From magic numbers to exotic nuclei

O. Sorlin – GANIL Caen

I . General introduction to the atomic nucleus, shell closures, nuclear forces

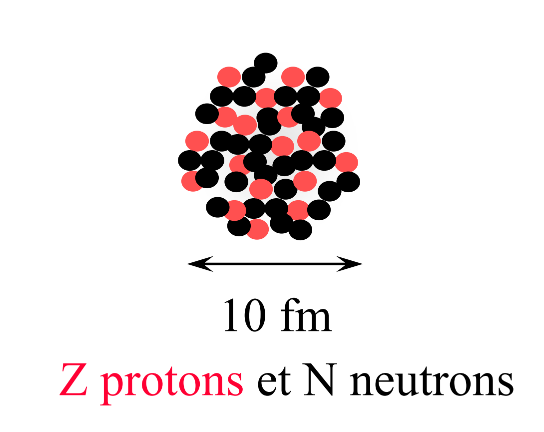
II. Study of the N=20 shell closure

III. Study of the N=28 shell closure

IV. General conclusions / perspectives

I . General introduction to the atomic nucleus, shell closures, nuclear forces

The atomic nucleus : a world apart !



Understand and model a microscopic system, the constituents of which are in strong and short range interaction ~1fm.

Paradoxically, Mean field approach appropriate for 'heavy' nuclei (Pauli)
From charge density to mean field potential
Nucleons arranged on orbits -> irregular spacing gives rise to shell gaps

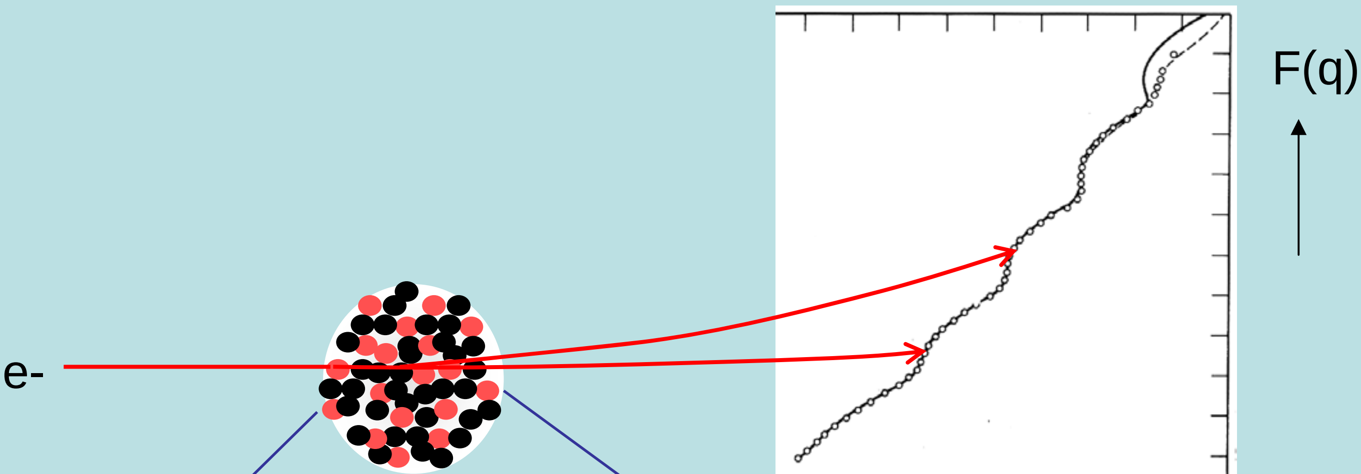
Residual interactions to account for excitations, e.g. two body interaction

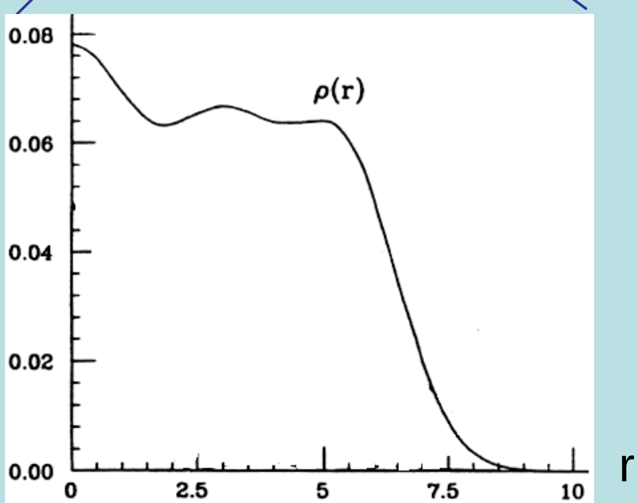
Two body interactions differ from the bare NN forces

Nucleons are self-generating their mean field (contray to e- in atoms)

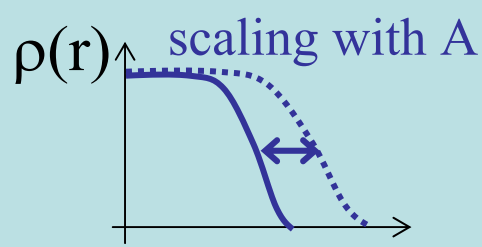
Two quantum 'fluids' -> allows nn, np, pp interactions having different strengths

Charge density of the nucleus : ρ(r)





Large transferred momentum **q** provides shape of the central density distribution



Probing nuclear orbits with (e,e'p) reaction

Orbital labelling

n,L,J

n nodes (n=0,1,2)
L angular momentum
(s,p,d,f,g,h…)
$(-1)^L$ parity

|L-s|<J<|L+s|
(2J+1) per shell

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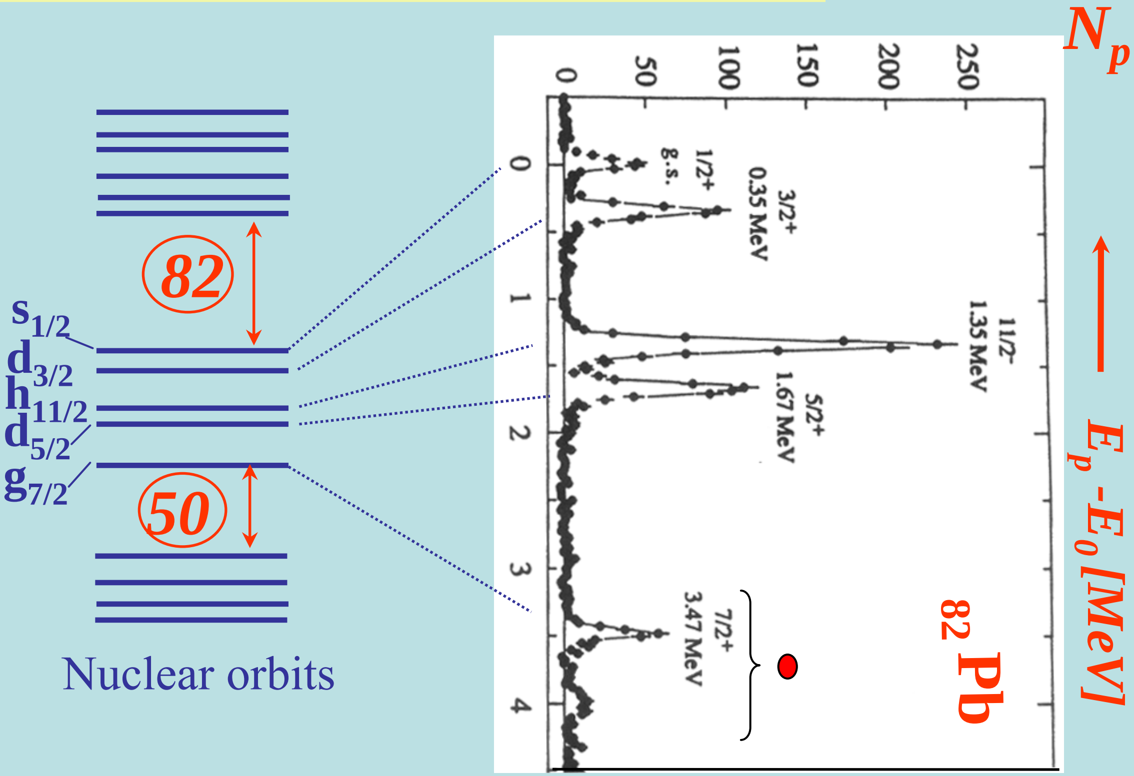
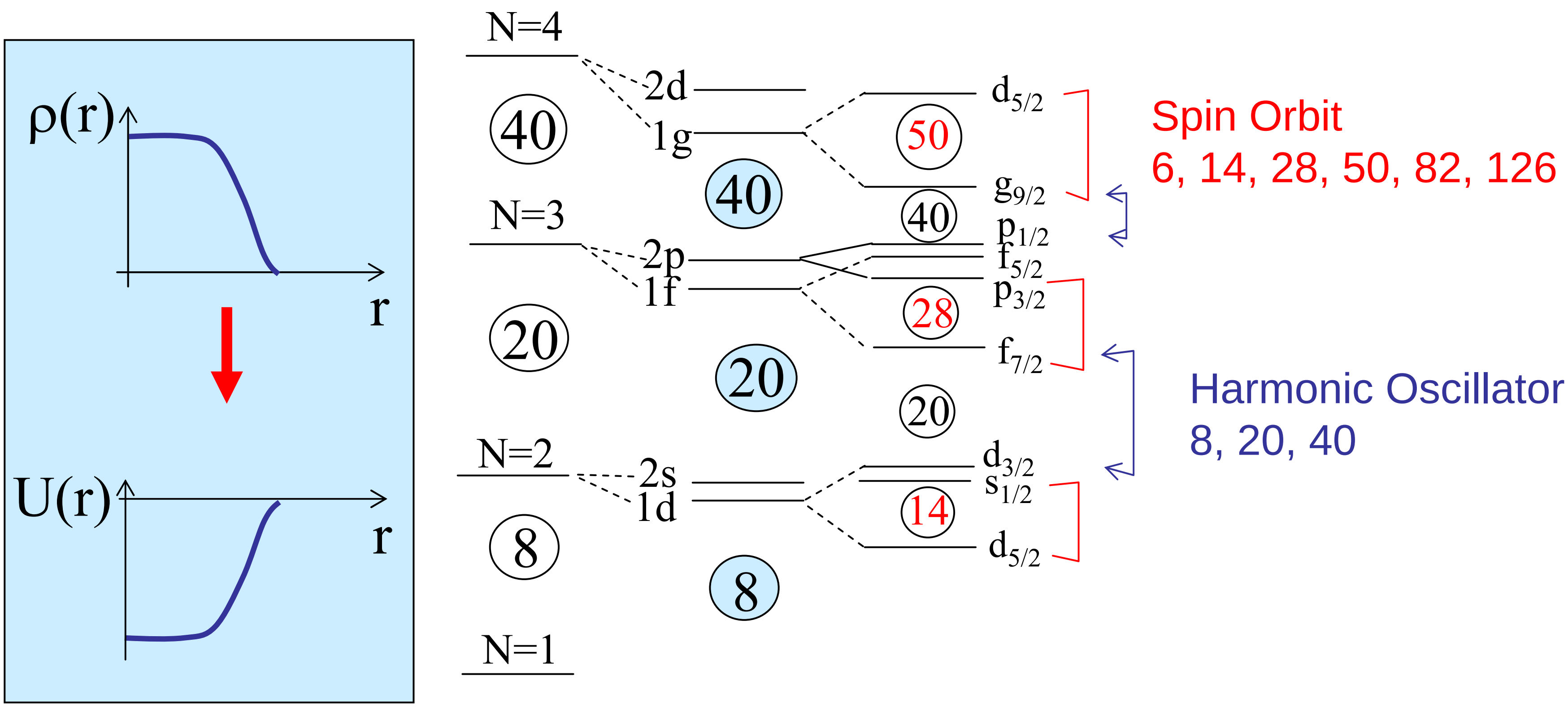
example :
$h_{11/2}$: L=5, J=11/2,
L and s aligned
contains 12 nucleons



->Nucleons are arranged on shells
-> Gaps are present for certain nucleon numbers
-> N_p detected follows orbit occupancy
-> Mixing with collective states at high E*
-> Study limited to STABLE nuclei

Simplified mean-field approach for atomic nuclei

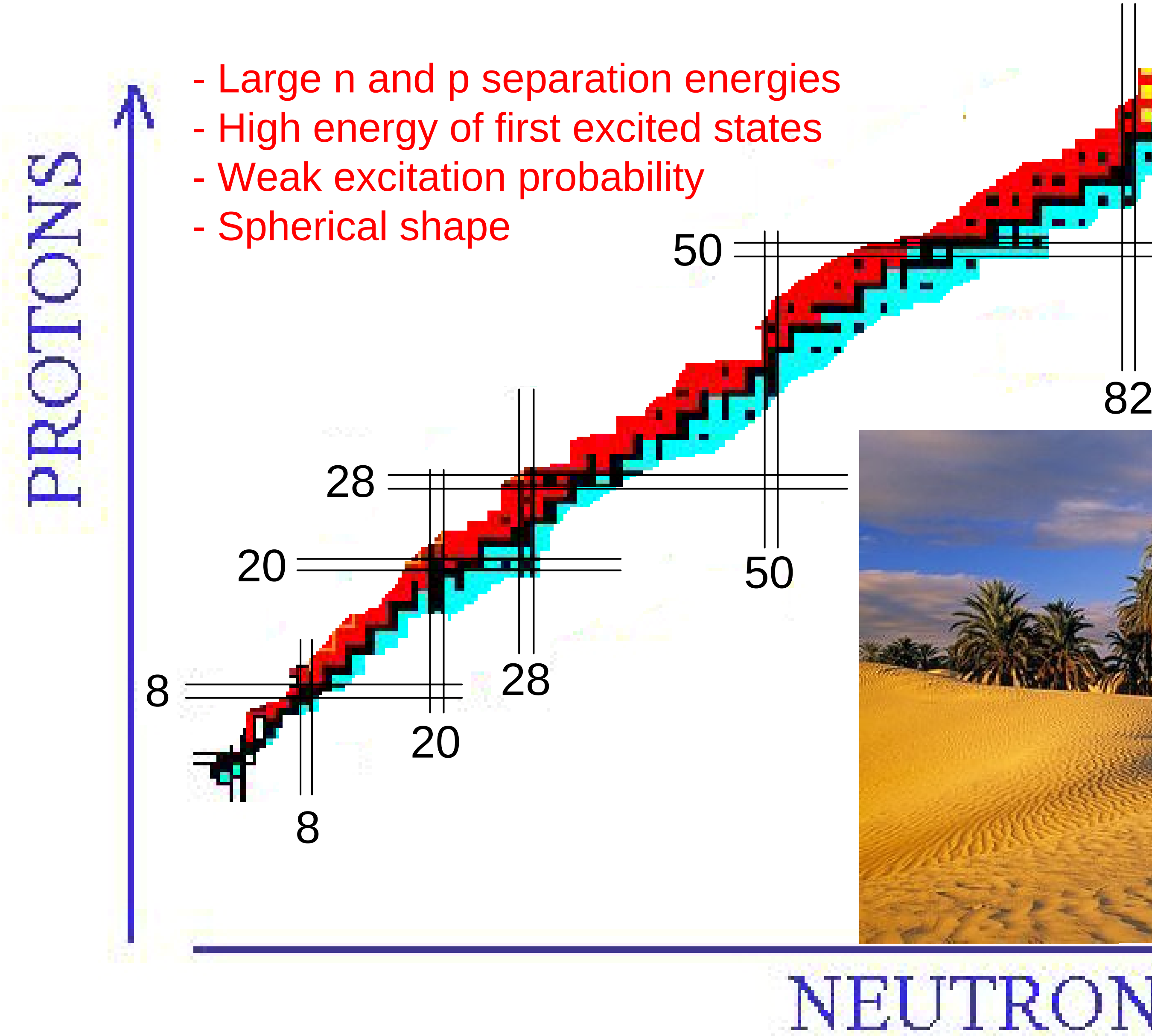


$$\mathrm{H.O} + L^2 + \vec{L}.\vec{S}$$

$$U(r) = \int_{vol} \rho(r')v(r,r')d^3r' = \int_{vol} \rho(r')[-v_0\partial(r-r')]d^3r' = -v_0\rho(r)$$

Our vision of MAGIC numbers up to 70's – universality …

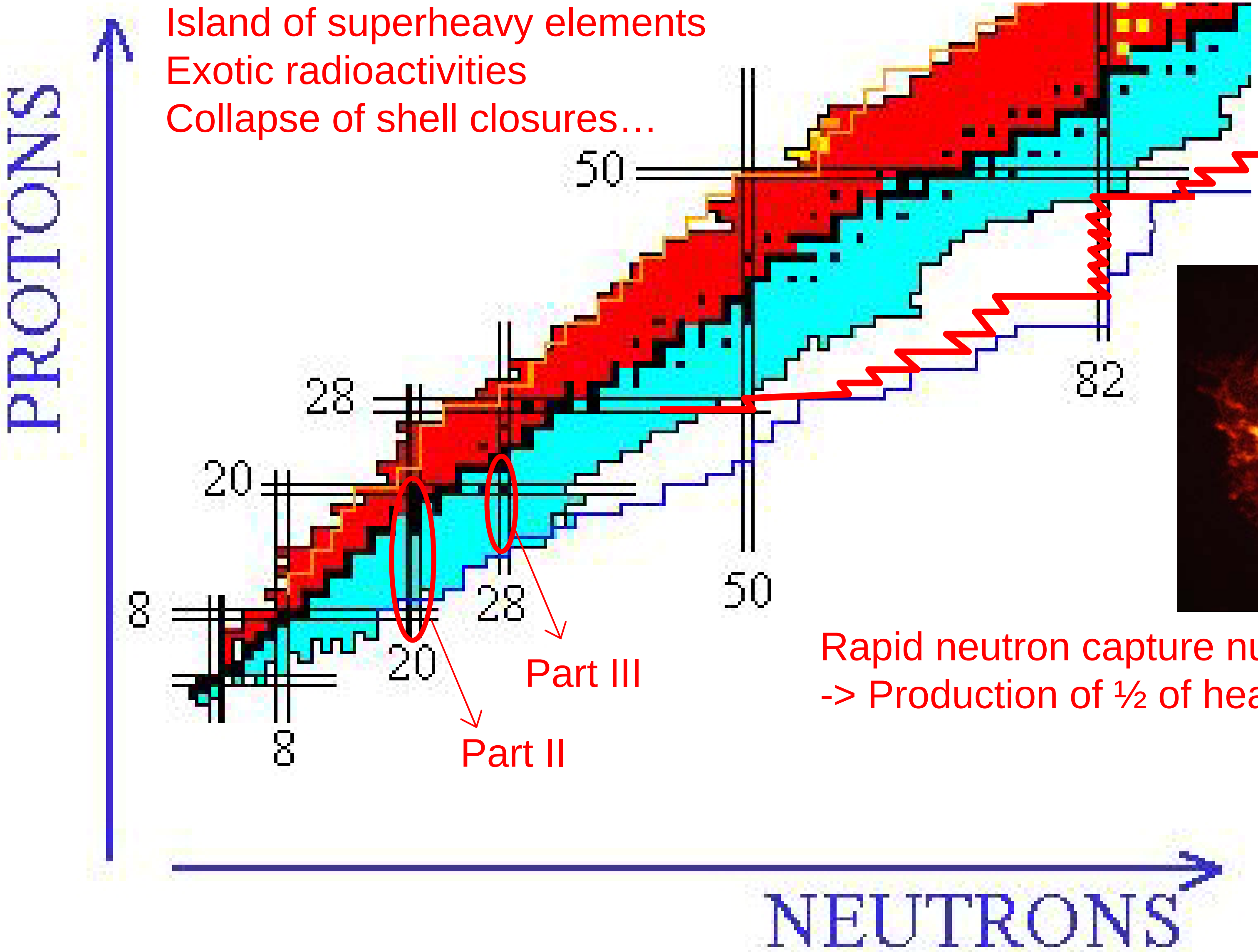
- Large n and p separation energies
- High energy of first excited states
- Weak excitation probability
- Spherical shape

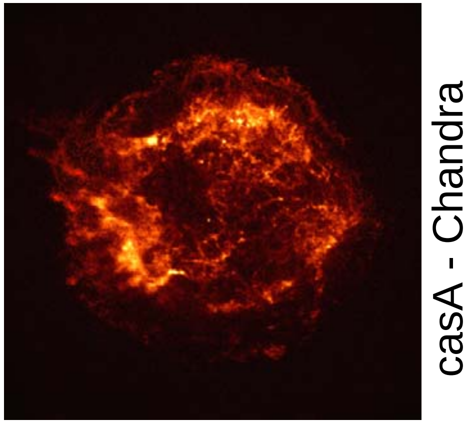


To real …

Enlarged vision of nuclear structure using worldwide accelerators

Haloes and cluster structures
Island of superheavy elements
Exotic radioactivities
Collapse of shell closures…





casA - Chandra

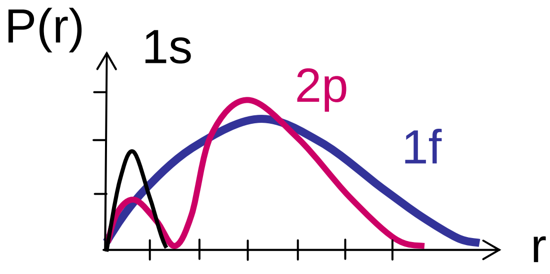
Rapid neutron capture nucleosynthesis
-> Production of ½ of heavy elements

How can magic numbers be modified by properties of nuclear forces ?

