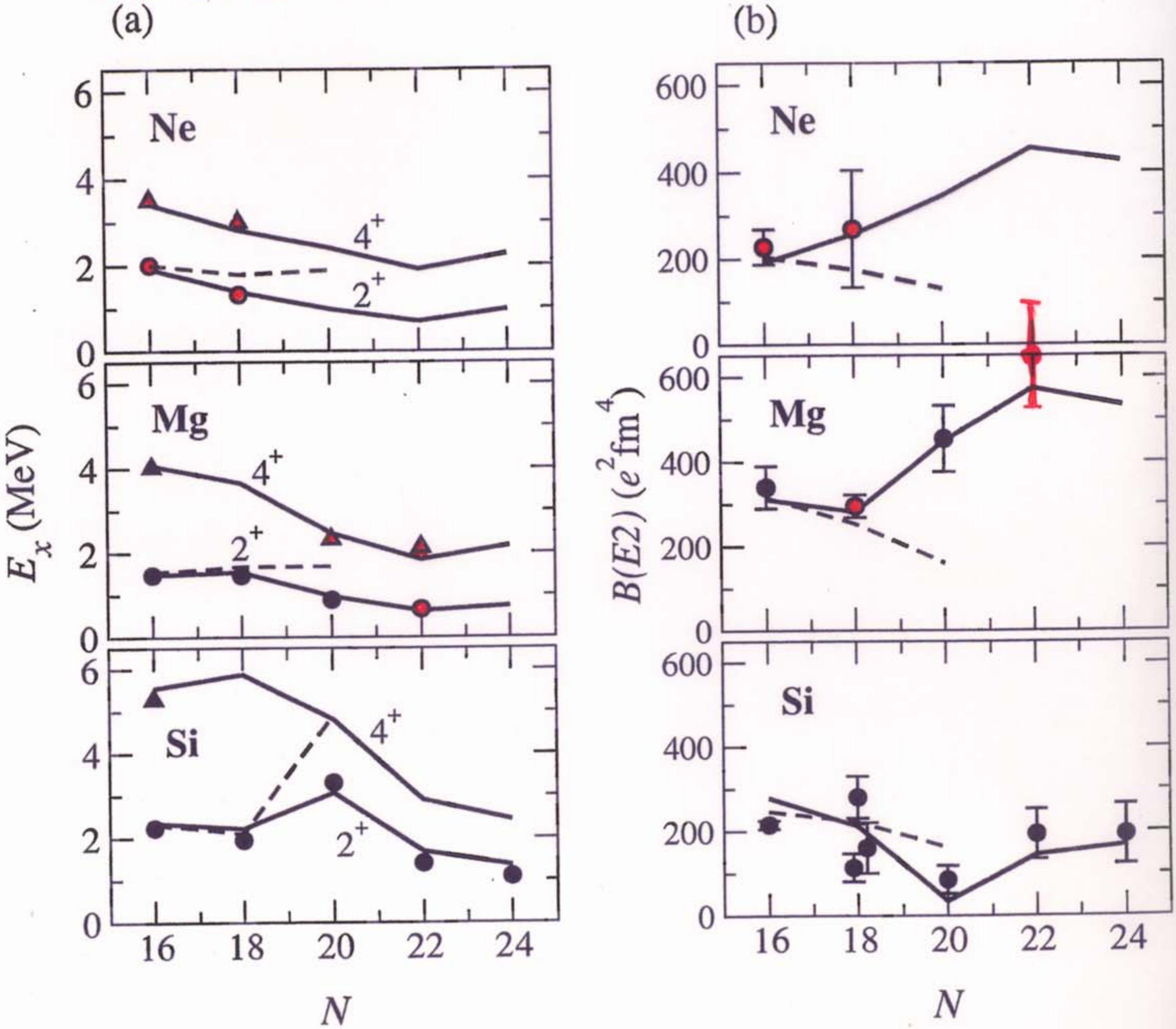
$\sim Q_p \; Q_n$

	Ne	Mg	Si
Q_p	large	largest	modest

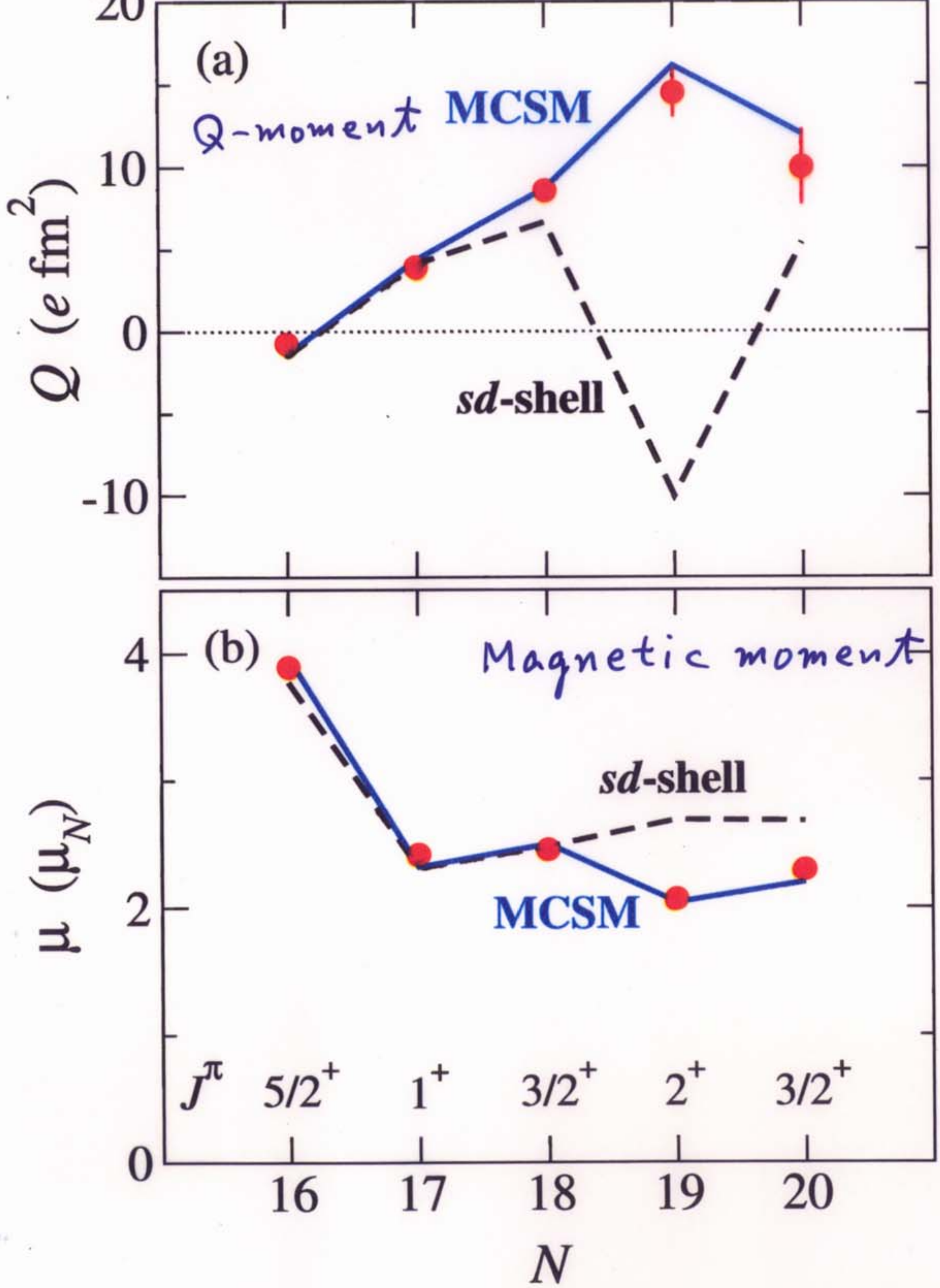
2^+_1 and 4^+_1 levels and $B(E2; 0^+_1 \to 2^+_1)$

Points : exp   Lines : MCSM calc.