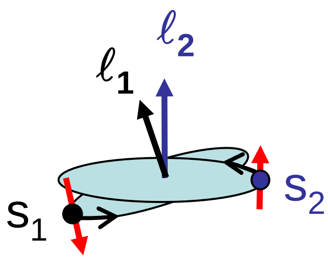
Main features of the nucleon-nucleon interaction

Radial overlap (radial WF) : larger when $n_1=n_2$

Angular momentum : Stronger for $\ell_1=\ell_2$

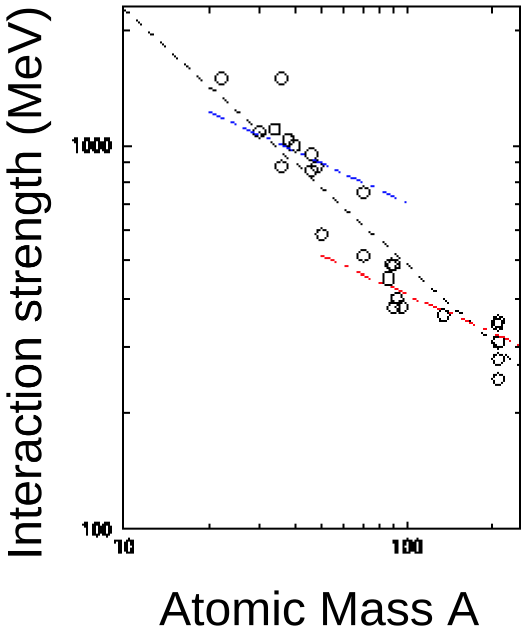


Relative spin – orbital momentum orientation : spin-orbit, tensor

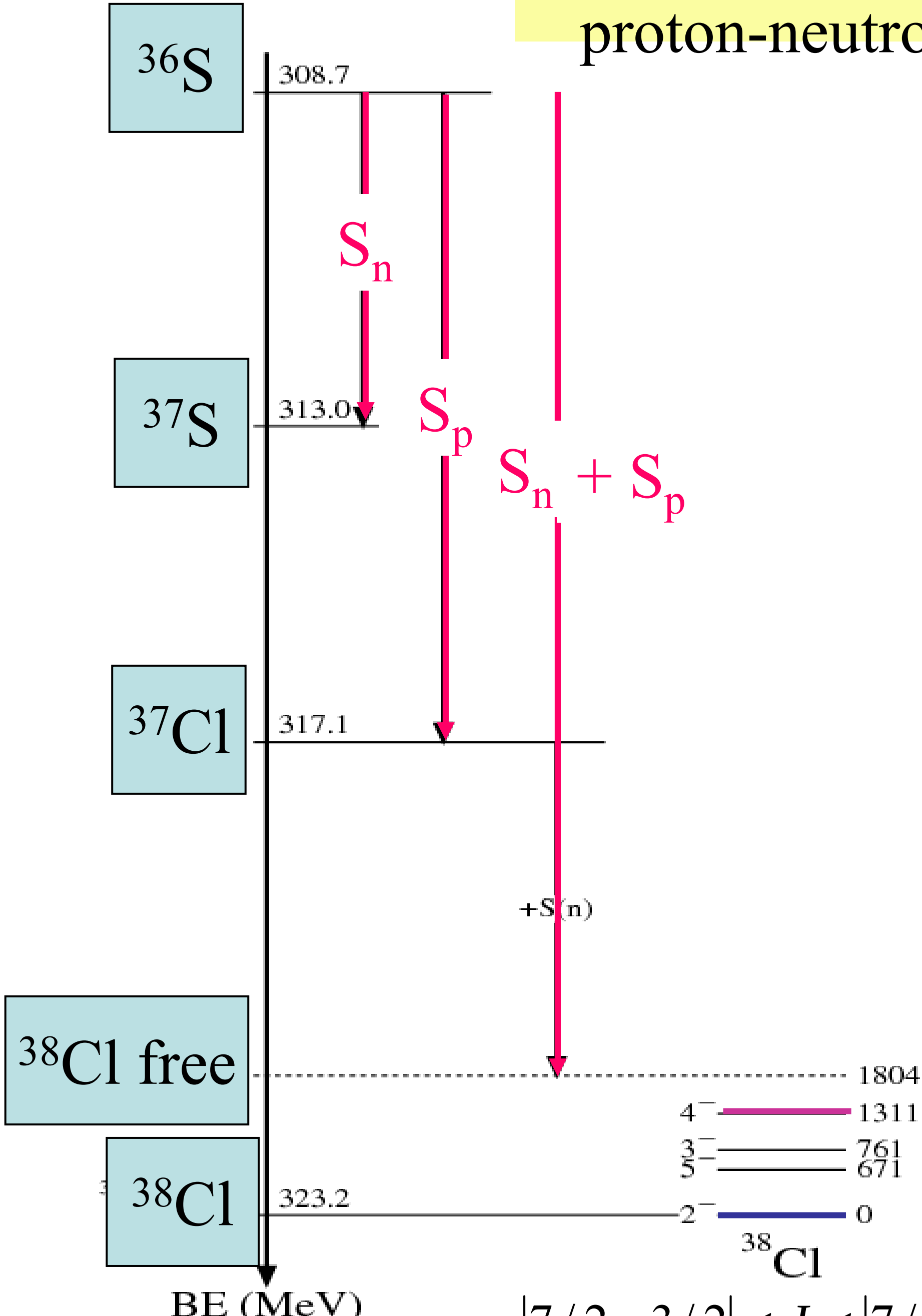


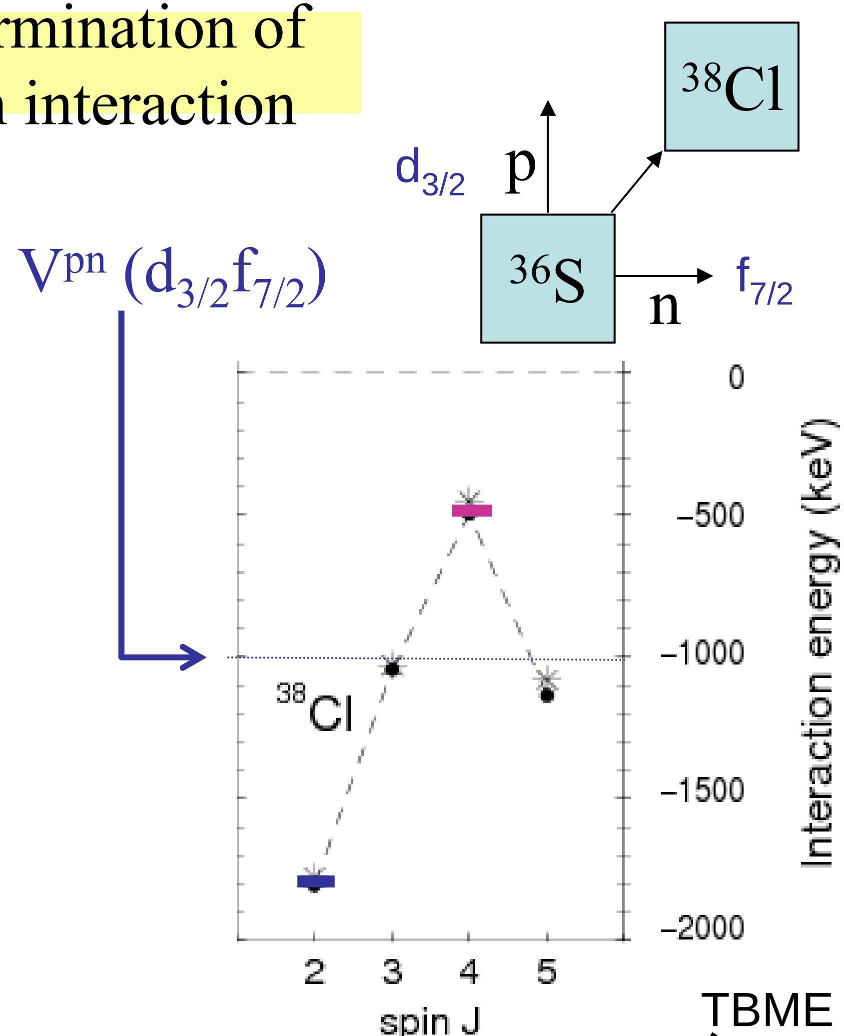
Radius of the orbits (scales with 1/r or $A^{-1/3}$)

smoother changes in structure of heavy nuclei



Empirical determination of proton-neutron interaction



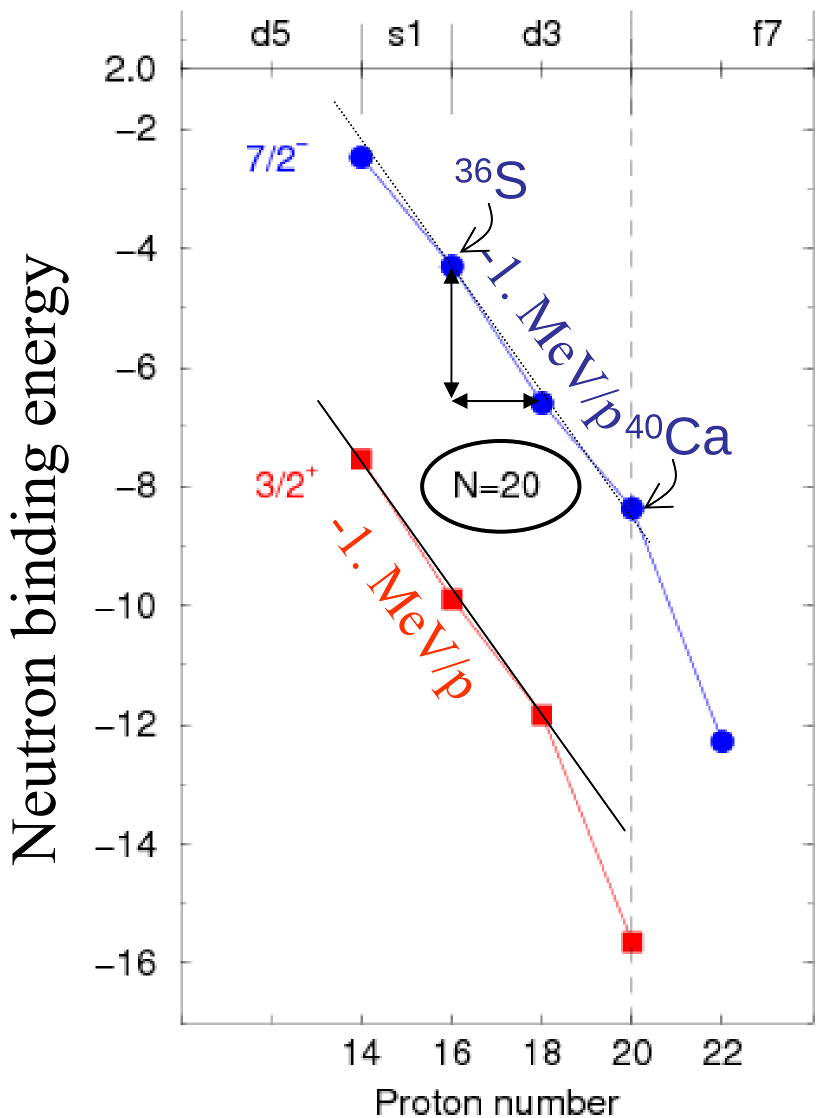


TBME

$$V_{pn} = \frac{\sum_J (2J+1) \times v_{pn}^J (j_p, j_n)}{\sum_J (2J+1)}$$

$$|7/2 - 3/2| < J < |7/2 + 3/2|$$

Additive n-p interactions in the ^{36}S region ?

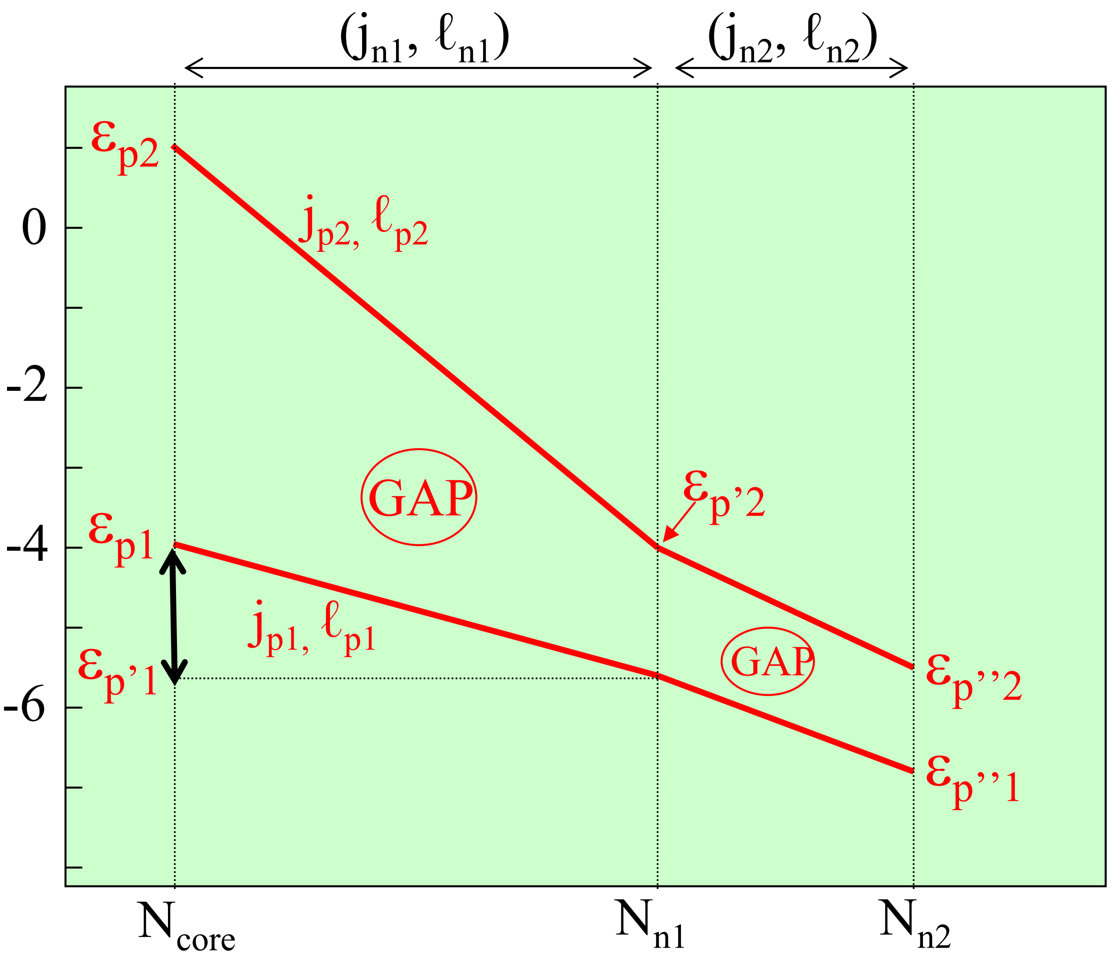


V^{pn} ($d_{3/2}f_{7/2}$) ~ -1 MeV per proton

Vpn ($d_{3/2}d_{3/2}$) ~ -1 MeV per proton

The N=20 shell gap is unchanged !

Evolution of nuclear structure from monopole interactions



Effective Single Particle Energy

Variations from monopoles only

At closed shells

ESPE ~ - Sp(Z)

=[BE(Z-1,N) – BE(Z,N)] c^2

Derived from experimental masses

$$(\varepsilon_{p'1} - \varepsilon_{p1}) = (2j_{n1}+1)\, V^{pn}_{jp1\, jn1}$$

$$(\varepsilon_{p'2} - \varepsilon_{p2}) = (2j_{n1}+1)\, V^{pn}_{jp2\, jn1}$$

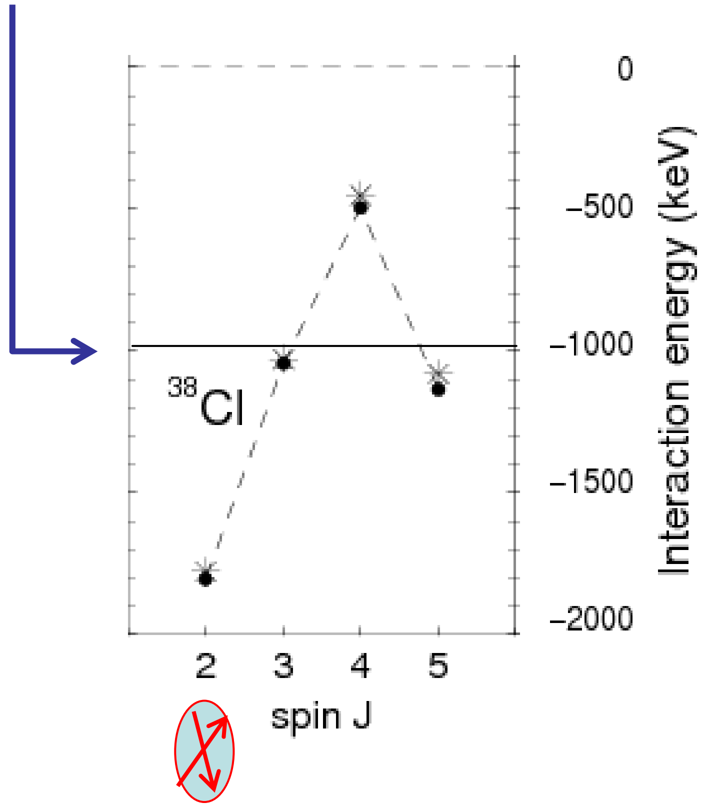
$$\Delta(GAP) = (2j_{n1}+1)\, (V^{pn}_{jp2\, jn1} - V^{pn}_{jp1\, jn1})$$

GAP are changed while significant monopole differences are present

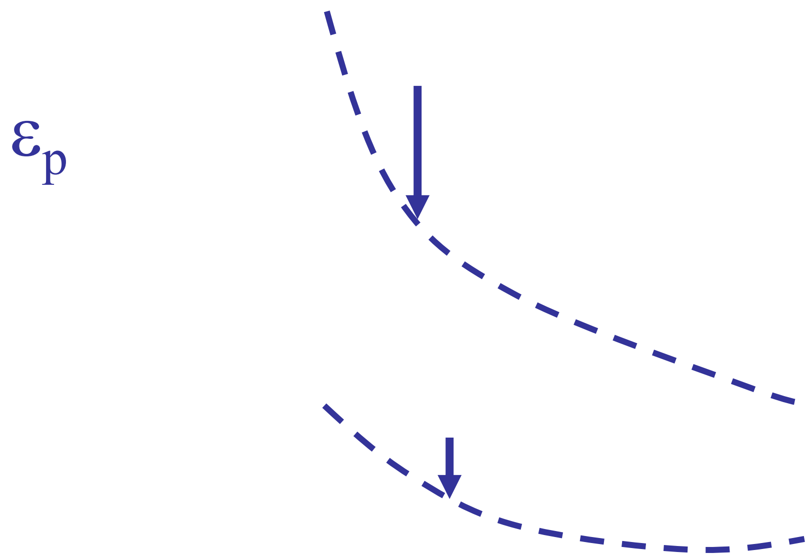
-> Governed by NN forces

The role of quadrupole correlations in atomic nuclei

$V^{pn}\ (d_{3/2}f_{7/2})$

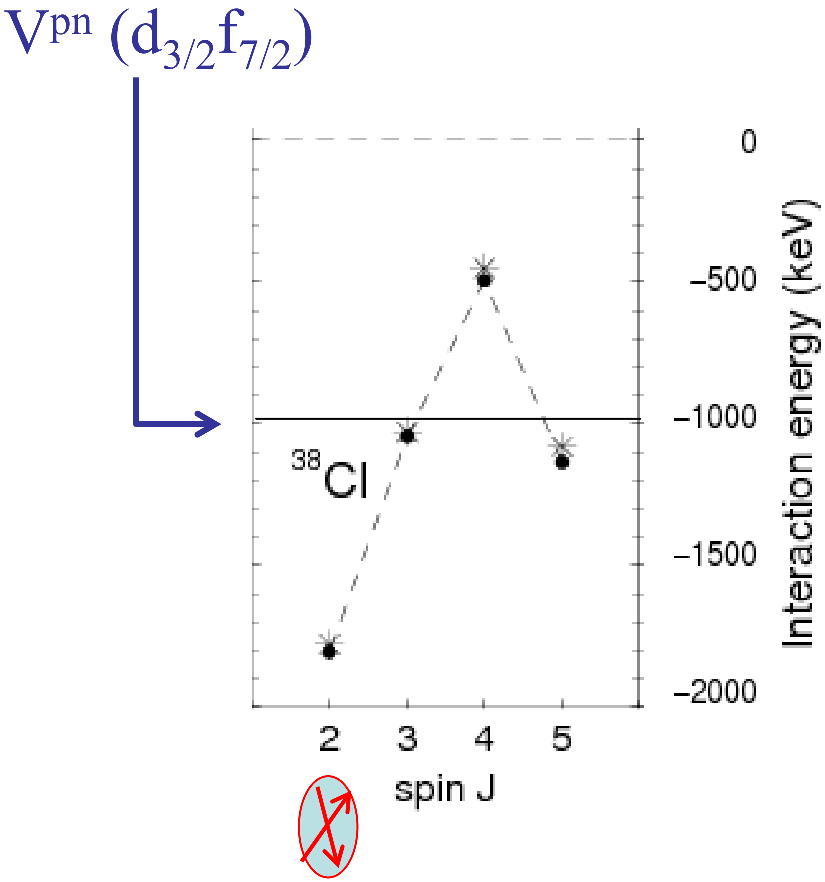


Quadrupole energy can be gained
for certain orientations of particles



At mid-shell, deviation from linear monopole trend is observed.