● ▲ after calc.   —— sd+pf   - - - sd only



Na isotopes

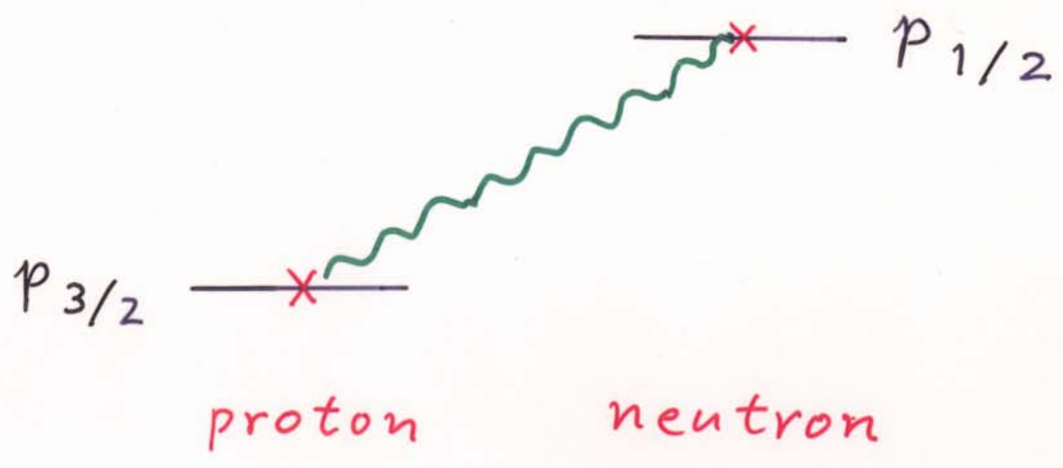


Ref.) M. Keim *et al.*, in *Proc. of "Exotic Nuclei and Atomic Masses" (1998).*
Eur. Phys. J A **8**, 31 (2000).

$N = 8 \rightarrow 6$

stable exotic

in p shell

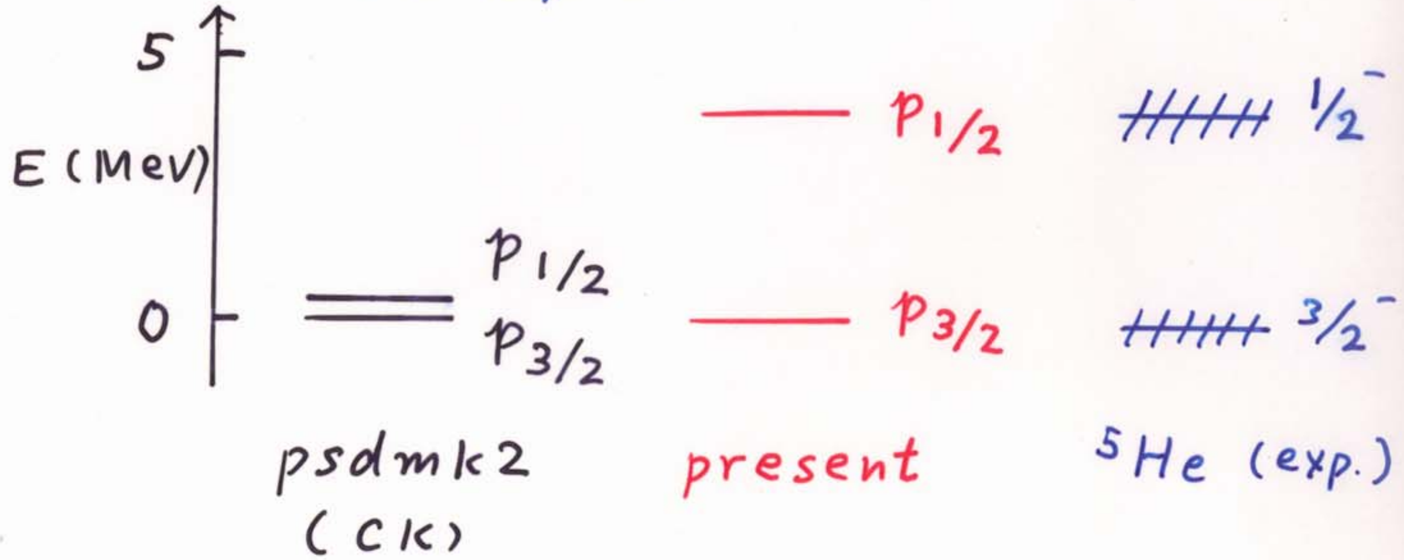


Modification of Shell-model Hamiltonian

Starting from psdmk2 (CK)

CK : Cohen-Kurath N.P. 73, 1 (65)

Bare single particle energies on top of the ^4He core



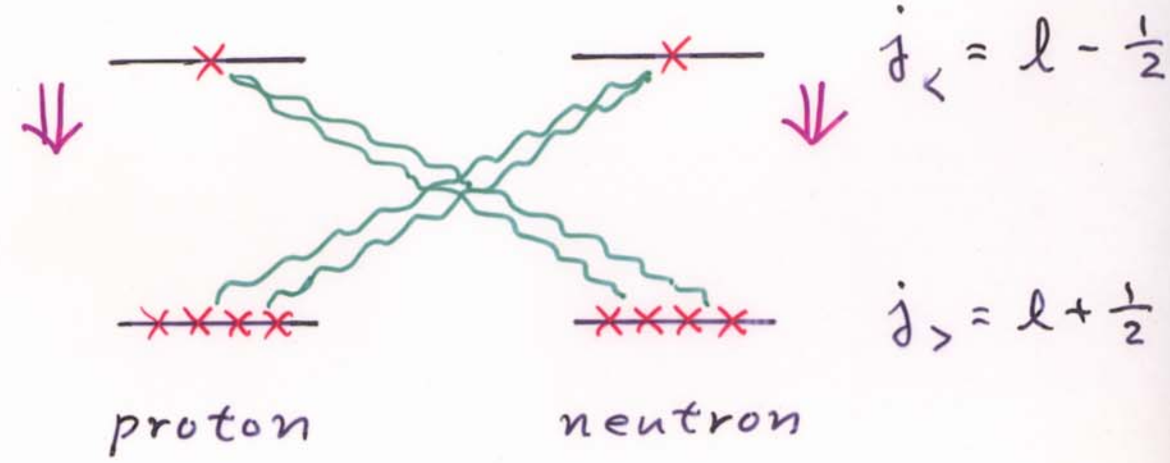
Two-body matrix elements (MeV) (diagonal ones)

	J	T	psdmk2 (CK)	present	G-matrix (H.-Jensen)
$p_{3/2} \otimes p_{1/2}$	1	0	−6.22	−8.22	−10.02
	2	0	−4.00	−6.00	−9.41

⇧ monopole 2MeV stronger than psdmk2

Cohen-Kurath vs. Present Interactions

$N \sim Z$ nuclei



high $\varepsilon(j_<)$ + strong $V_{j_> - j_<}$

present

$\approx$

low $\varepsilon(j_<)$ + weak $V_{j_> - j_<}$

Cohen-Kurath

$N \gg Z$ or $N \ll Z$

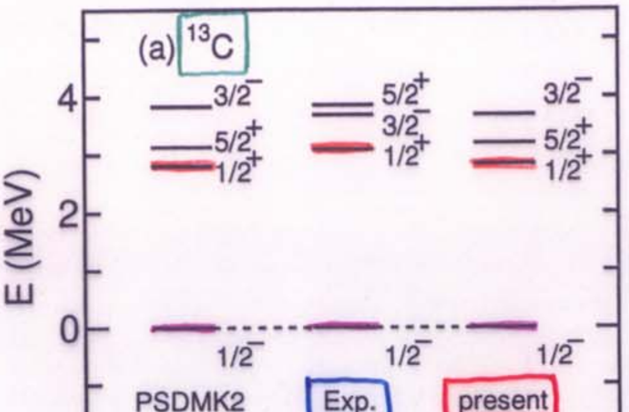
no such similarity

Energy Levels of ^{13}C, ^{11}Be & ^{9}He relative to experimental ground state

$^{13}_{6}C_{7}$ stable

$^{11}_{4}Be_{7}$ unstable

^{9}He unstable (unbound)