The role of quadrupole correlations in atomic nuclei



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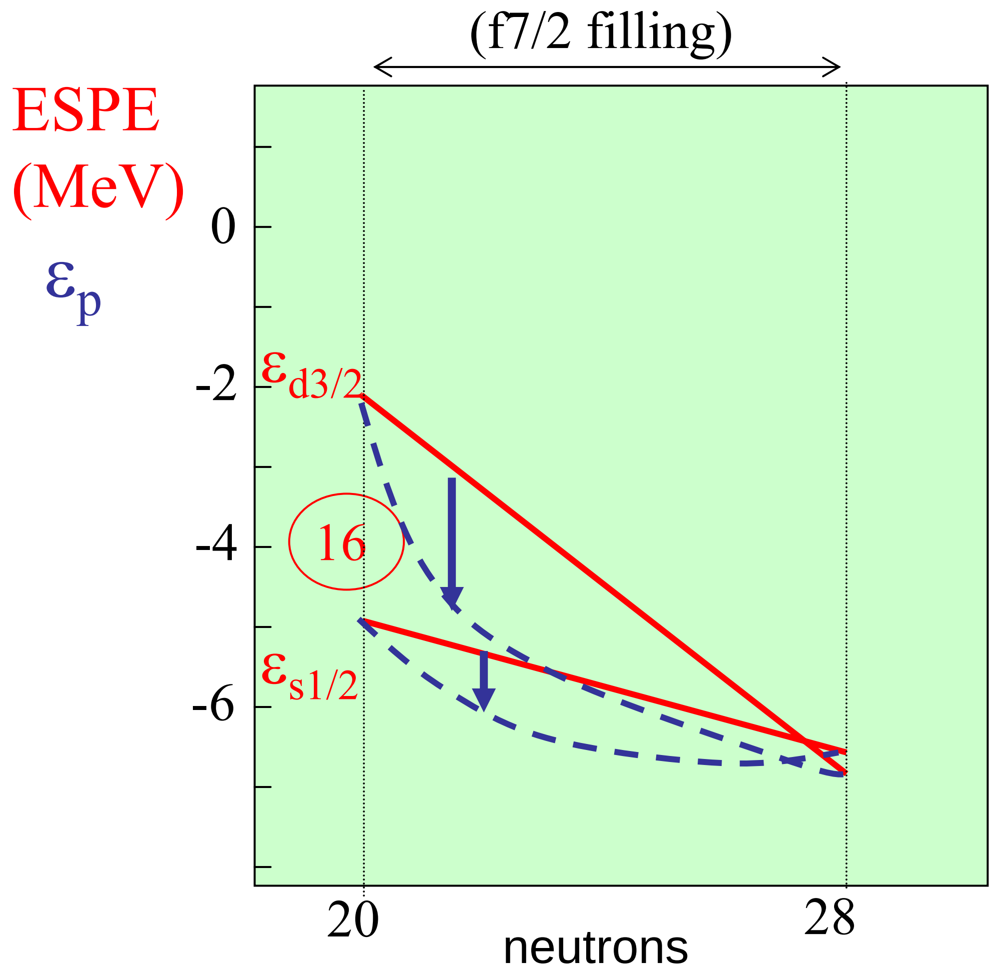
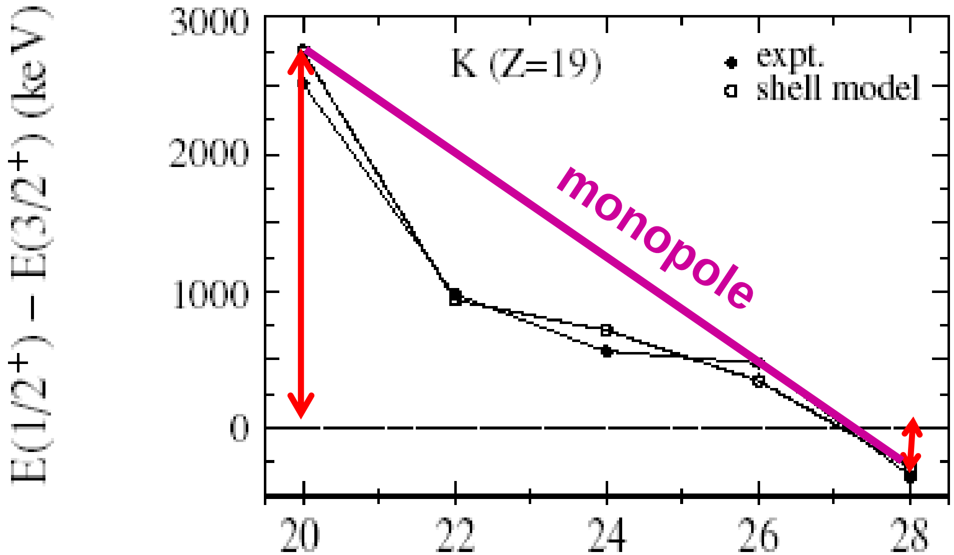


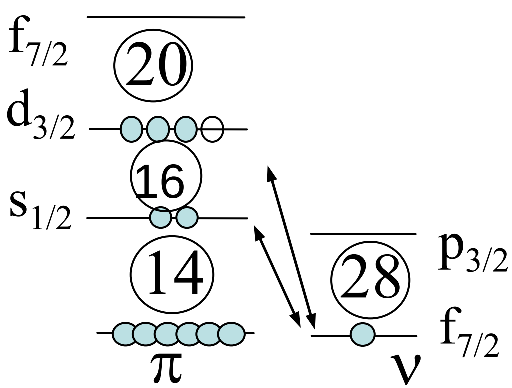
At mid-shell, deviation from linear monopole trend is observed.

Evolution of proton configurations in the K chain

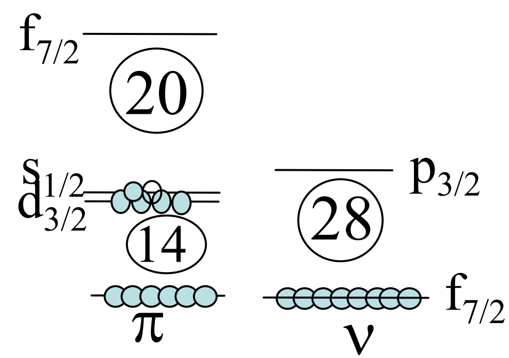


Exp :(d,3He) or ee'p.
[Doll 76, Banks 85, Kramer01]

Role of pn monopole force
$Vd_3f_7 >> Vs_1f_7$



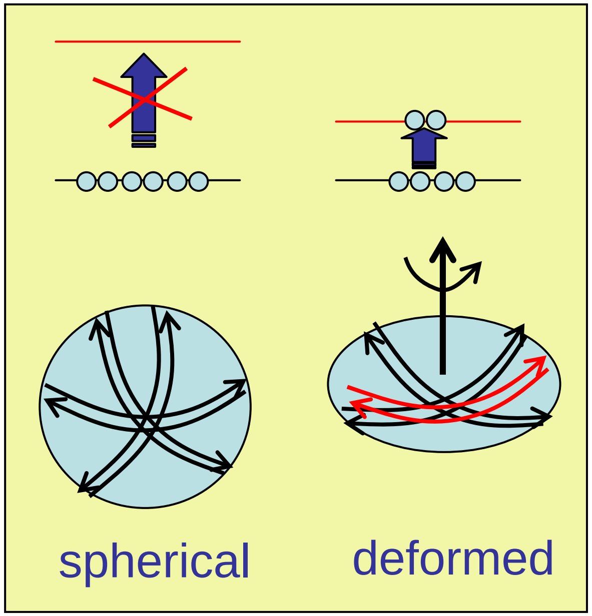
Z=19 K **N=21**



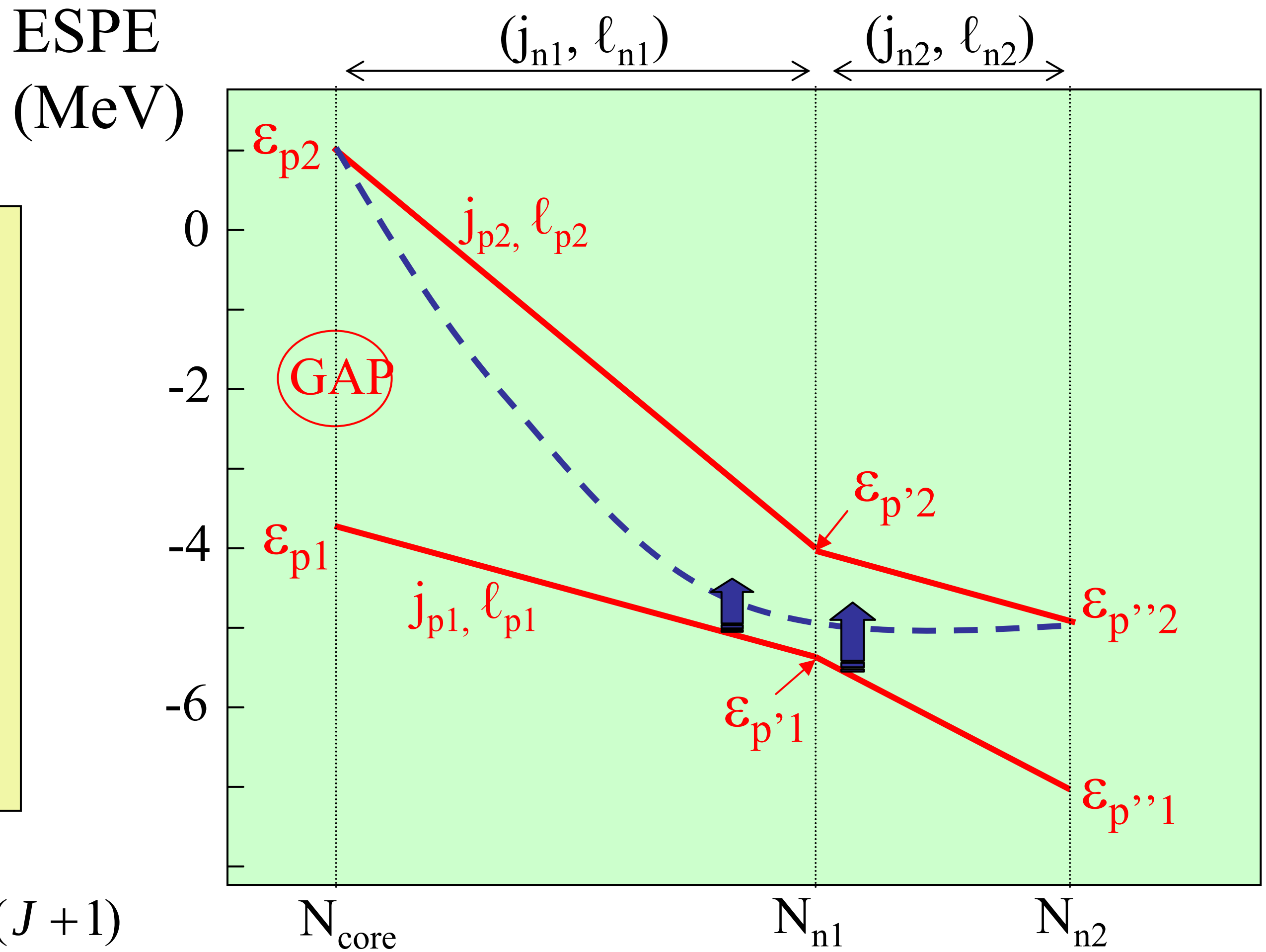
Z=19 K **N=28**

Proton $s_{1/2}$ and $d_{3/2}$ orbits degenerate

From spherical to deformed nuclei



$$E(J) = \frac{\hbar^2}{2\Im} J(J+1)$$

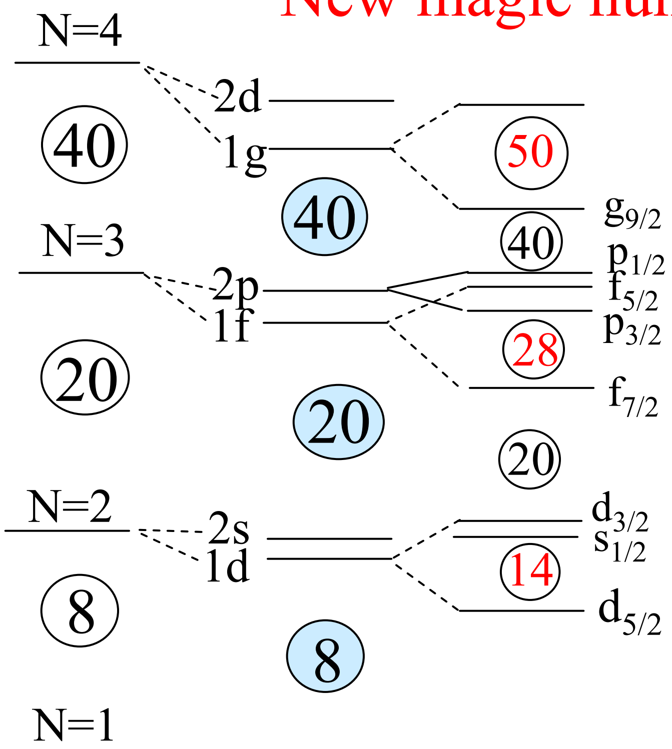


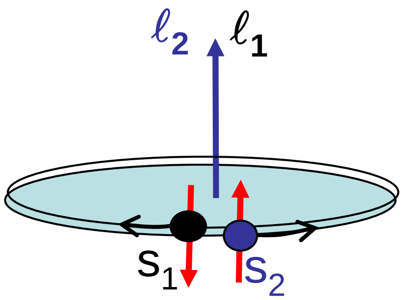
When a spherical gap weakens, cross shell excitations can develop
Quadrupole energy gain can bring the nucleus to deform
If large deformation : low 2^+ energy, large B(E2) value


From two-body short-range interactions to collective motion

II . The N=20 shell closure

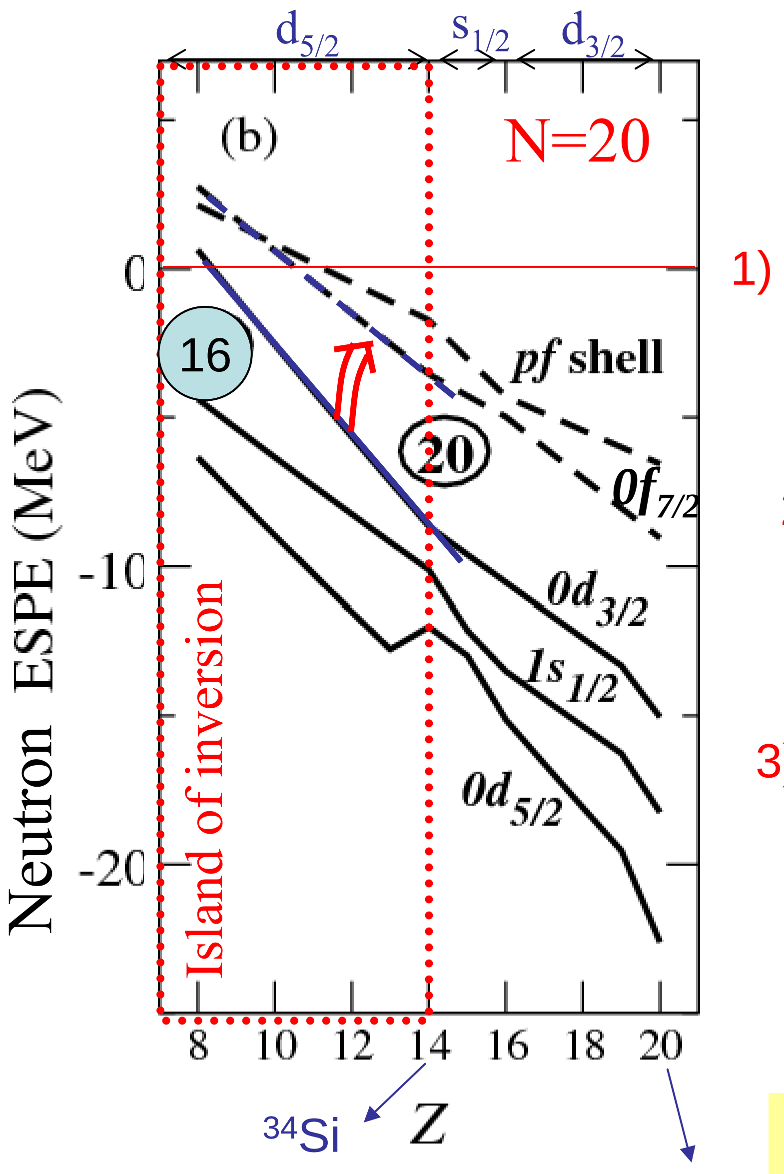
Role of proton-neutron interaction $\pi d_{5/2}$-$\nu d_{3/2}$?
Collapse of shell closure
New magic number





$$H.O + L^2 + \vec{L}.\vec{S}$$

ESPE in N=20 isotones and structural changes



1) ^{28}O unbound ?

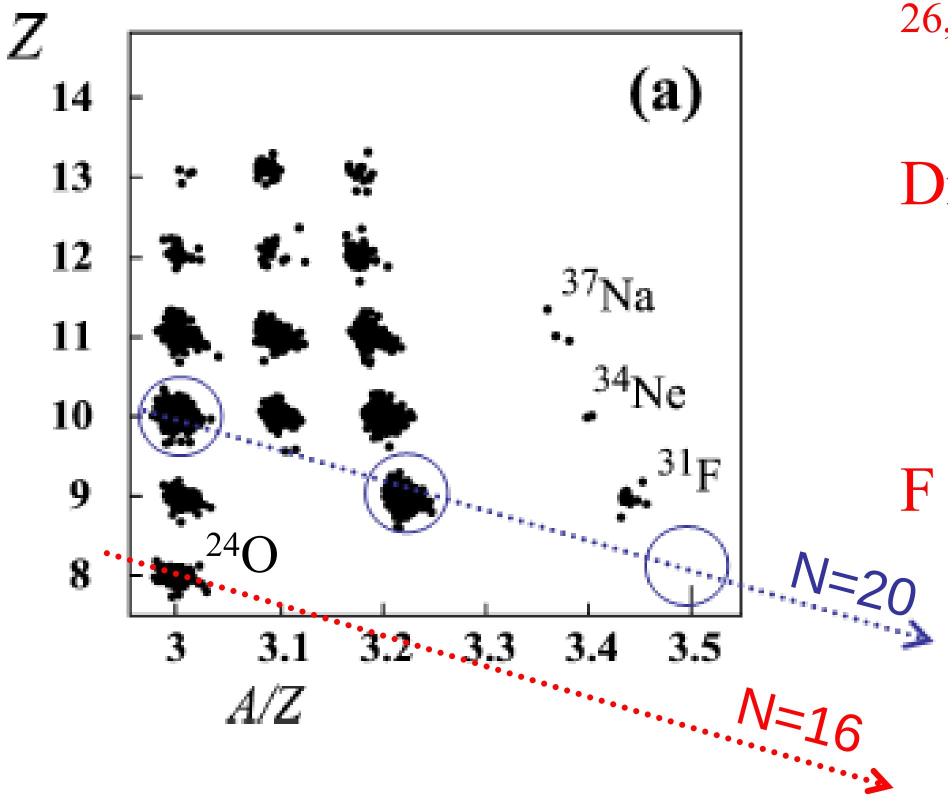
2) N=20 disappears :
   Enhanced cross shell excitations
   Low 2^+, high B(E2)

3) Birth of a new magic number at N=16

Role of $V^{pn}d_{5/2}d_{3/2}$ to break the N=20 shell closure

T. Otsuka EPJA (2004) 69

^{28}O unbound ?
Bounderies of the N=20 playground

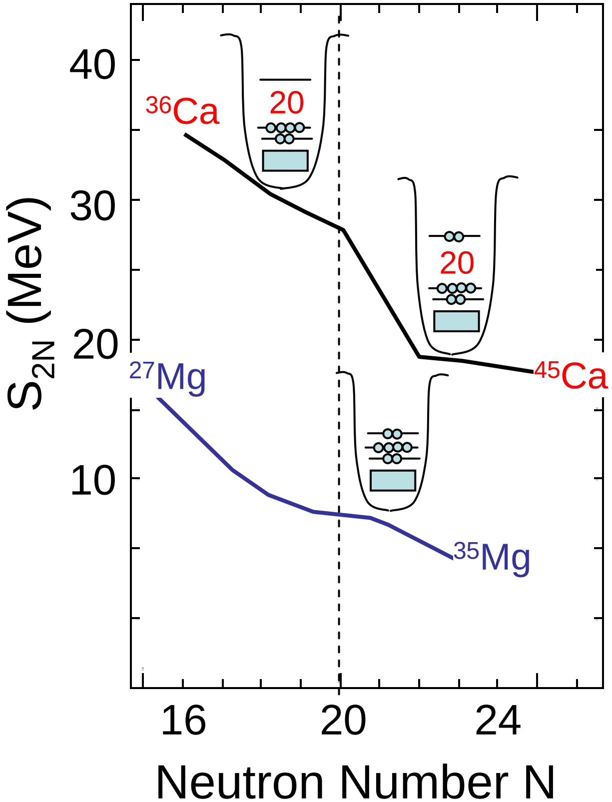


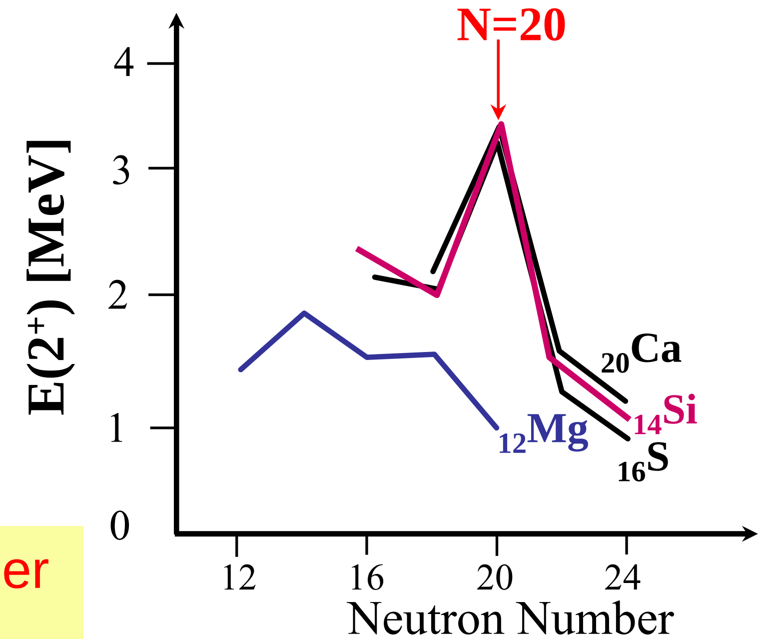
$^{26,28}O$ nuclei unbound

Drip line reached at N=16 in ^{24}O
- $d_{3/2}$ orbit unbound

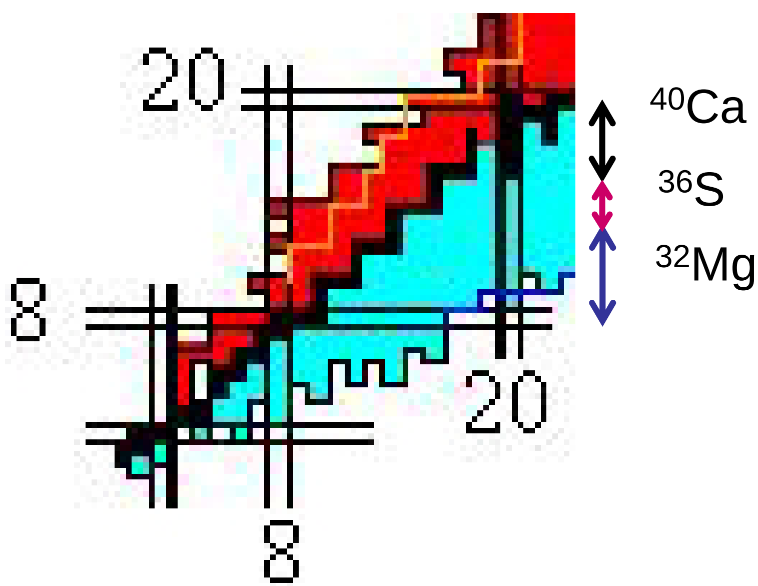
F and Ne are bound up to N=22, 24

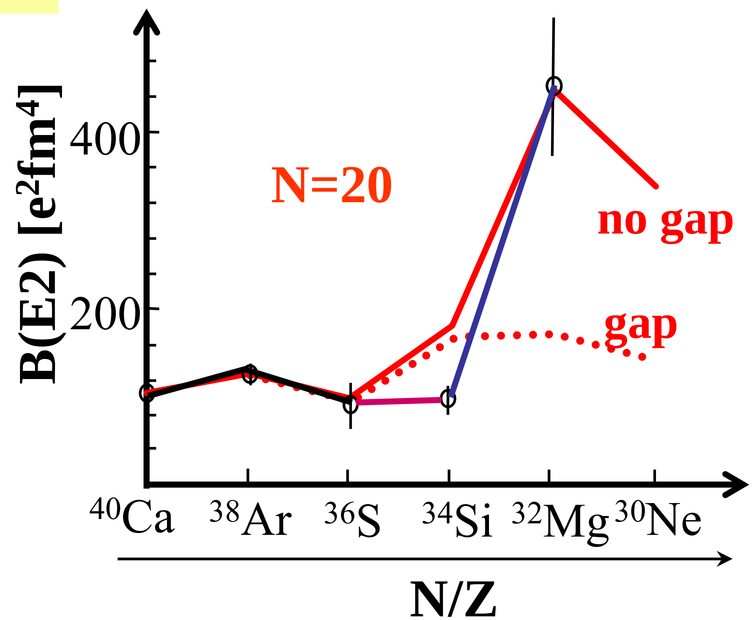
Notami et al., PLB B542 (2002) 49



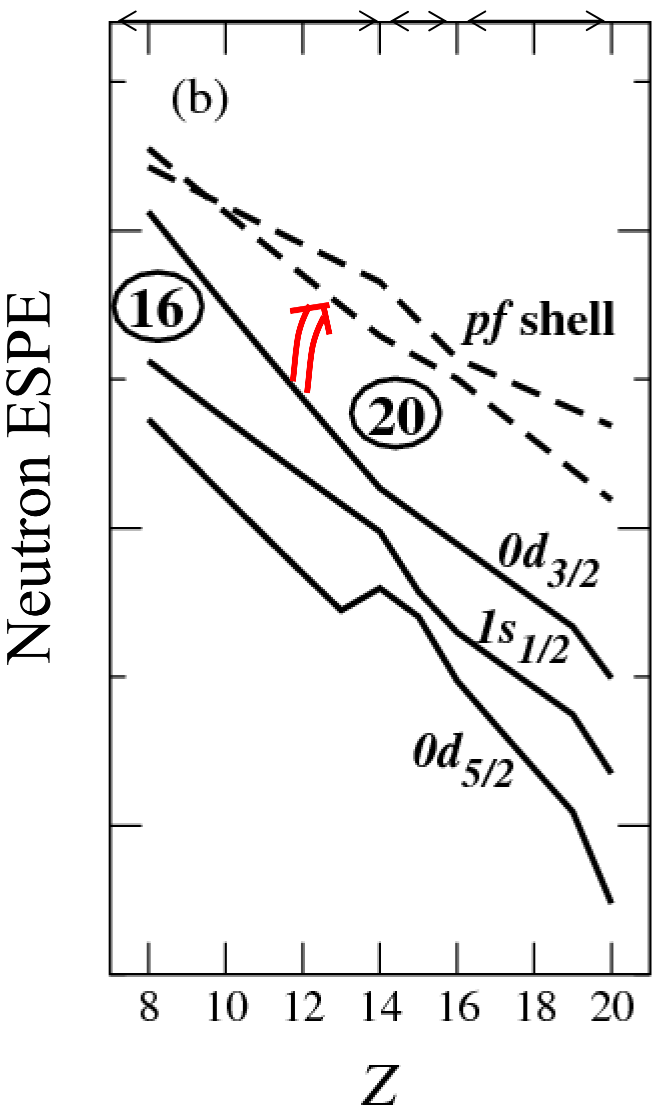


N=20 magic number Disappears !

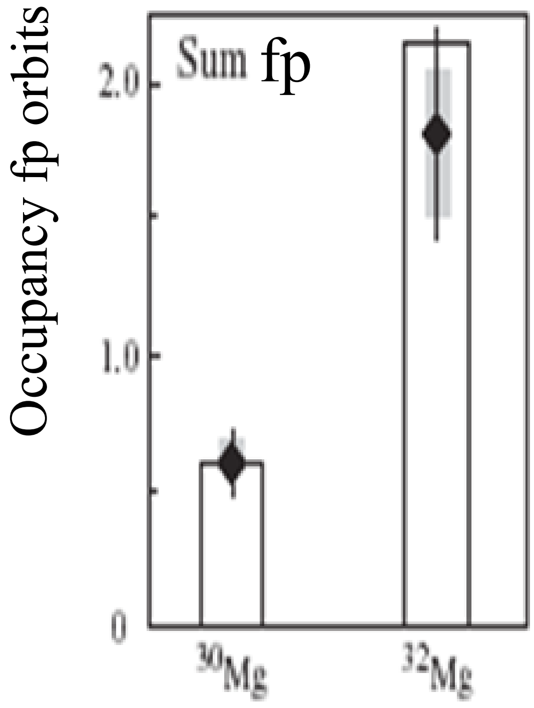




Large occupancy of fp shells above N=20 ? at Z=12 ?



^{30,32}Mg (-1n) -> occupancy and L value of neutron orbits

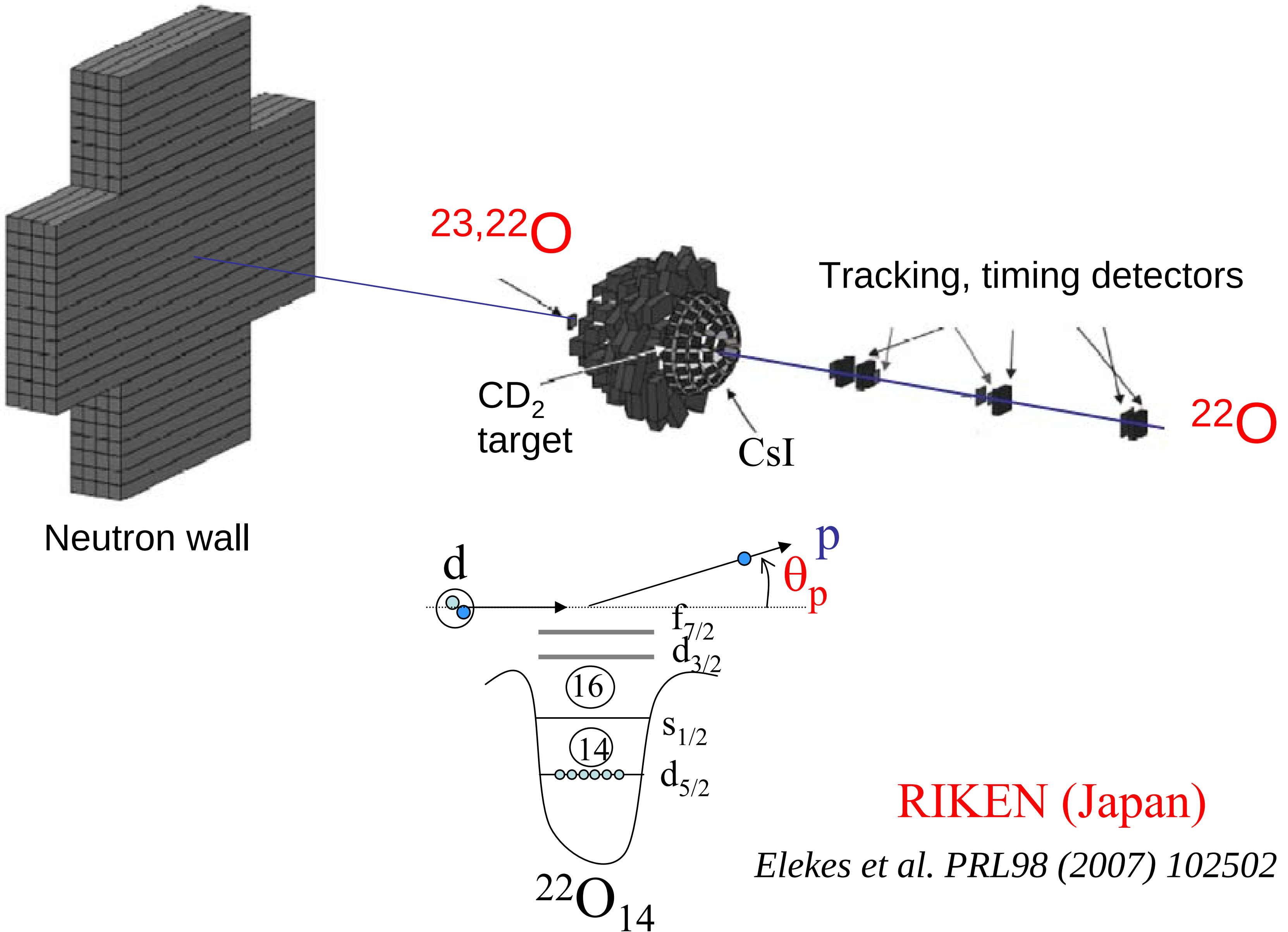


J. R. Terry et al., PRC 77 (2008) 014316.

In ^{32}Mg (N=20), ~2 neutrons occupy the fp shells

Cross shell excitations are largely favoured

Search for a new magic number N=16 :
Use of $^{22}O(d,p)^{23}O$ to probe the neutron N=16, 20 shell closures

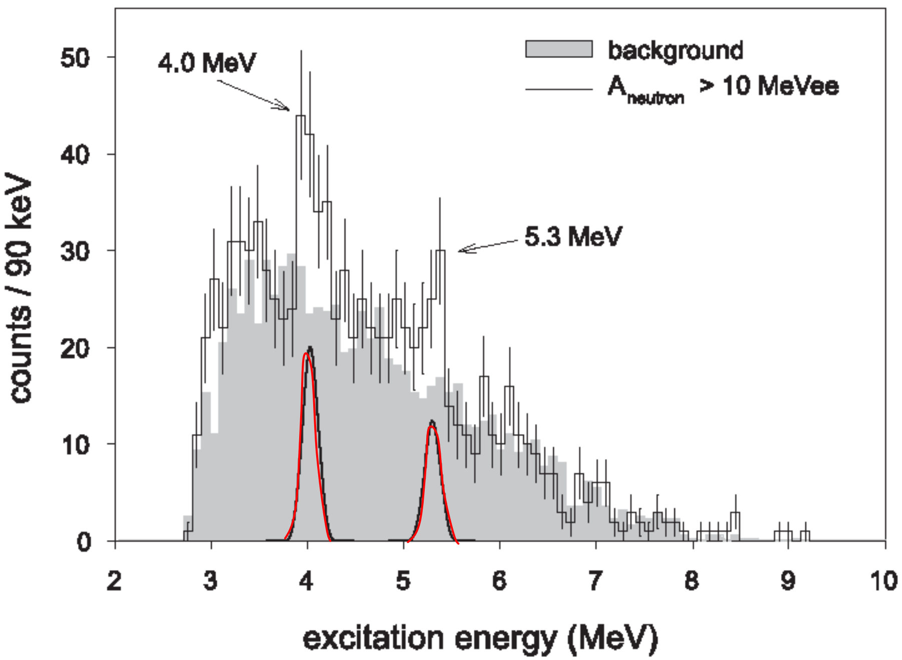


RIKEN (Japan)

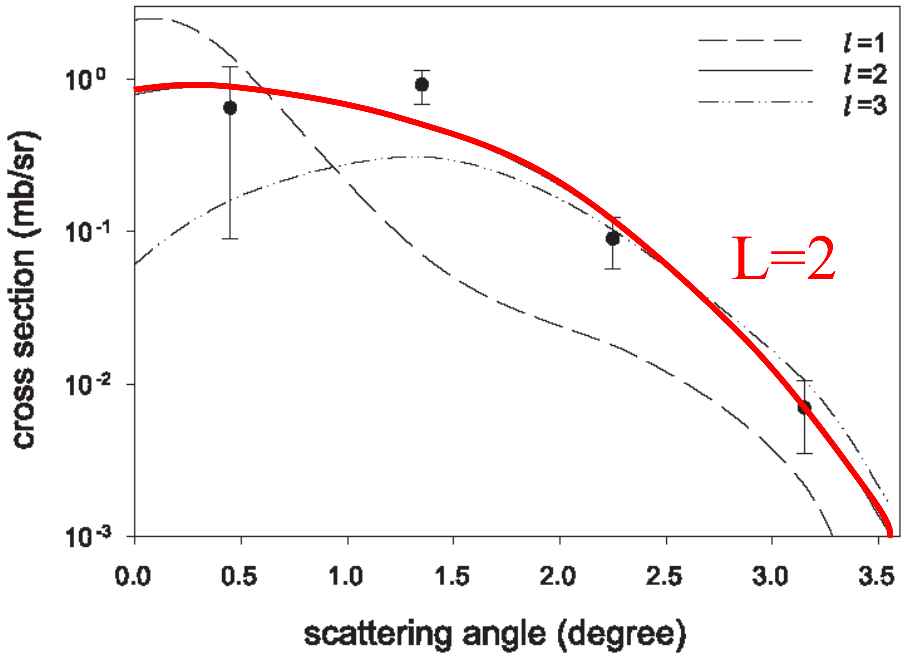
Elekes et al. PRL98 (2007) 102502

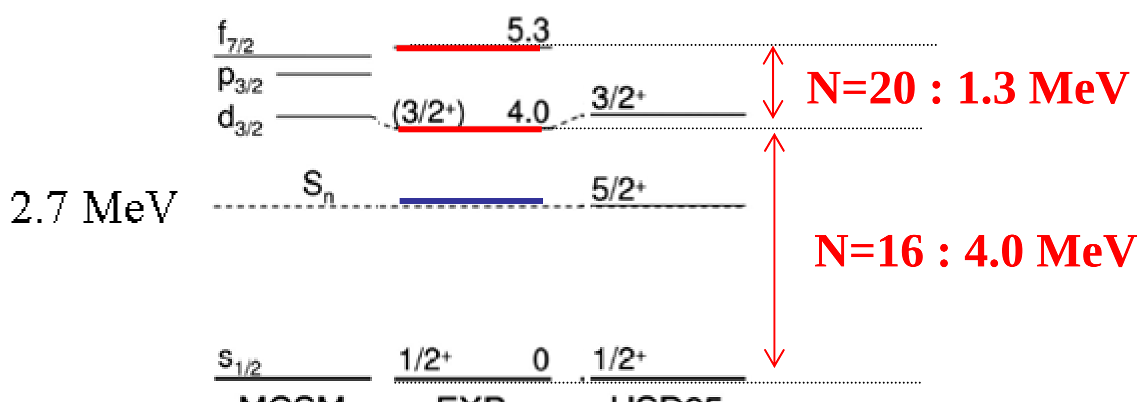
The ‘sizes’ of the N=20 and N=16 gaps in Oxygen

Gated on neutrons



Gated on 4 MeV neutron peak



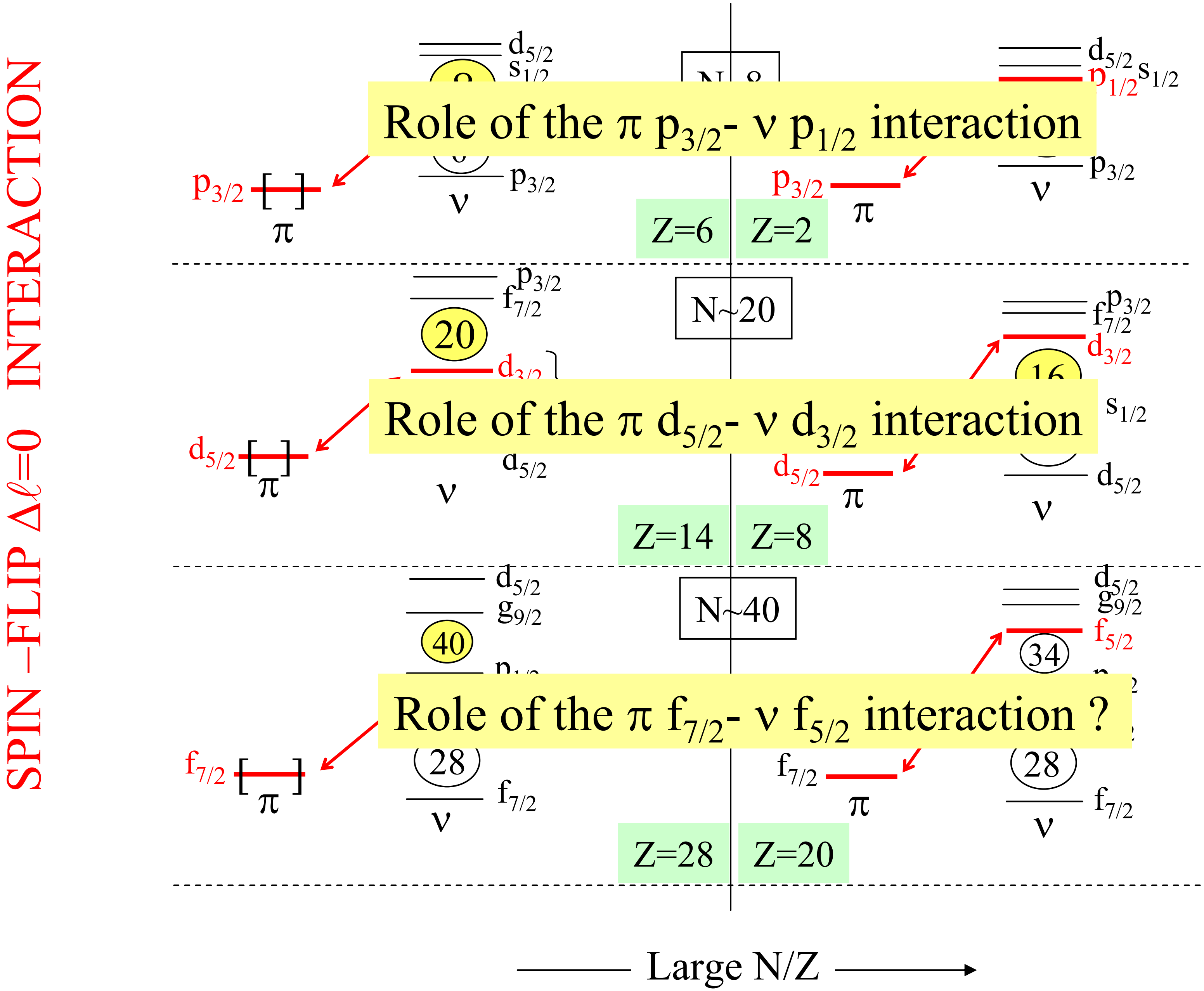


^{23}O

Elekes et al. PRL98 (2007) 102502

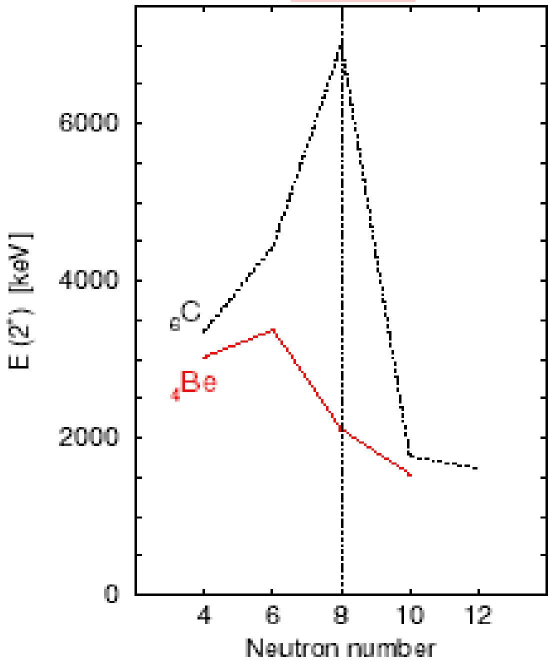
$5/2^+$ observed PRL99 (2007)