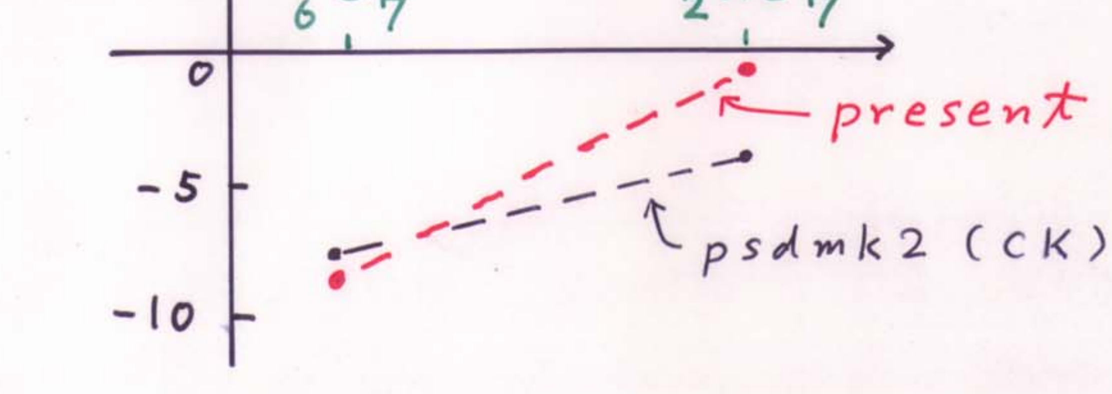
PSDMK2 Exp. Present Calc.

spin and GT properties are preserved or improved

S-factor of $2s_{1/2}$ in the $(1/2)_1$ state ~ 75%

- magnetic mom. Neugart et al.
- Transfer reaction Fortier et al
- B(GT; $3/2^-$ (^{11}B) → $1/2^-$ (^{11}Be)) Ohnishi et al.

Effective single-particle energy of $1p_{1/2}$ relative to $2s_{1/2}$



pf shell

new interaction

new magic (?)

$^{58}Ni(^3He, t)^{58}Cu$

^{56}Ni

New effective interaction GXPF1/2

- effective interaction for full pf-shell calculations

  p shell   Cohen-Kurath 1965

  sd shell   Wildenthal-Brown 1988

- 195 two-body matrix elements

  4 (bare) single particle energies

- G-matrix with core polarization correction by Hjorth-Jensen

  ⇨ starting point

- χ^2-fit

  70 (or 60) best determined linear combinations

  ⇕

  699 (623) data from 87 nuclei ($^{47}Ca \sim {}^{65}Ge$)

  699 = 490 yrast + 198 yrare + 11 higher

- rms error 168 (188) keV

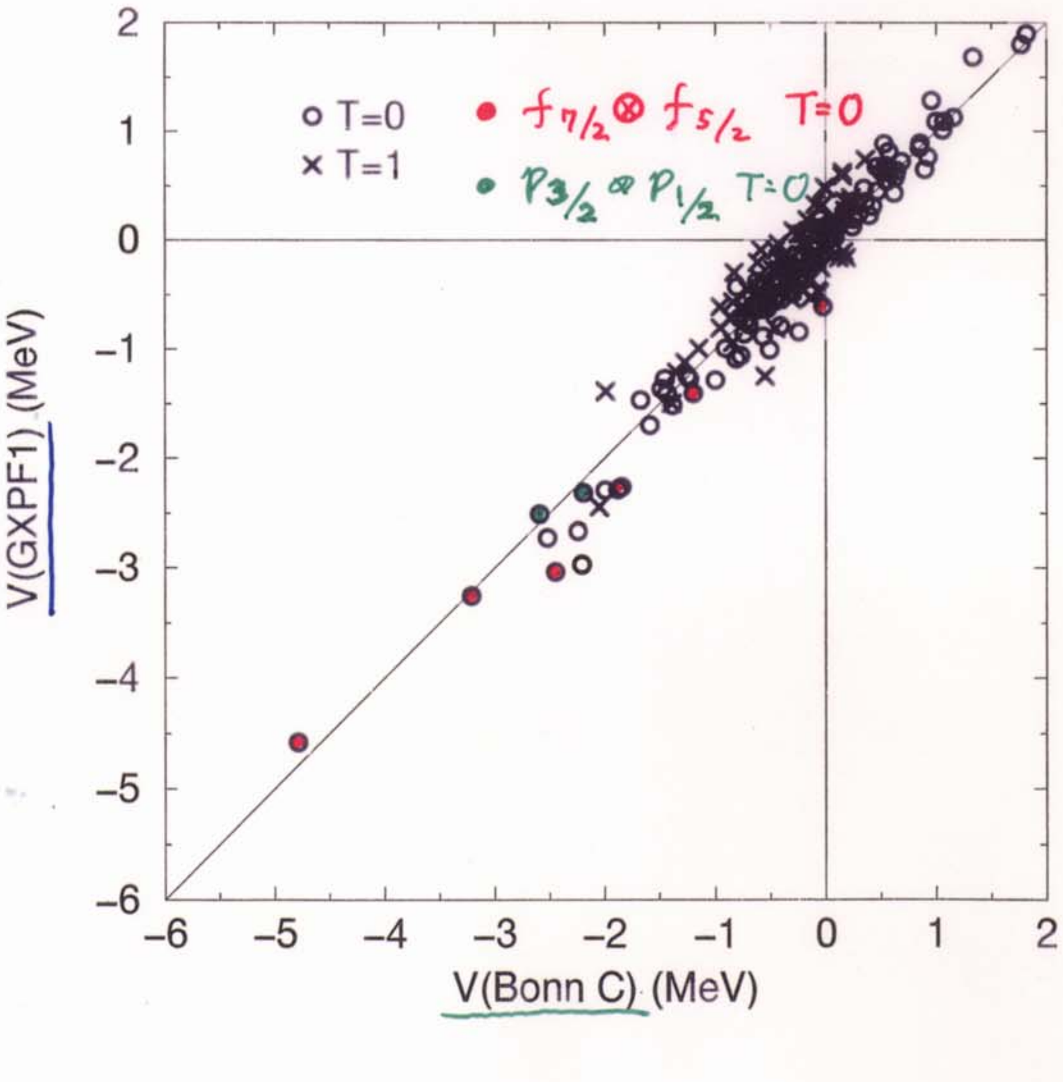
  for mass, ~130 keV

pf-shell interactions
(2-body matrix elements)

GXPF1 : empirically determined
two-body interaction

vs.

G-matrix with core-polarization
corrections from Bonn-C (H.-Jensen)



Energy Levels of $^{56,57,58}Ni$

Full pf-shell calculation by MCSM

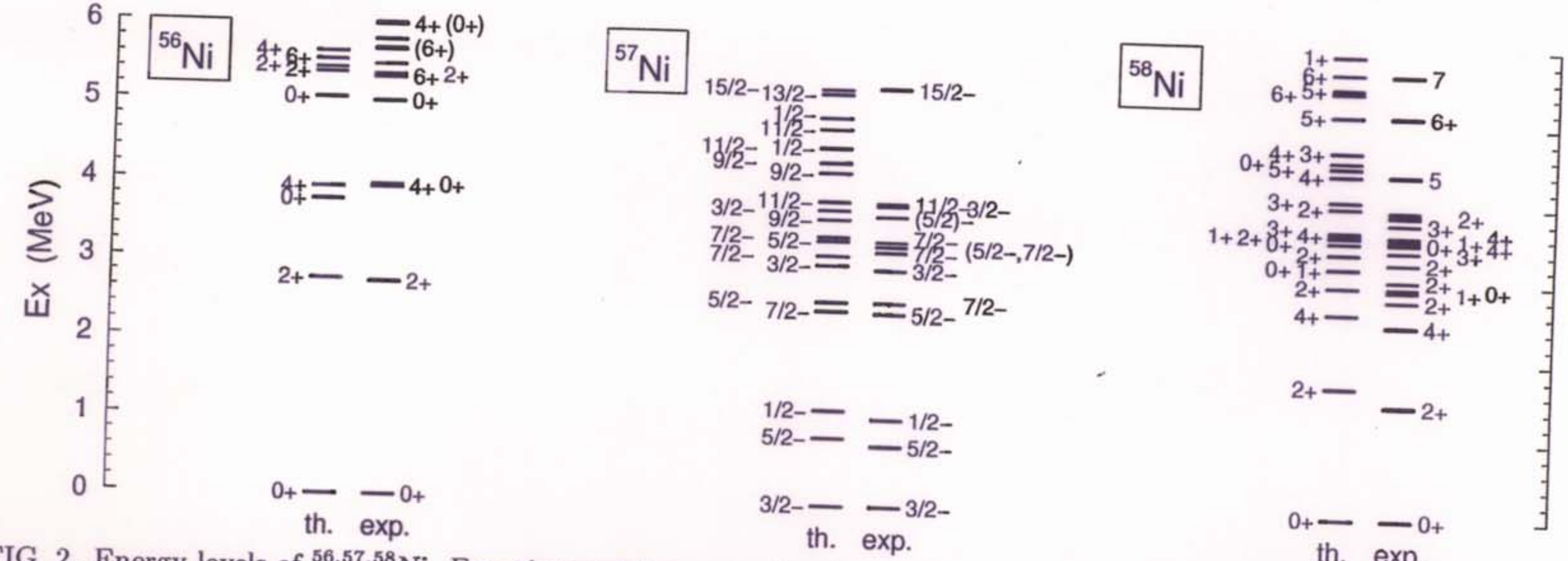
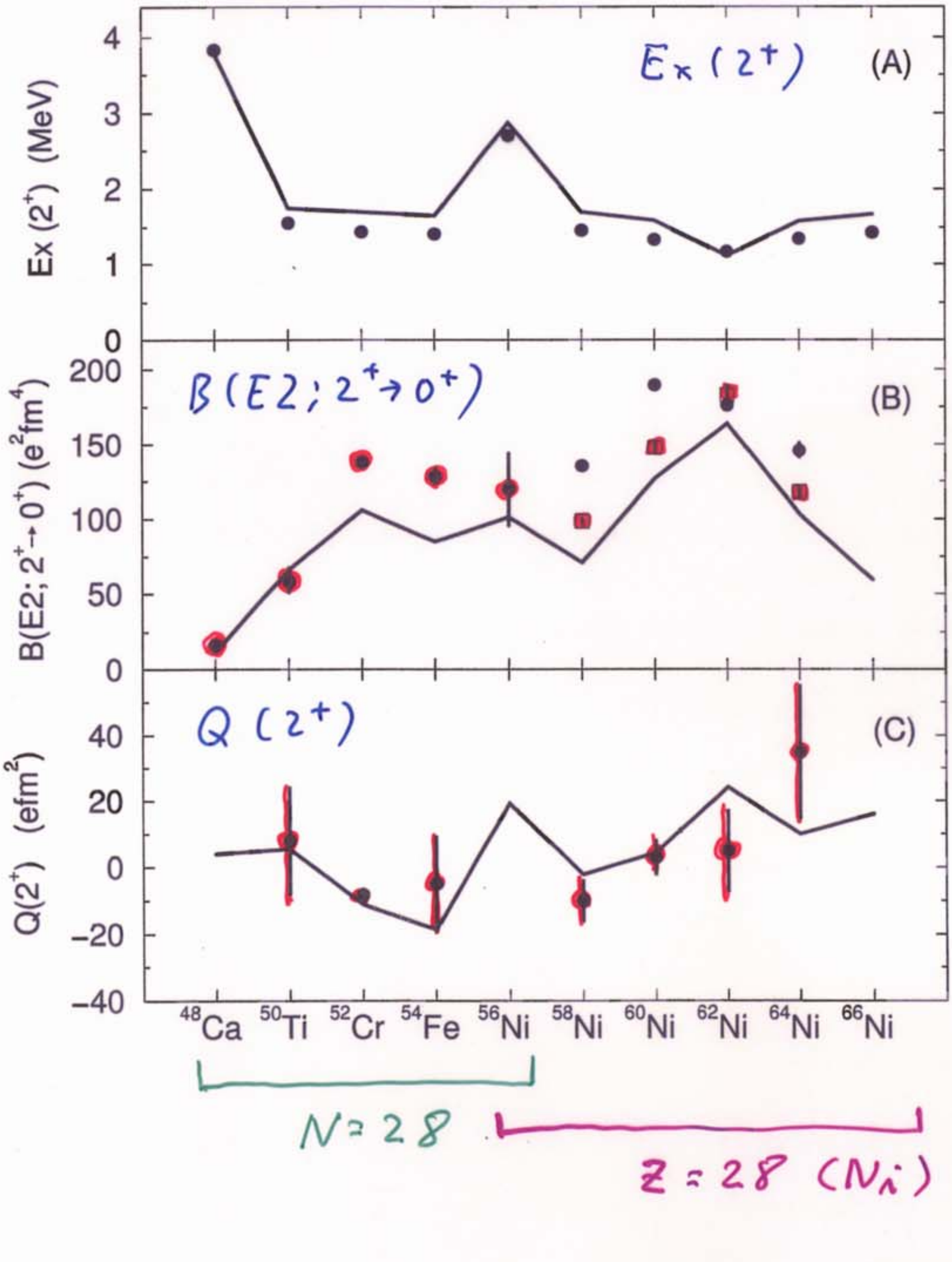