Evolution of Harmonic Oscillator shell closures

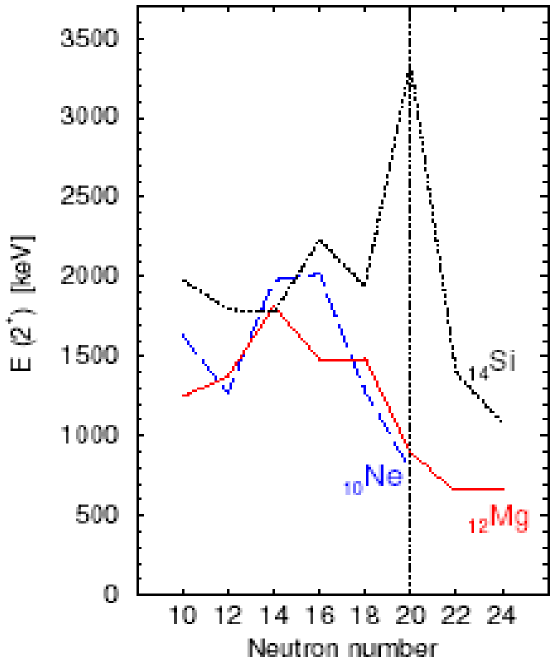


Great similarity between the three cases of HO shell numbers

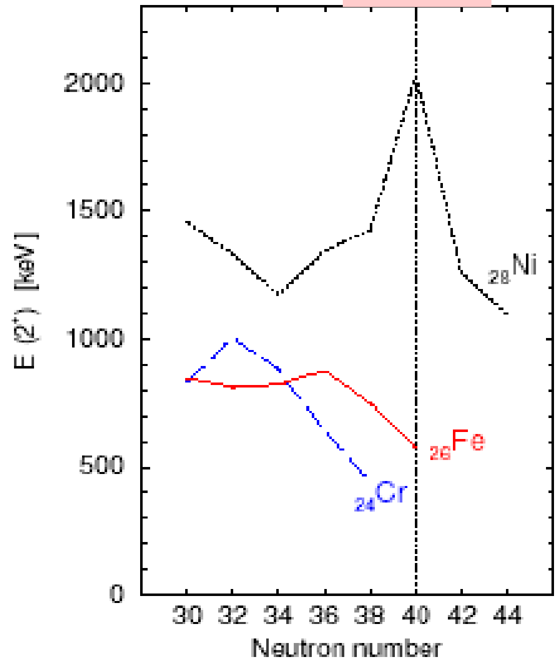
N=8



N=20



N=40

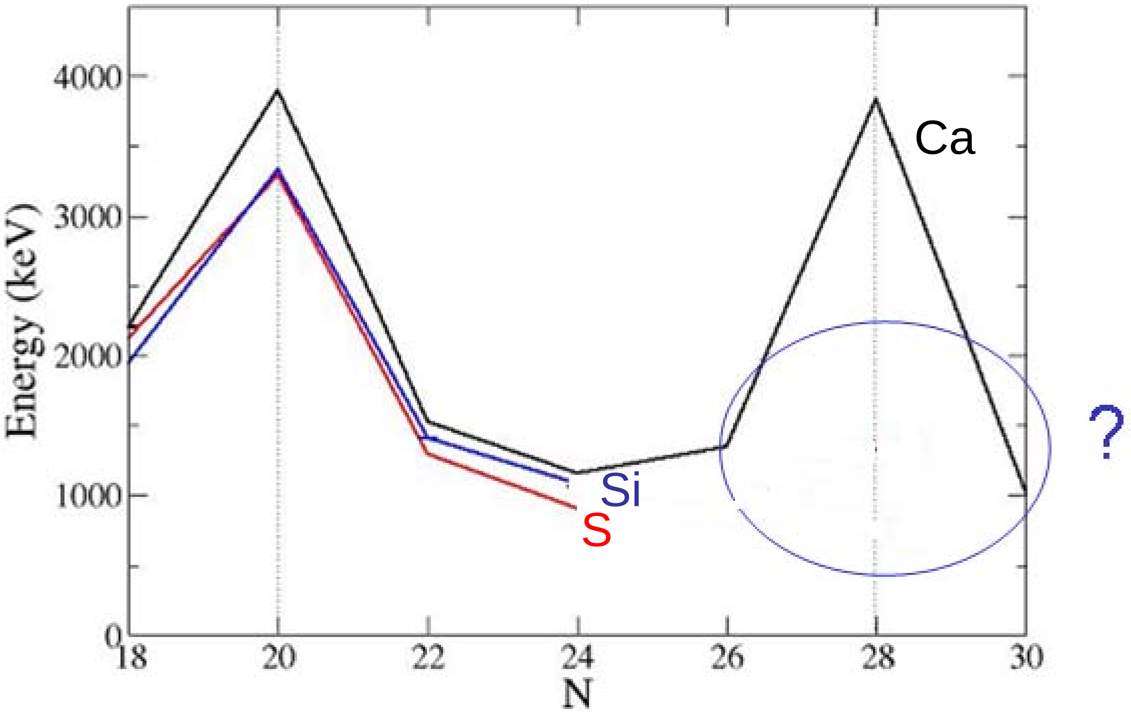


Beta decay studies
M. Hannawald, PRL 82 (1999) 1391
O. Sorlin et al. EPJA 16 (2003) 55

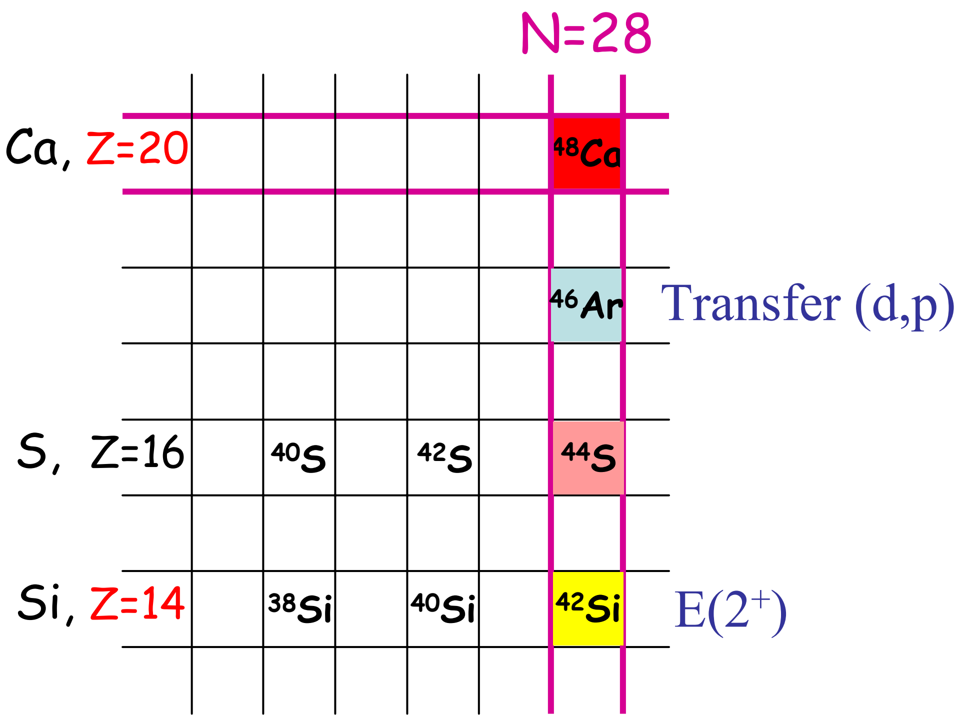
Dramatic change of nuclear structure due to spin-flip pn interaction !

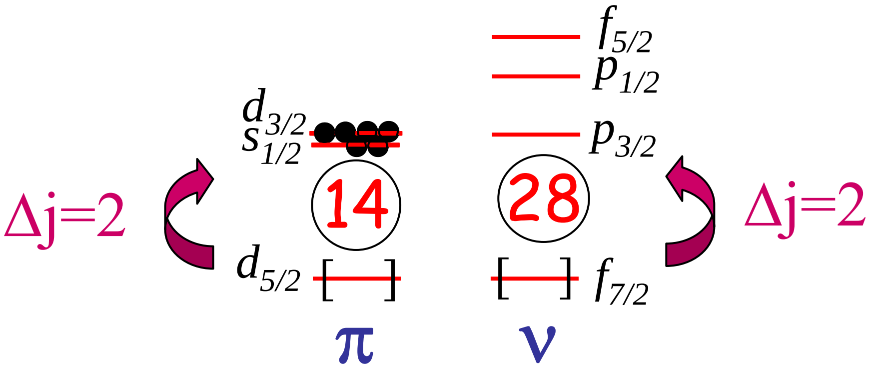
Part III. The 'SO' magic numbers

The case of the N=28 shell closure



Study of the N=28 shell closure far from stability





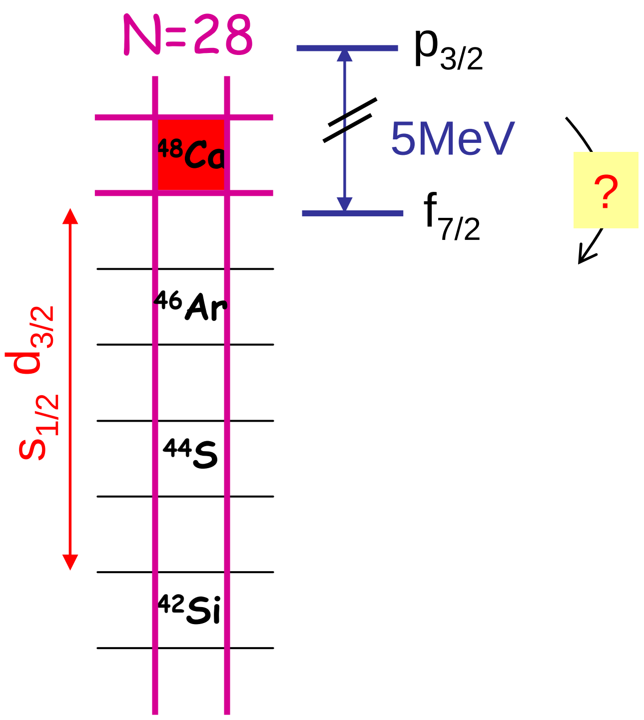
$\pi d_{3/2}$-$\nu f_{7/2}$, $\pi d_{3/2}$-$\nu f_{5/2}$ interactions
ΔL=1

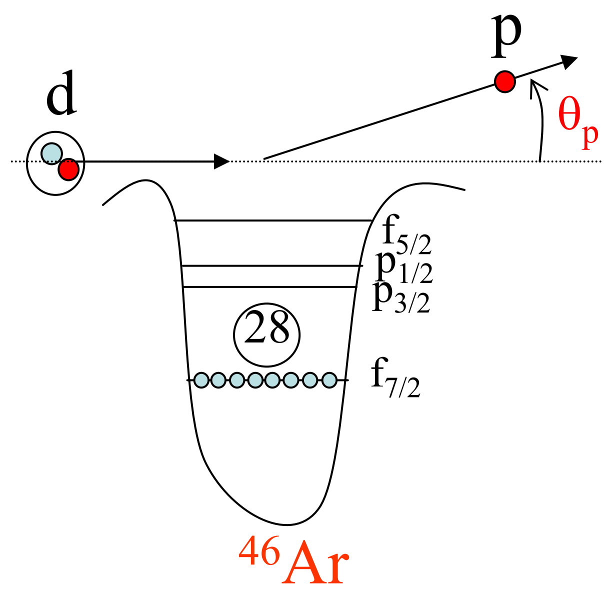
> Role of nuclear forces :
Modification of the N=28 shell gap ?
SO and Tensor interactions

➢Enhanced collectivity due to Δj=2

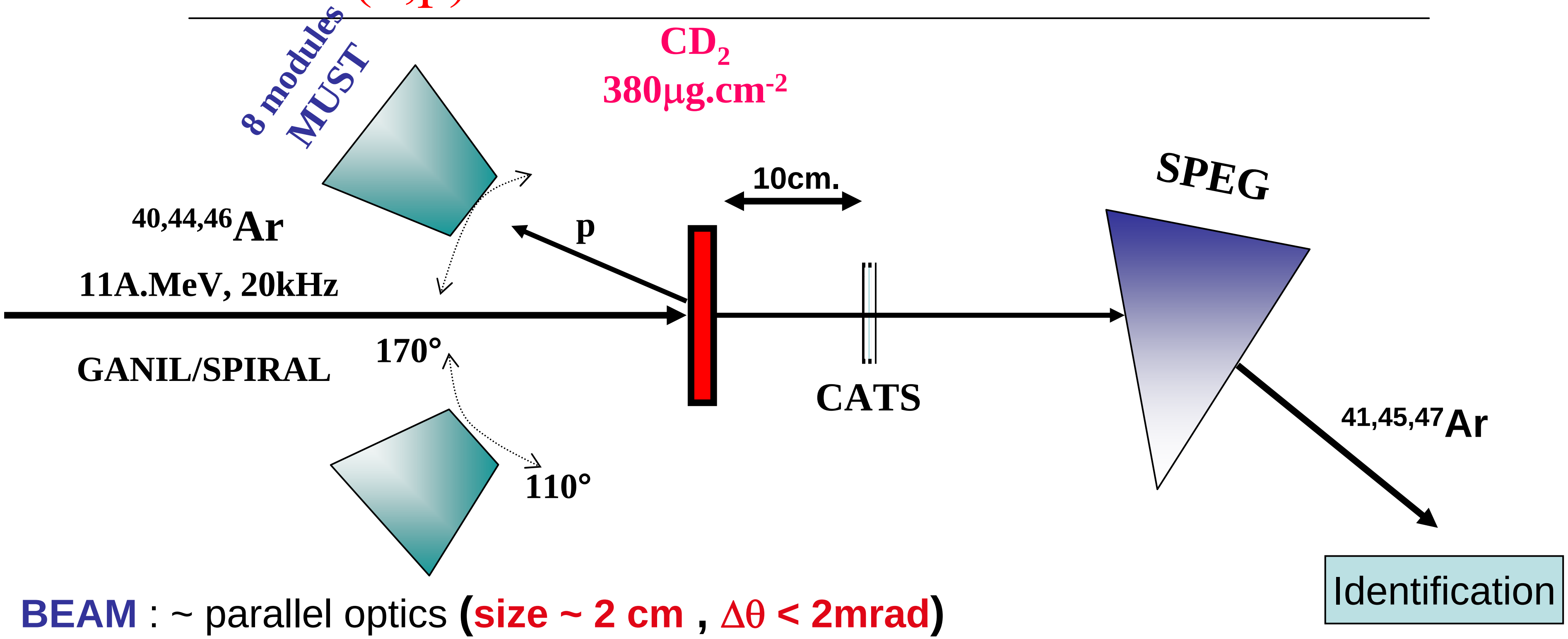
2- Evolution of the N=28 shell gap

→ Use of transfer (d,p) reaction with ^{46}Ar beam





(d,p) reactions with $^{40,44,46}Ar$ beams



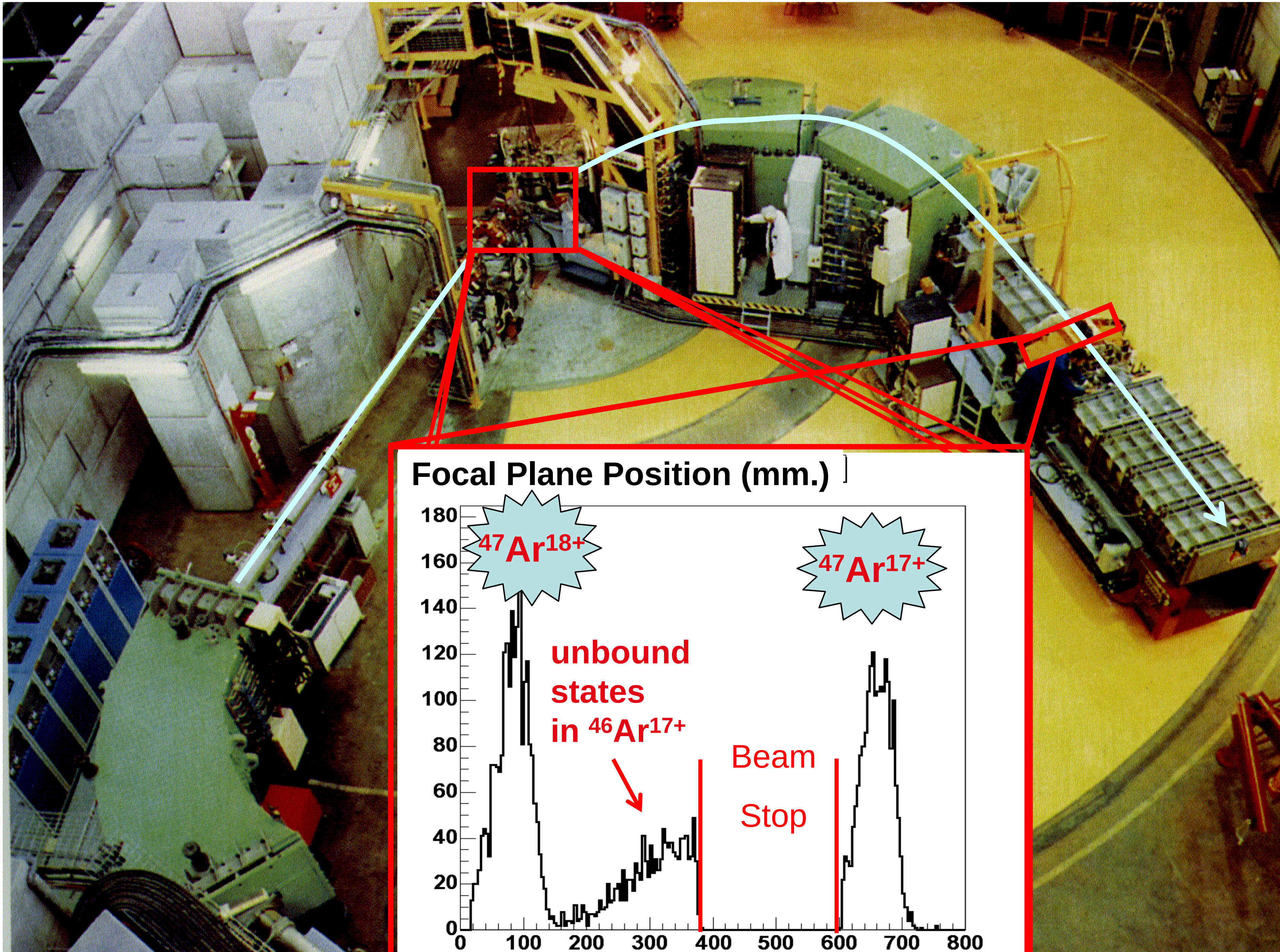
BEAM : ~ parallel optics **(size ~ 2 cm , Δθ < 2mrad)**

CATS : -**beam**-tracking detector

- Proton **emission point**.
  resolution : ~1 mm

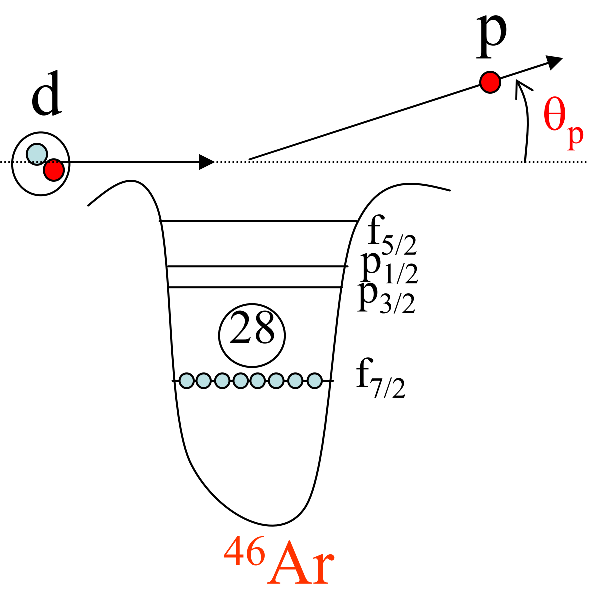
MUST : -**Si Strip** detector
-Proton **impact localisation**
resolution : 1 mm; size 6 x 6 cm²
-Proton **energy** measurement.
resolution : 50 KeV

SPEG : Energy loss spectrometer : **recoil ion** identification→transfert-like products



Focal Plane Position (mm.)
$^{47}Ar^{18+}$
$^{47}Ar^{17+}$
unbound states in $^{46}Ar^{17+}$
Beam Stop
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800

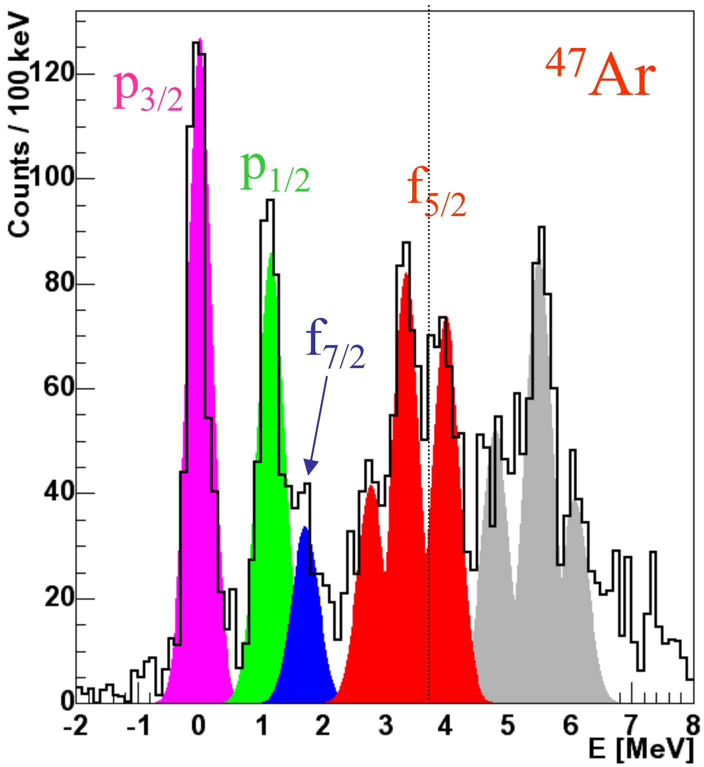
Evolution of the neutron SPE below $^{48}_{20}Ca$