FIG. 2. Energy levels of ^{56,57,58}Ni. Experimental data are taken from ref. [17]. Above 4MeV, experimental levels are shown only for yrast states for ^{57,58}Ni.

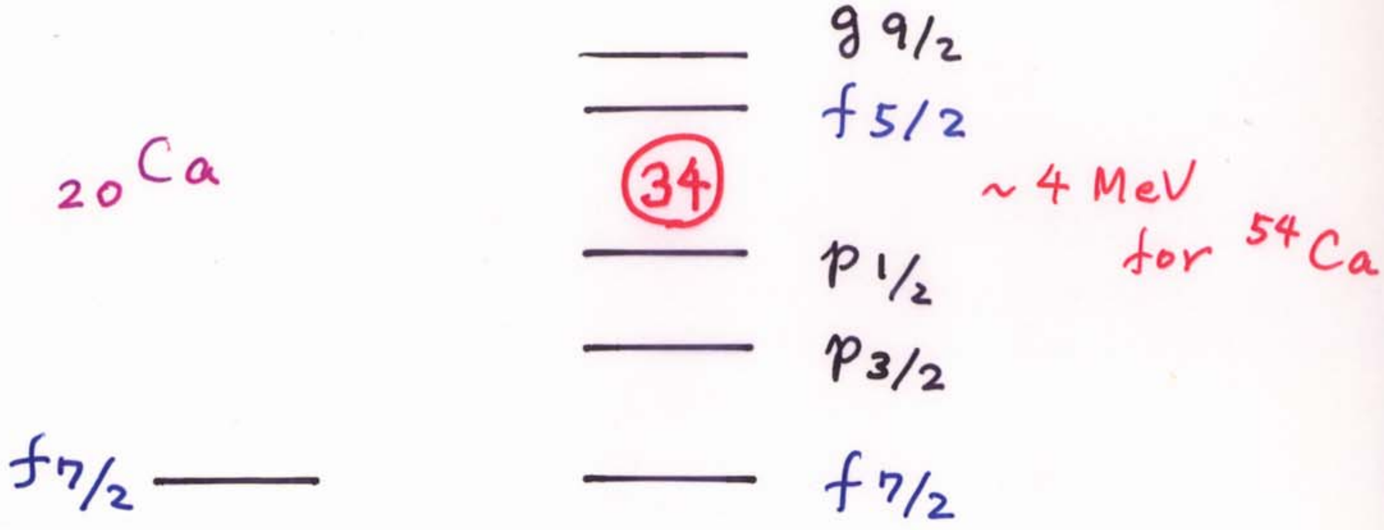
GXPF1 interaction

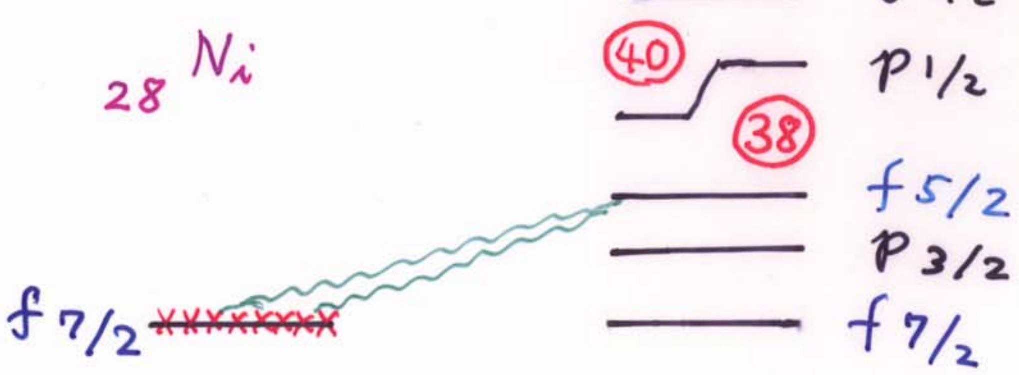
Honma et al. 2001



Ex (2+)
(A)
Ex (2+) (MeV)
B(E2; 2+→0+)
(B)
B(E2; 2+→0+) (e2fm4)
Q (2+)
(C)
Q(2+) (efm2)
48Ca 50Ti 52Cr 54Fe 56Ni 58Ni 60Ni 62Ni 64Ni 66Ni
N = 28
Z = 28 (Ni)