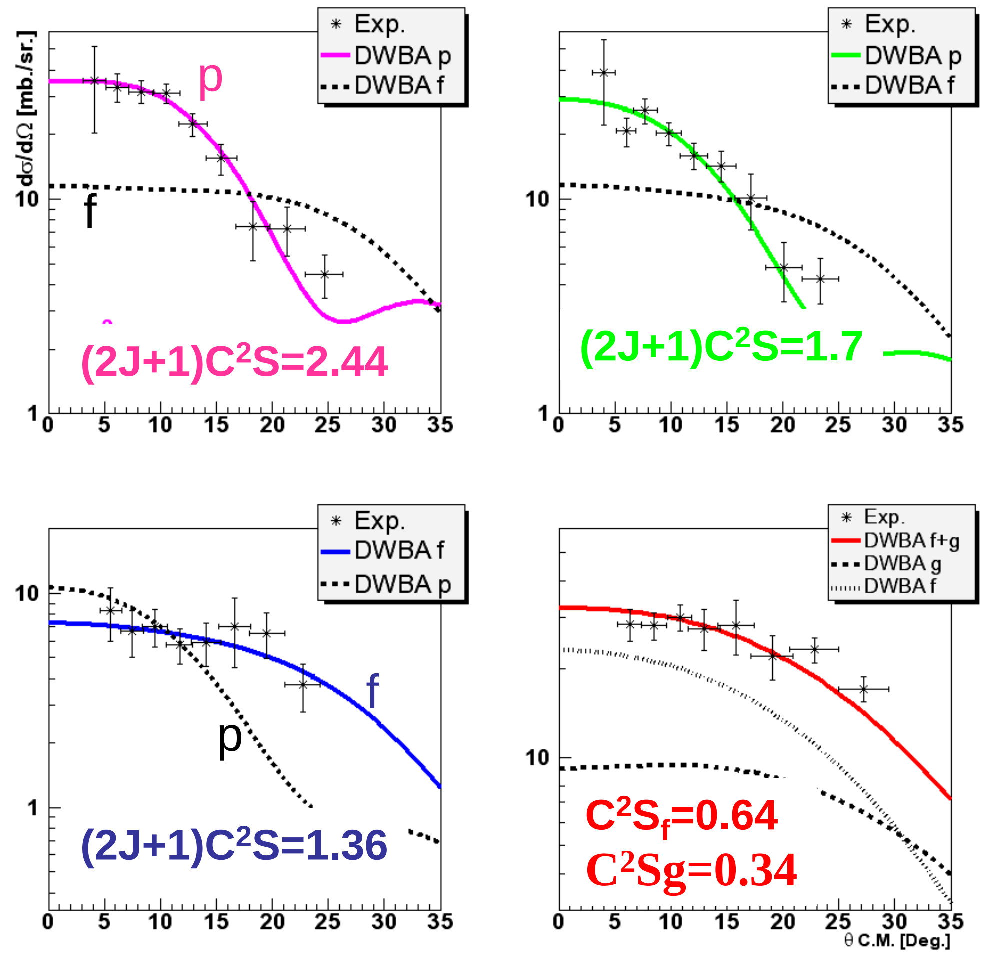


Use of $^{46}_{18}Ar$ (d,p) transfer reaction

- Size of the N=28 shell gap : reduced by 330keV
- Reduction of SO splitting

L. Gaudefroy et al. PRL 97 (2006)

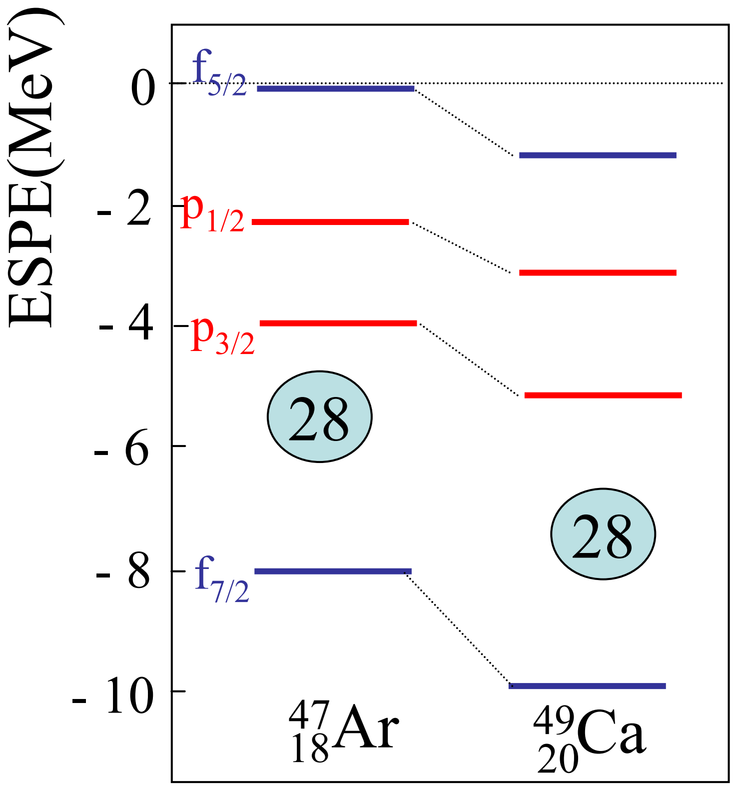


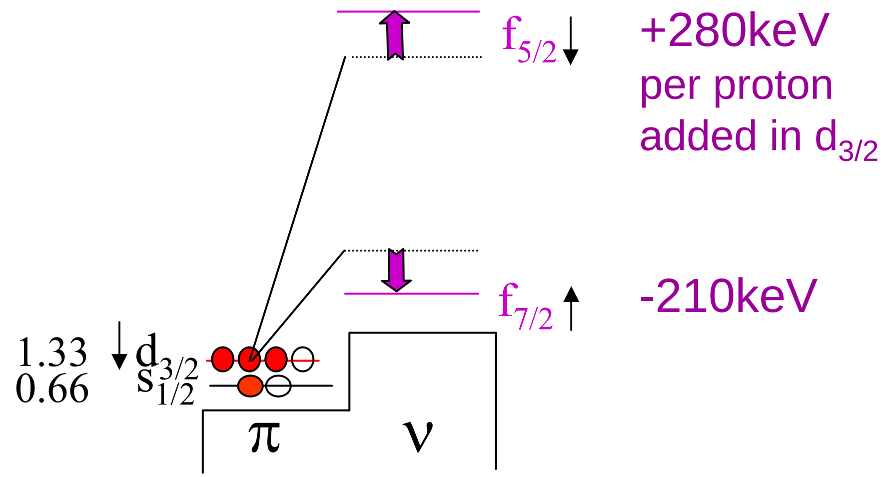


Variation of single particle energies (SPE)

-From ^{47}Ar to ^{49}Ca, 2 protons added to $d_{3/2}$ and $s_{1/2}$ equiprobably, i.e. 1.33 ($d_{3/2}$), 0.66 ($s_{1/2}$)

-The $\pi d_{3/2}$ acts differently on $\nu f_{5/2}$ and $\nu f_{7/2}$ orbits $\longrightarrow$ tensor forces ?





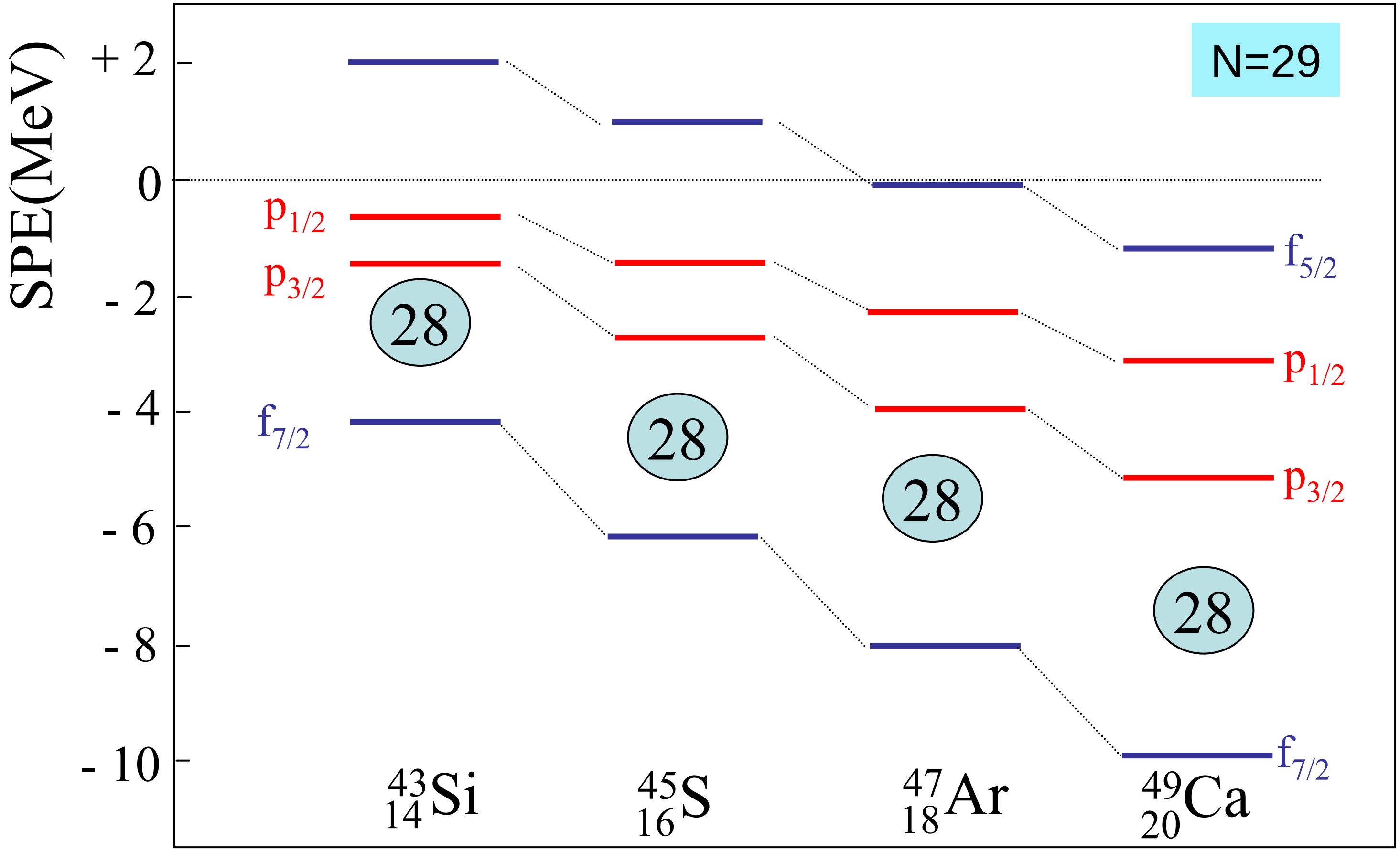
Tensor interaction (*Otsuka)*

$\pi d_{3/2} - \nu(f_{7/2} - f_{5/2})$

Evolution of SPE's from tensor part of the proton-neutron interaction

Global trend of single particle energies between ^{49}Ca and ^{43}Si

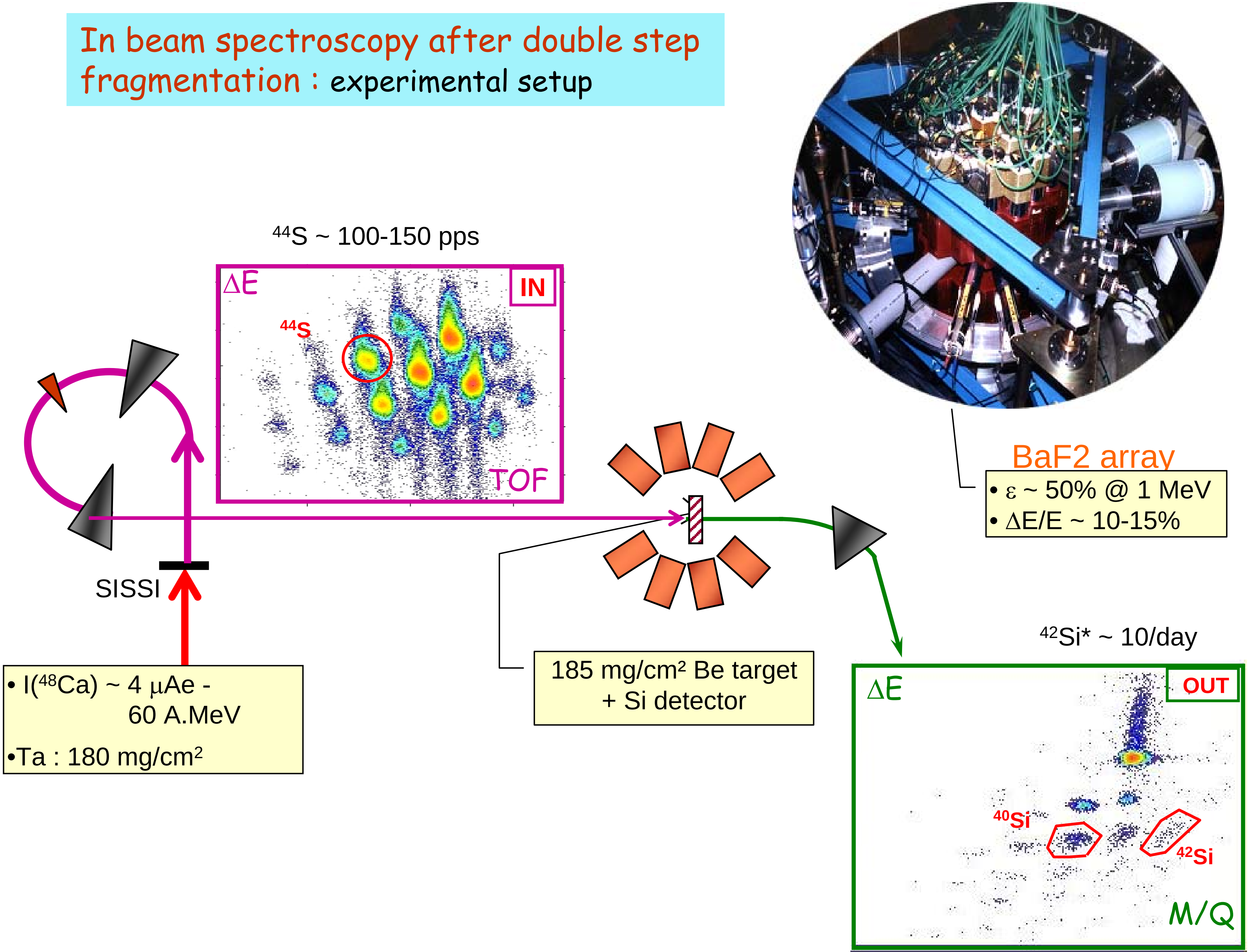
derived from experimentally-constrained monopole variations



-A shrink of SPE's is occurring gradually when N>>Z due to two-body p-n interactions…

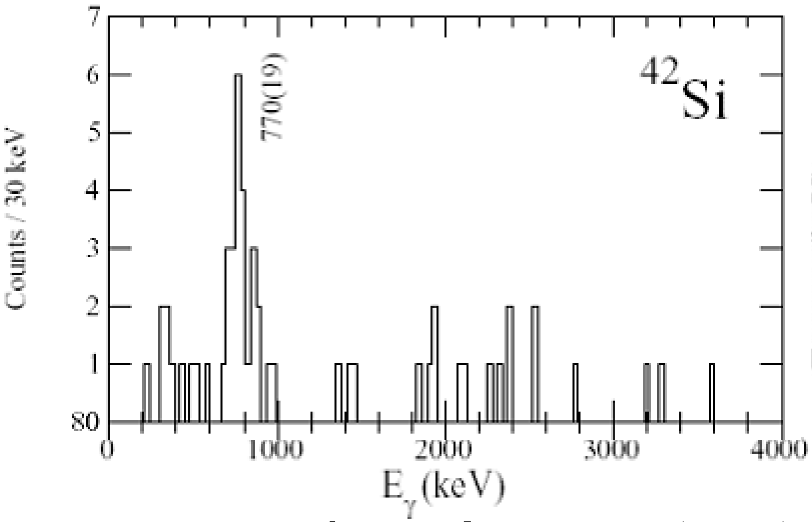
- Favor particle-hole excitations and E2 collectivity

In beam spectroscopy after double step fragmentation : experimental setup

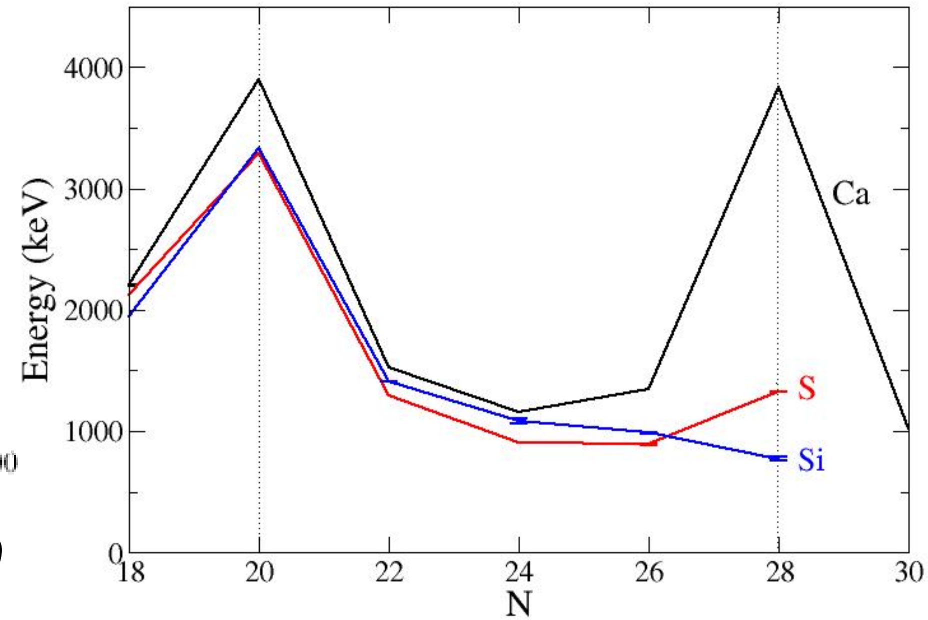


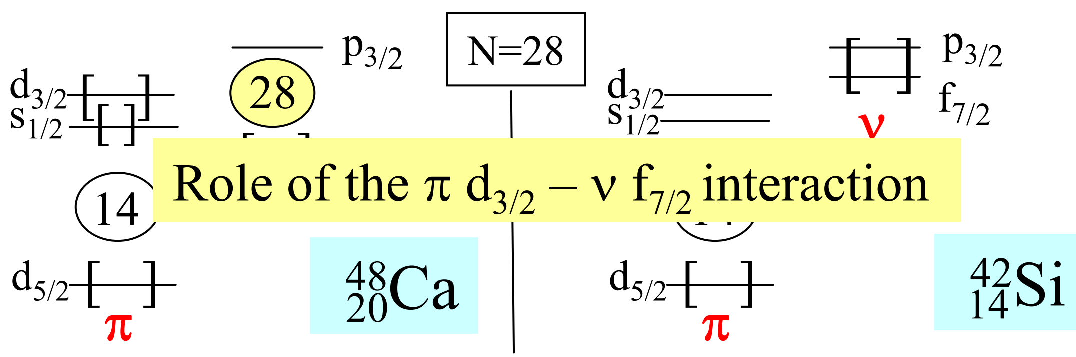
Collapse of the N=28 shell closure in ^{42}Si

SPIN-FLIP $\Delta\ell=1$ INTERACTION



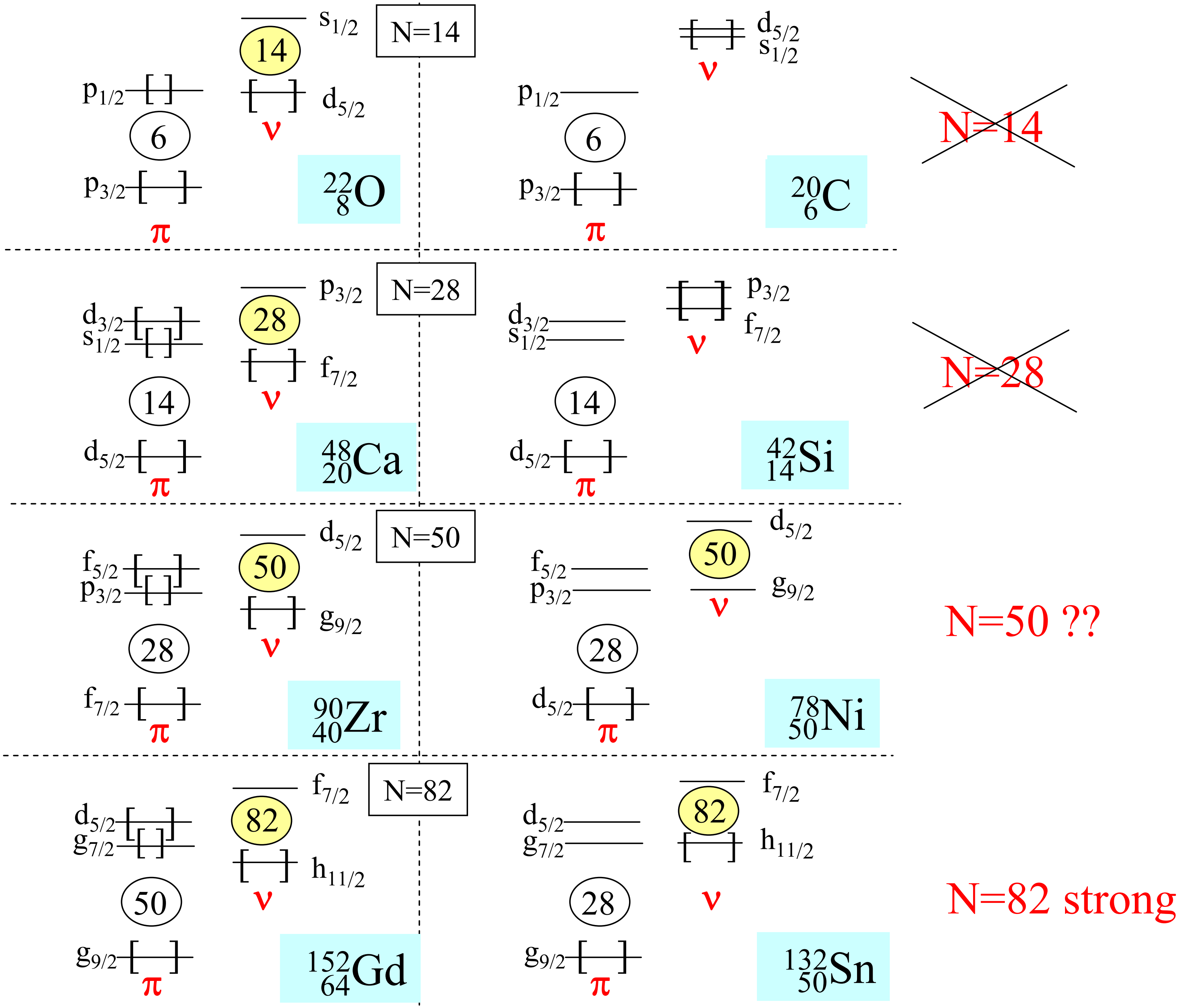
B. Bastin, S. Grévy et al., PRL 99 (2007)



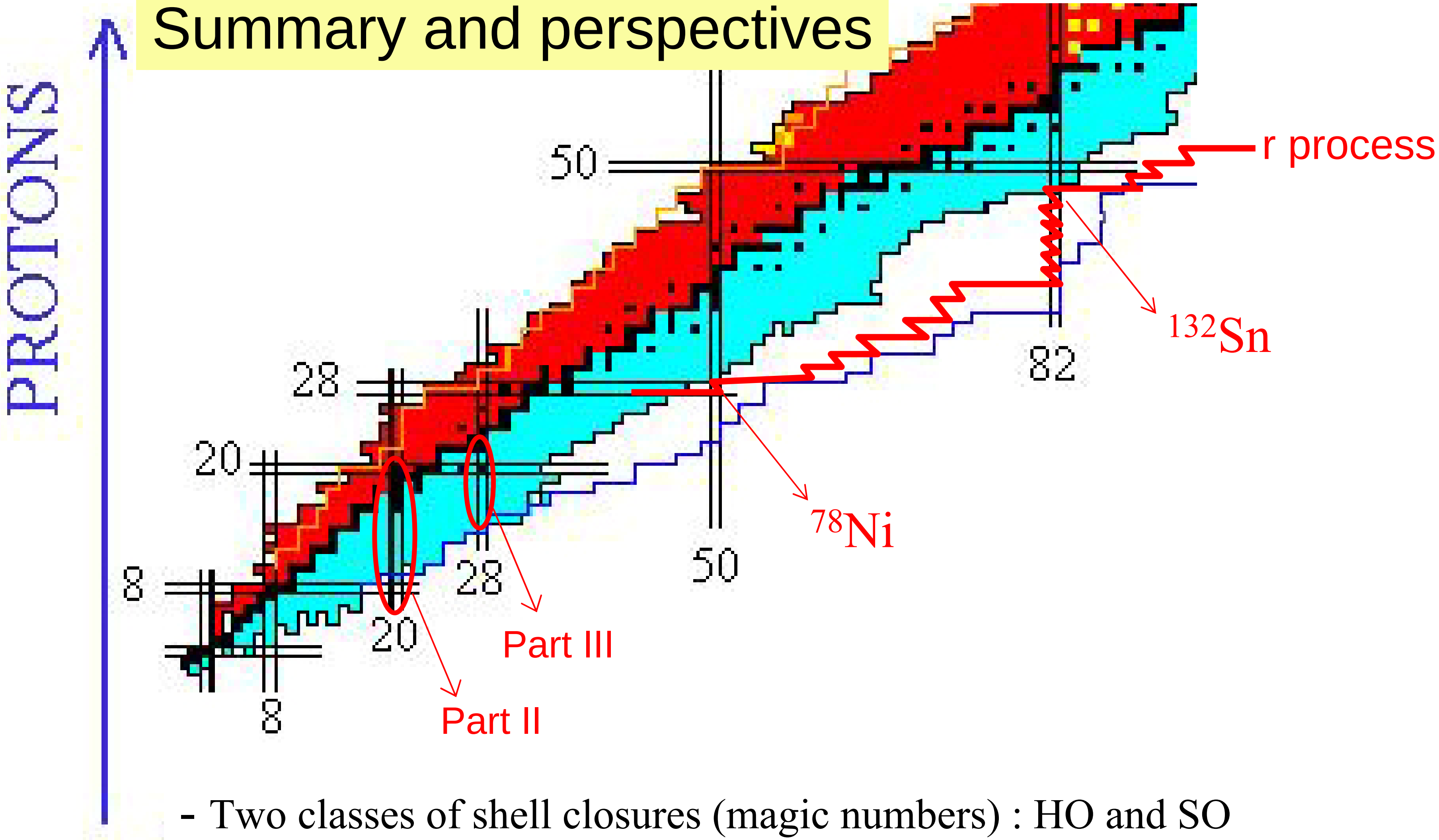


Role of the $\pi\ d_{3/2} - \nu\ f_{7/2}$ interaction

SPIN-FLIP $\Delta\ell=1$ INTERACTION

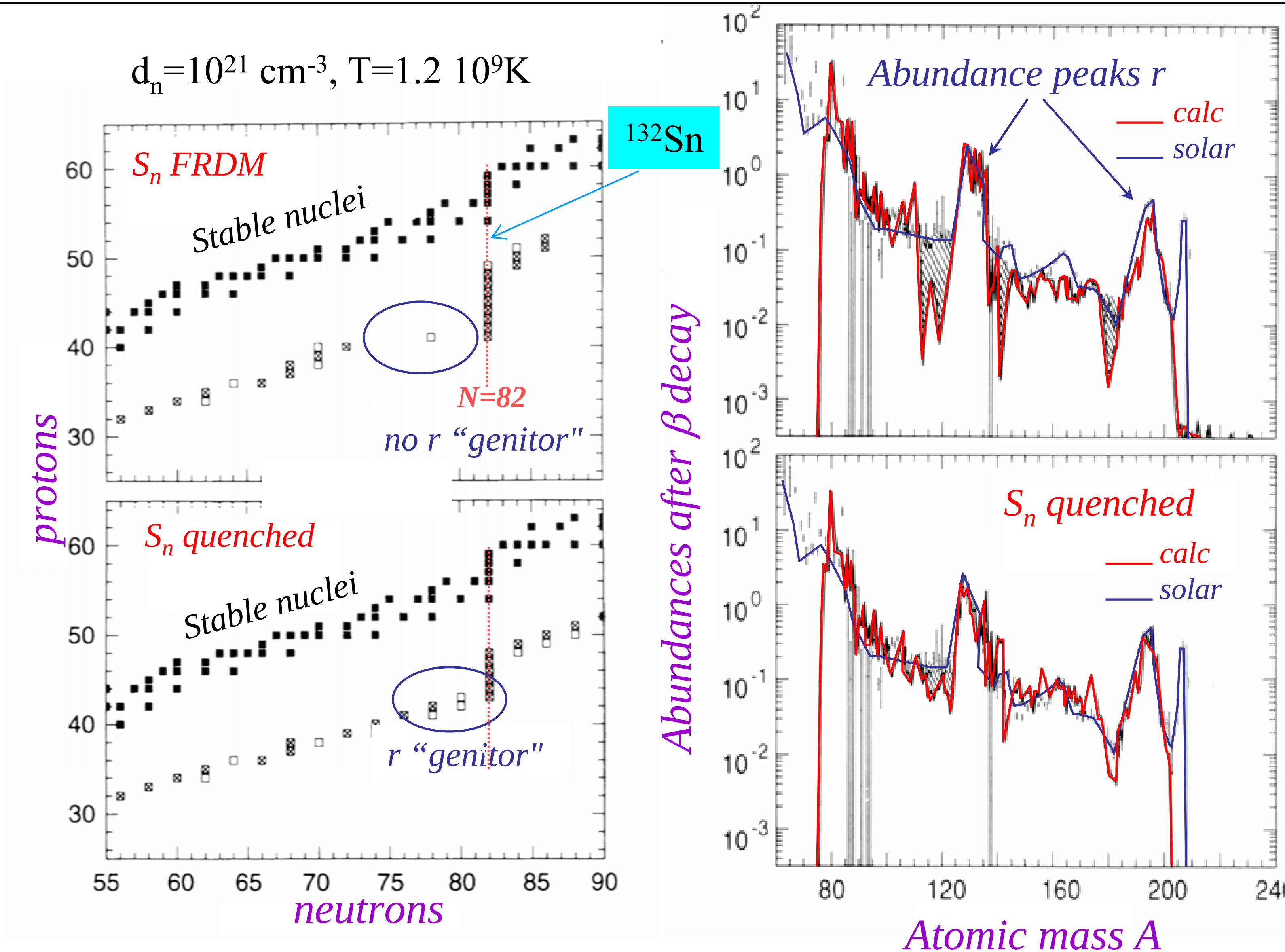


Summary and perspectives



- Two classes of shell closures (magic numbers) : HO and SO
- Proton-neutron interactions usually act to destroy them !!!
- Takes root in NN bare forces – link with in-medium forces in progress
- Are forces strong enough to destroy shell closures in exotic heavy nuclei ?
- Astrophysical consequences for explosive burning ?
- Are extrapolation to superheavies or unknown regions reliable ?

Sensitivity of nuclear structure at N=82 on the r abondance curve



Shape of the abundance peak depends strongly on the behaviour of the N=82 shell

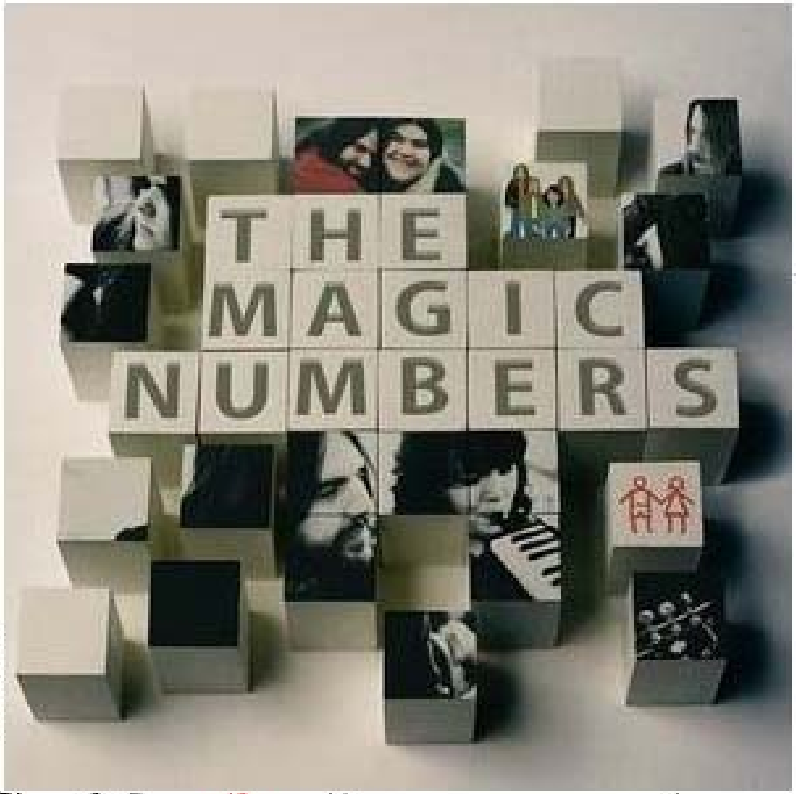
Summary

- Two classes of shell closures (magic numbers) : HO and SO
- Proton-neutron interactions usually act to destroy them
- Takes root in NN bare forces – link in progress
- Forces be strong enough to destroy shell closures in heavy nuclei ?
- Astrophysical consequences expected
- Extrapolation to superheavies or unknown regions ?

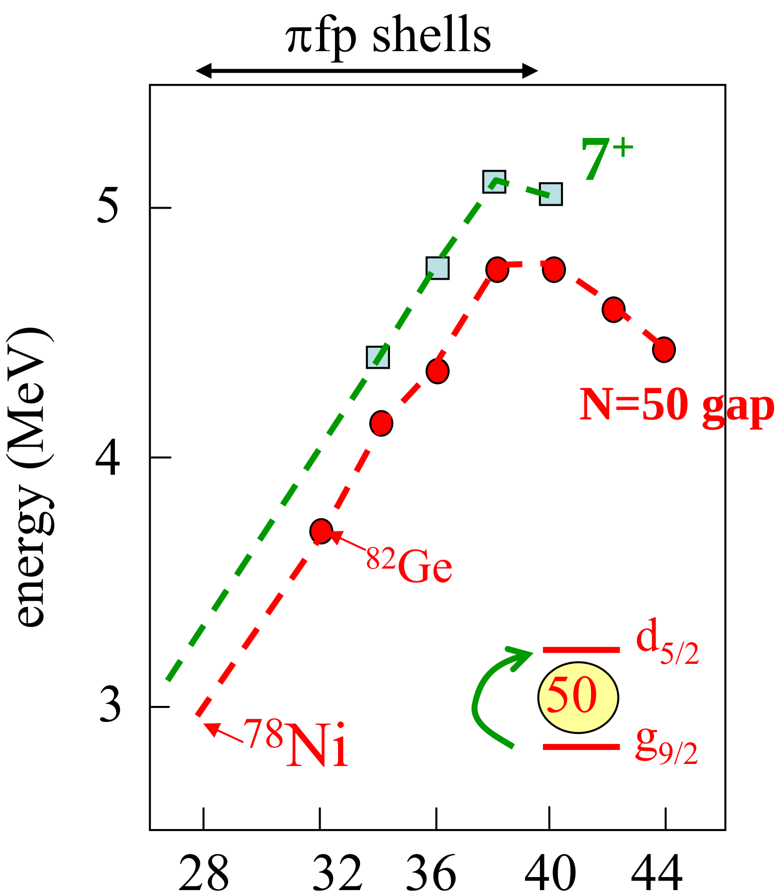
From Wikipedia, the free encyclopedia

The Magic Numbers

Magic Numbers are a four-piece **rock band** from England comprising two pairs of brother and sister who previously went to The Cardinal Wiseman Roman Catholic High School in Greenford. The group was formed in 2002, releasing their critically acclaimed album titled *The Magic Numbers* in June 2005….

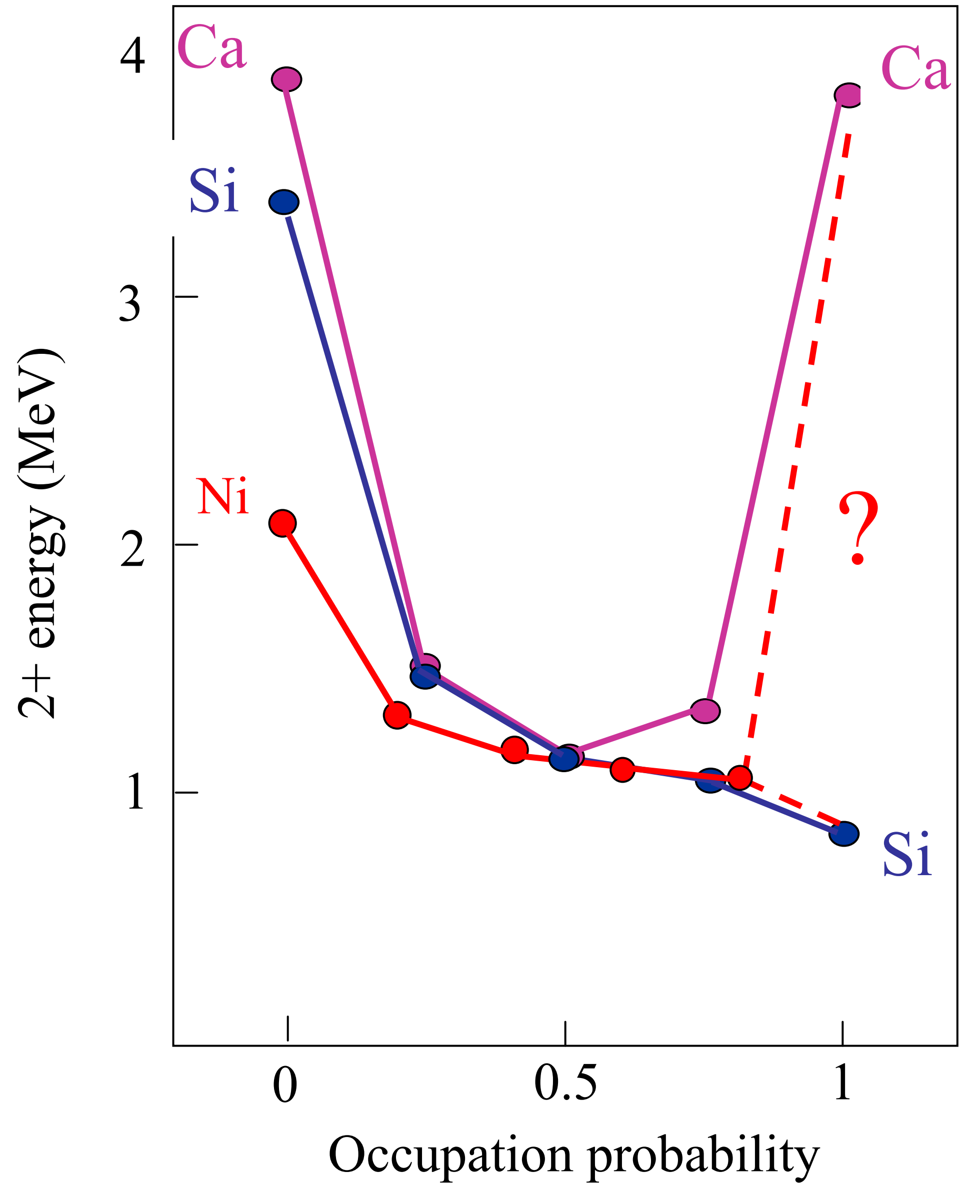


The N=50 shell closure when approaching $^{78}Ni_{50}$



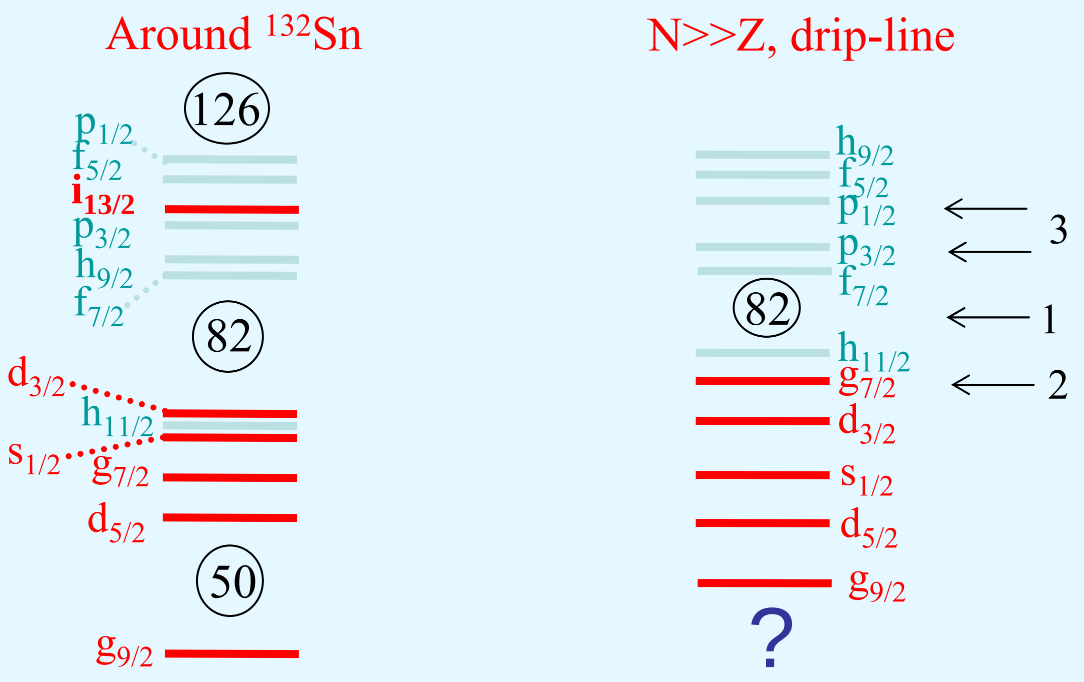
A. *Prévost et al. EPJA 22 (2004)*

B. *Ref on masses …*



Mazzochi et al. PLB 622 (2005)

Nuclear Shell Structure Evolution



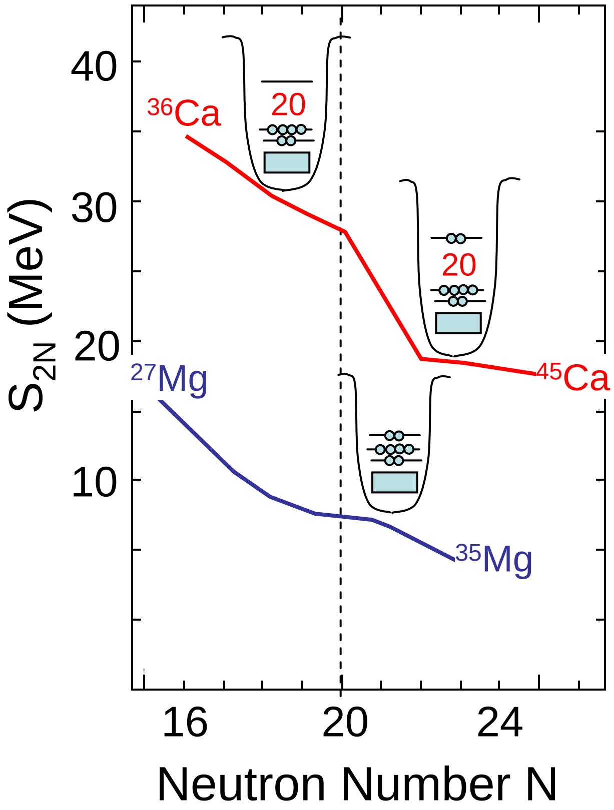
Mean field near stability
Strong spin-orbit interaction

Reduced spin-orbit
Tensor forces
Mean field for N>>Z ?
Effect of continuum ?