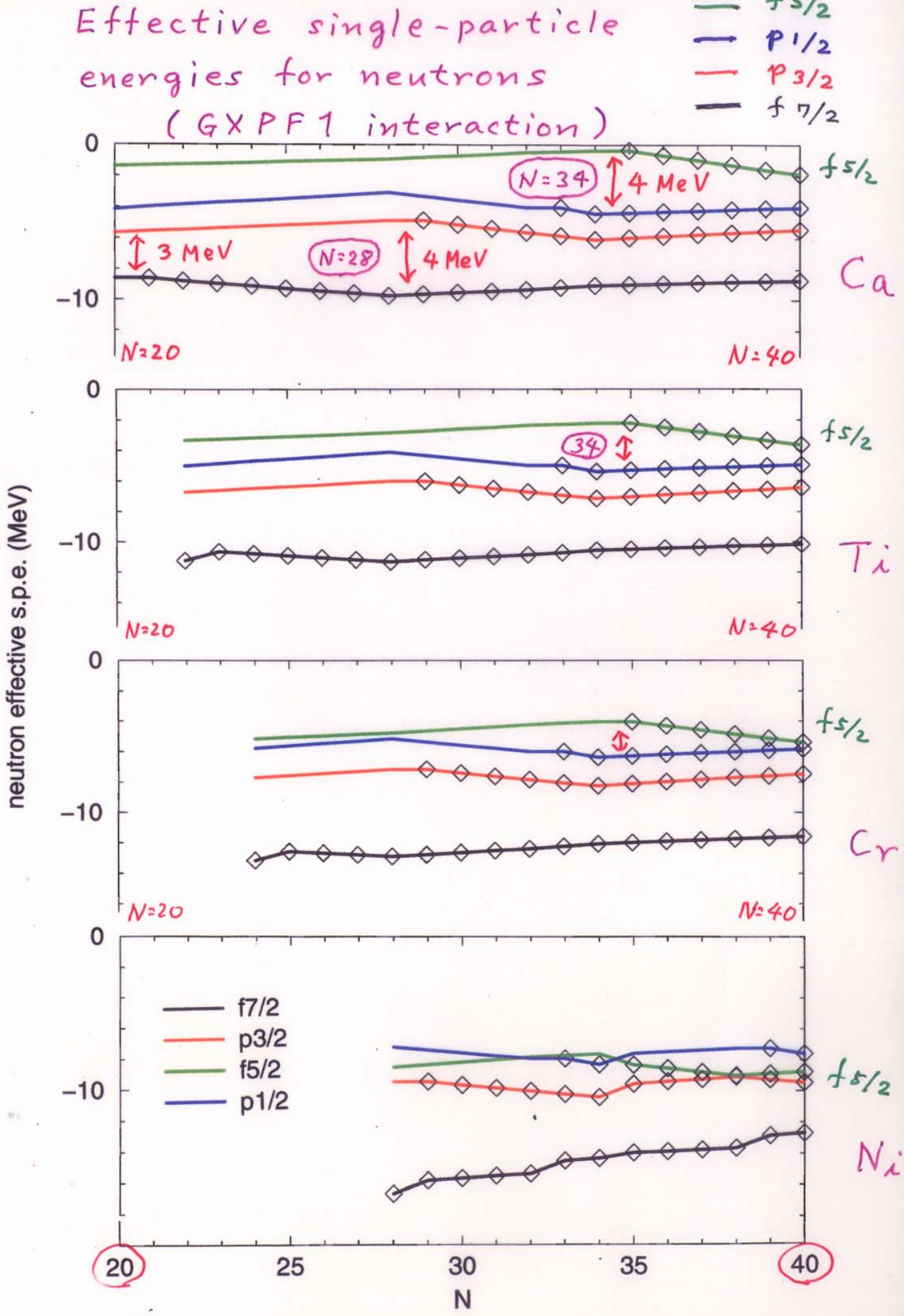
N = 34 magic structure





Note : A new effective interaction GXPF1 (2) by Honma et al.

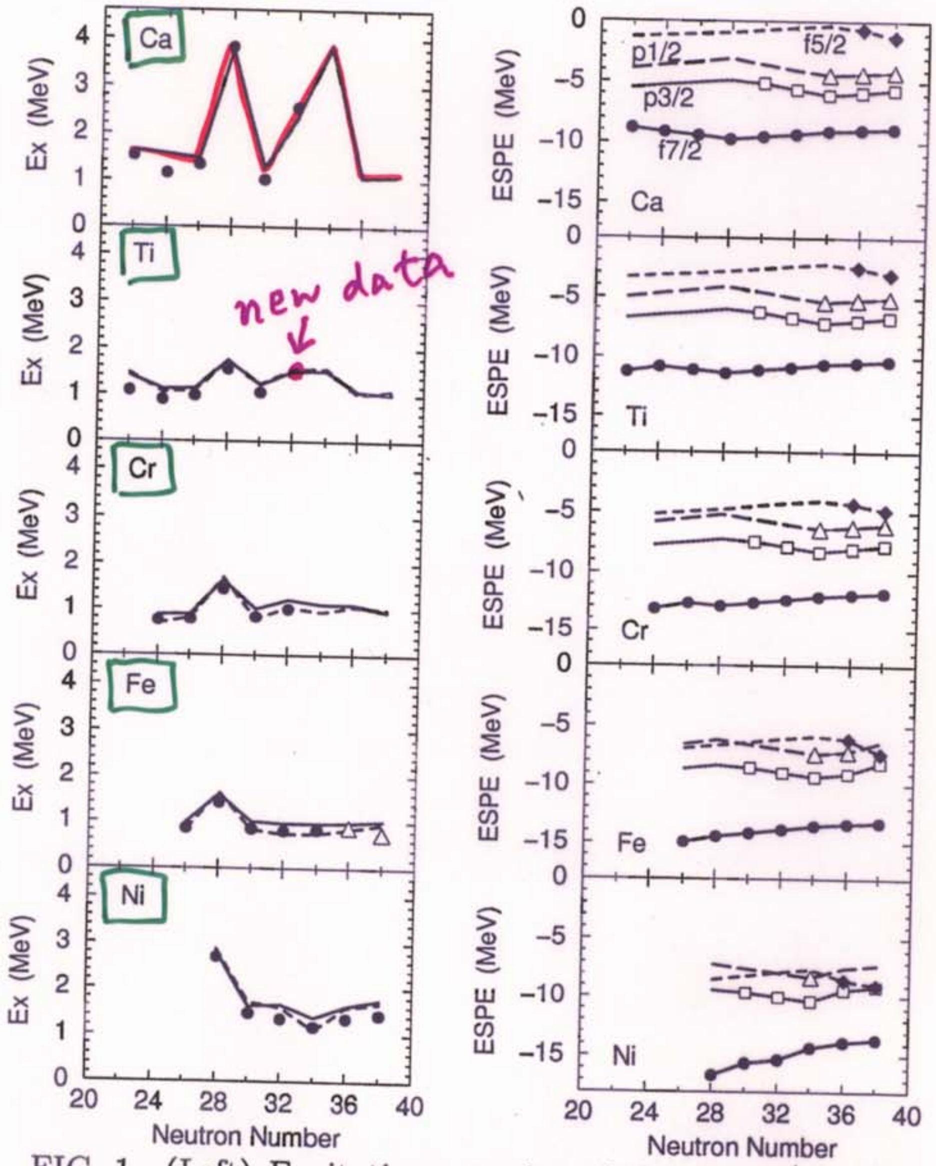
⇨ strongest attractive diagonal matrix elements are for $| f_{7/2} \otimes f_{5/2} ; J, T=0 \rangle$



Effective single-particle energies for neutrons (GXPF1 interaction)
f5/2
p1/2
p3/2
f7/2
N=34
4 MeV
3 MeV
N=28
4 MeV
Ca
N=20
N=40
34
Ti
Cr
Ni
neutron effective s.p.e. (MeV)
N
0
-10
20
25
30
35
40

Full pf-shell calculations with GXPF1 interaction

2⁺ levels   eff. s.p.e's



Honma et al. 2001

FIG. 1. (Left) Excitation energies of the first 2^+ states. Experimental data are shown by filled circles [17] and open triangles [18]. Theoretical values obtained by shell model calculations are shown by solid lines. The truncation order t (the maximum number of nucleons which are allowed to excite from $f_{7/2}$ to higher orbits: $p_{3/2}$, $p_{1/2}$, $f_{5/2}$) is 5 for ^{56}Fe and ^{58,60,62}Ni, 6 for ^{52,54}Fe and ^{56}Ni, and 7 for ^{58,60}Fe. Other results are exact. Dashed lines show the results obtained by the FDA*. (Right) Effective single particle energies for neutron orbits. Symbols indicate that the corresponding orbit is occupied by at least one nucleon in the lowest filling configuration.

Summary

In some exotic nuclei, the magic numbers do change from those for stable nuclei.

stable	2,	8,	20,	28,	38 / 40,	...
exotic	2,	6,	16,	28,	34,	...

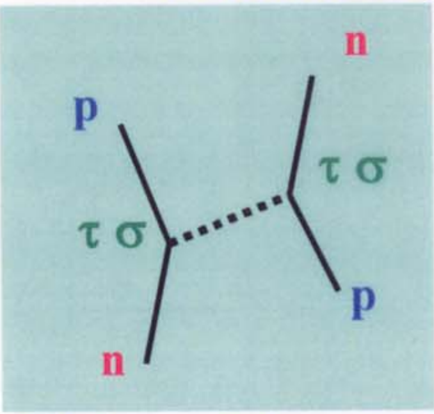
Origin : strong $j_{>}$ - $j_{<}$ coupling in T=0 channel

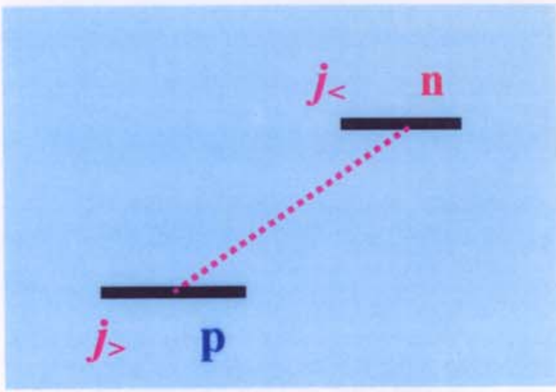
as confirmed by G-matrix and empirical fit

A major basic mechanism producing this coupling :

$$(\tau\,\tau)\,(\sigma\,\sigma)\,f(r)$$

meson exchange and $1/N_c$ expansion of QCD





This explains various structures of exotic nuclei.

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

* * * * * * * * * * * * * * *

The same interaction affects spin-isospin properties.

GT transitions : ^{11}B(d, ^{2}He) ^{11}Be, ^{58}Ni(^{3}He,t) ^{58}Cu, etc

Magnetic moments : p-shell nuclei, e.g., ^{12}B-^{12}N