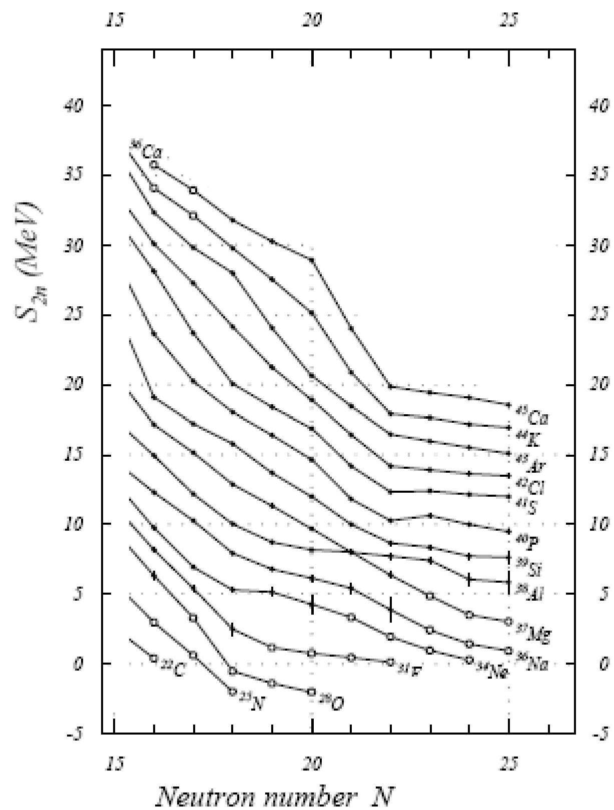
Adapted from J Dobaczewski

Major consequences :

1 : Reduction/disappearence of shell gaps -> modify the shape of r abundance peaks
2 : Change of $g_{7/2}$ energy, increase the $g_{7/2} \rightarrow g_{9/2}$ GT transition, shorten β-decay lifetimes
3 : The valence p states appear at weak excitation energy, favor neutron capure with ℓ_n =0

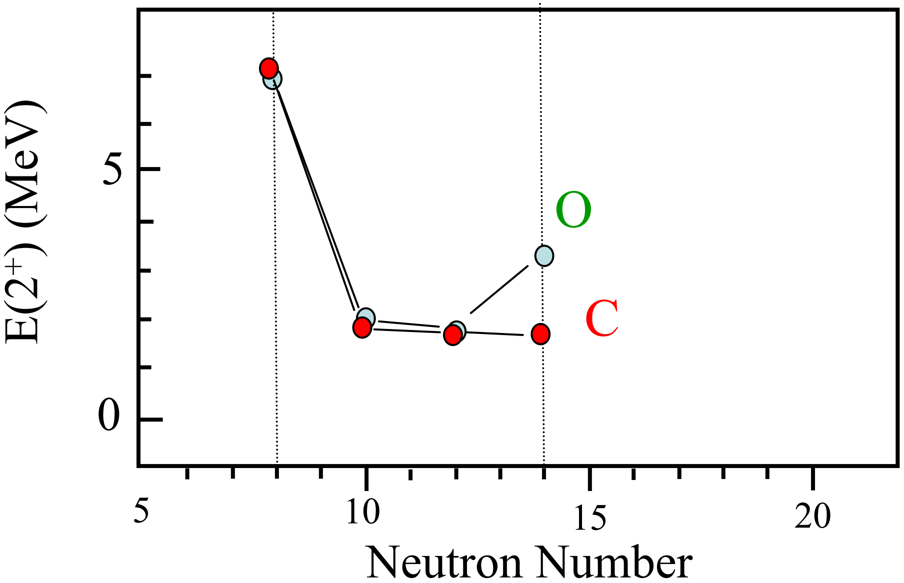


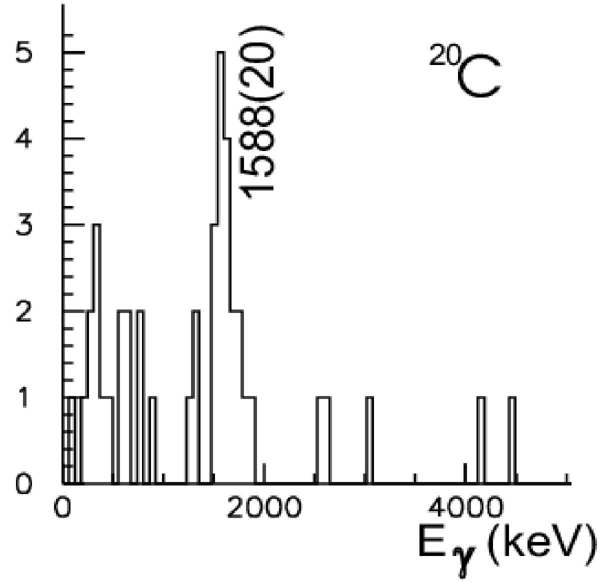
S_{2N} (MeV)
40
30
20
10
^{36}Ca
^{45}Ca
^{27}Mg
^{35}Mg
20
20
16
20
24
Neutron Number N



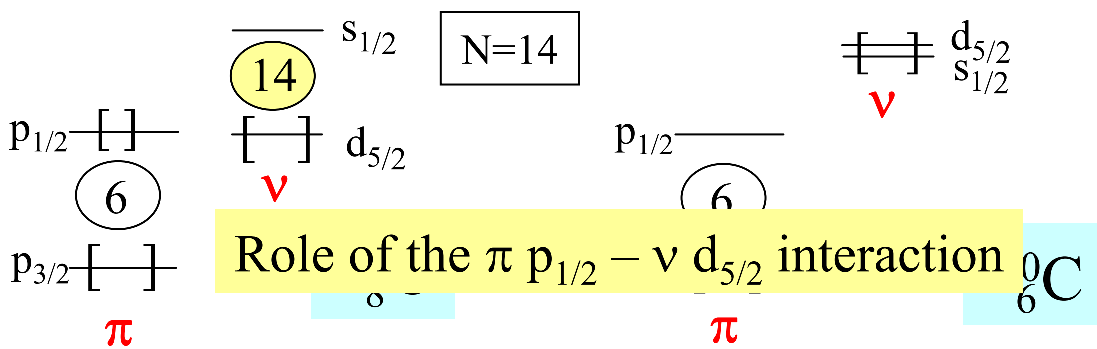
S_{2n} (MeV)
Neutron number N
15
20
25
40
35
30
25
20
15
10
5
0
-5
^{36}Ca
^{45}Ca
^{44}K
^{43}Ar
^{42}Cl
^{41}S
^{40}P
^{39}Si
^{38}Al
^{37}Mg
^{36}Na
^{34}Ne
^{31}F
^{28}O
^{25}N
^{22}C

N=14 shell closure in ^{22}O and ^{20}C



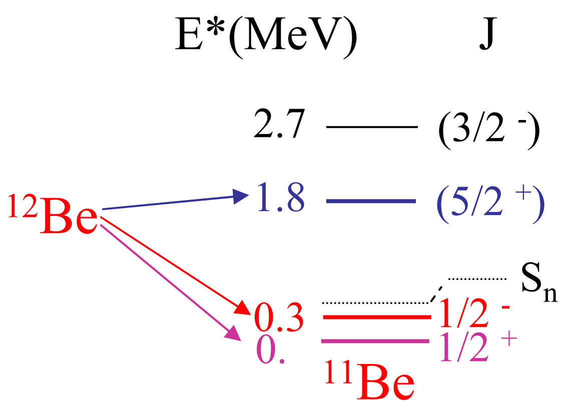


Thirolf et al. PLB 485 (2000) M. Stanoiu et al. PRC 69 (2004), M. Stanoiu subm.



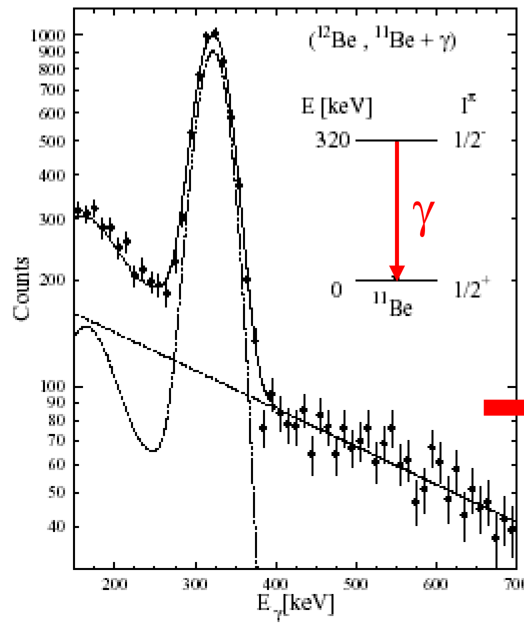
Role of the $\pi\ p_{1/2} - \nu\ d_{5/2}$ interaction

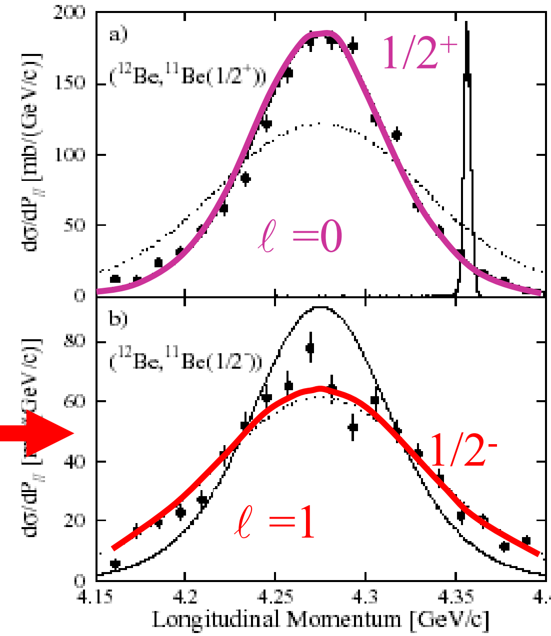
Knock-out reaction ^{12}Be(-1n) to probe g.s. composition of ^{12}Be



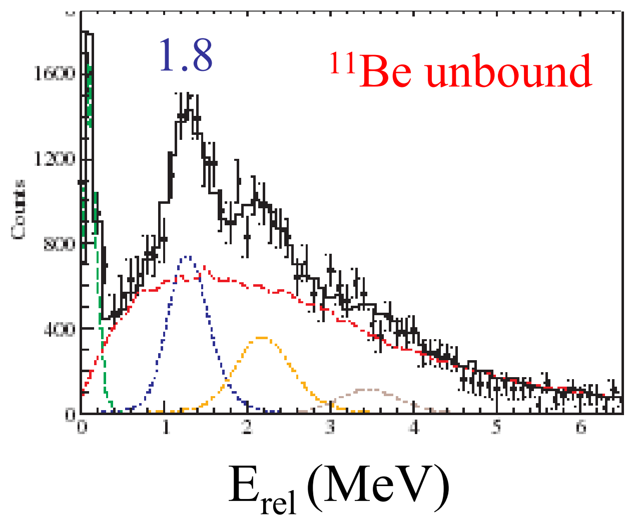
Almost equal SF values 0.4

Admixtures of s, p and d states
N=8 shell closure no longer present





Navin et al., PRL 85 (2000) 266



Pain et al., PRL 96 (2006) 032502

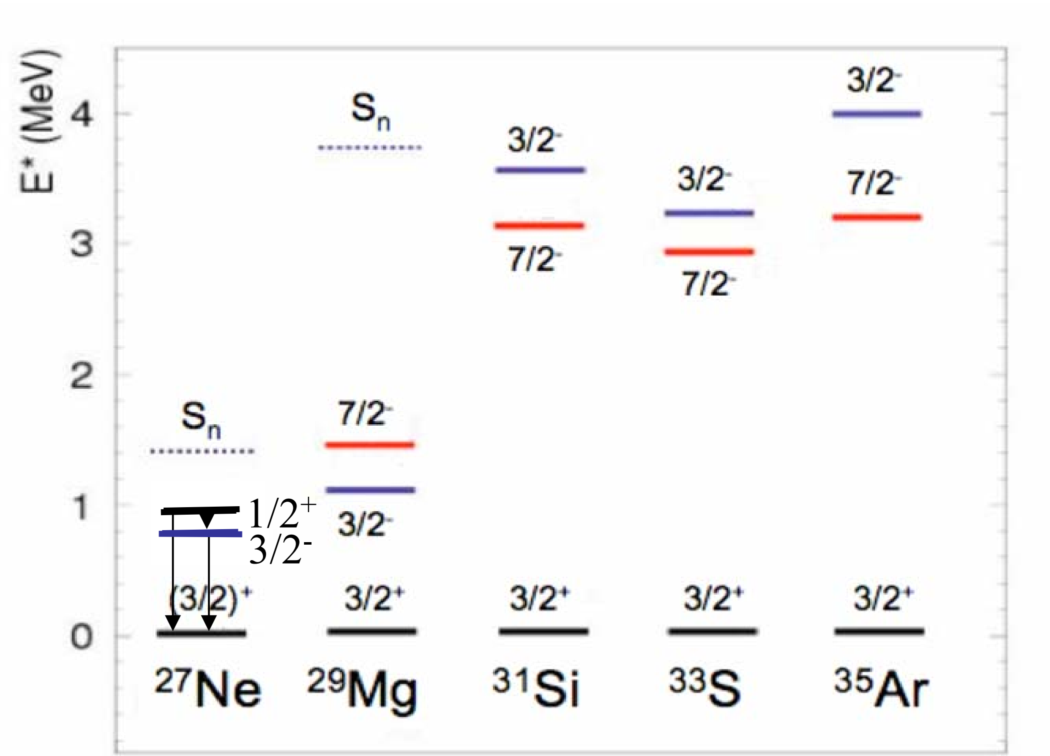
Confirms that the N=8 gap has collapsed

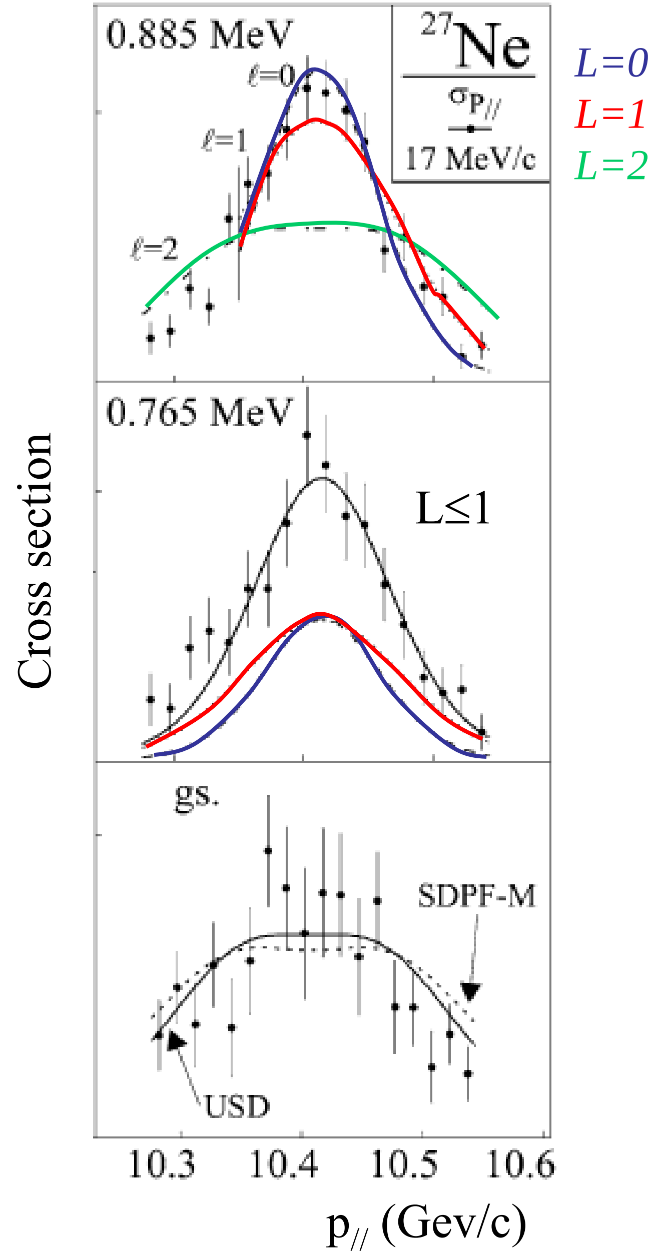
Evidence of intruder configurations in neutron-rich Ne isotopes

A. Obertelli Phys. Lett. B633 (2006)33 *J.R. Terry, Phys. Lett. B 640 (2006) 86*

^{26}Ne(d,p)^{27}Ne in thick CD_2 target
2 states at 765 and 885keV
Inclusive σ for 765keV, compatible with intruder

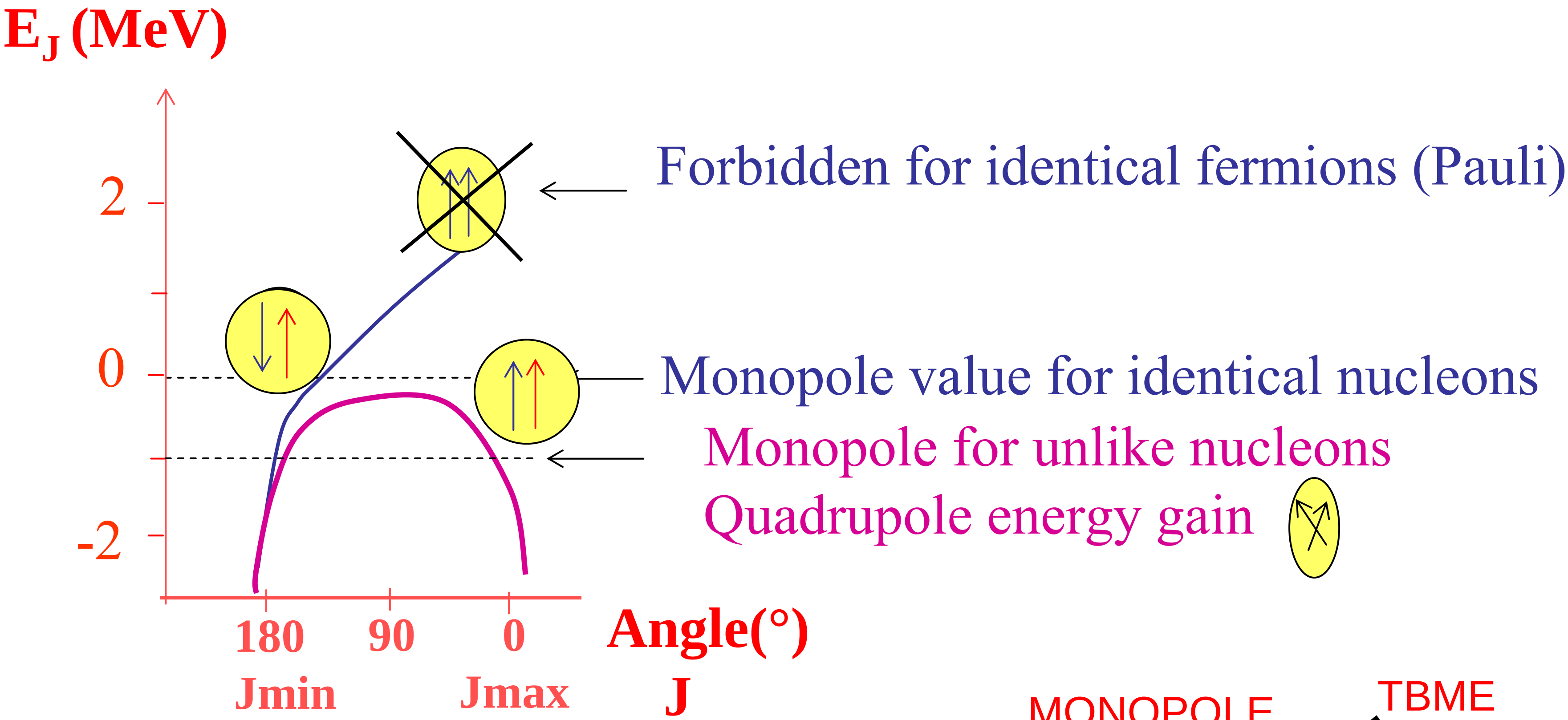
^{28}Ne(-1n)^{27}Ne
transition between 765 and 885keV
Intruder state (765keV) has L≤1 from momentum distrib.





⇨ Reduction of the N=20 shell gap ?

Main features of the nucleon-nucleon interaction –Part 2



MONOPOLE TBME

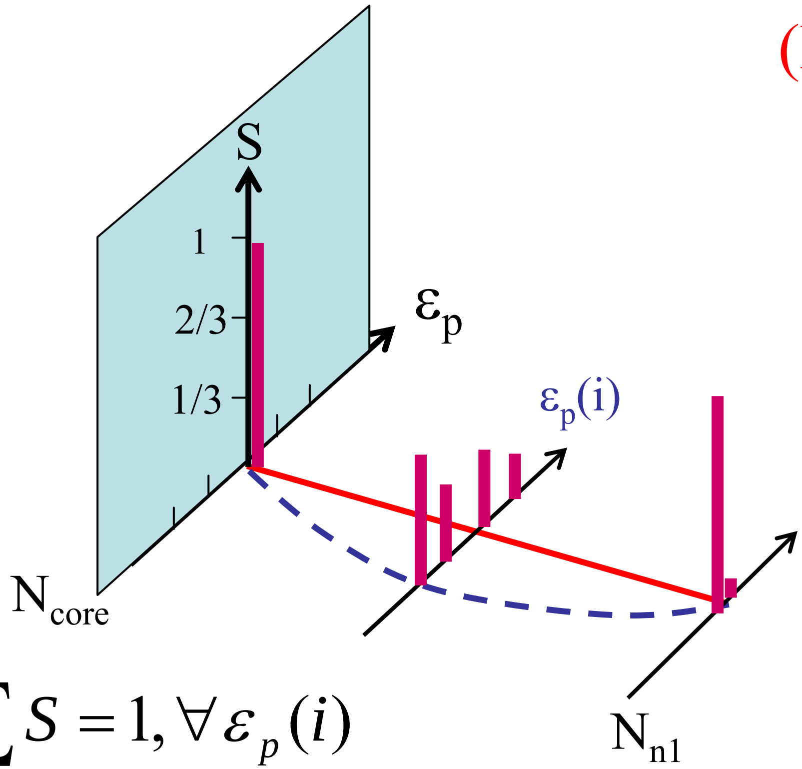
$$V_{pn} = \frac{\sum_J (2J+1) \times v_{pn}^J (j_p, j_n)}{\sum_J (2J+1)}$$

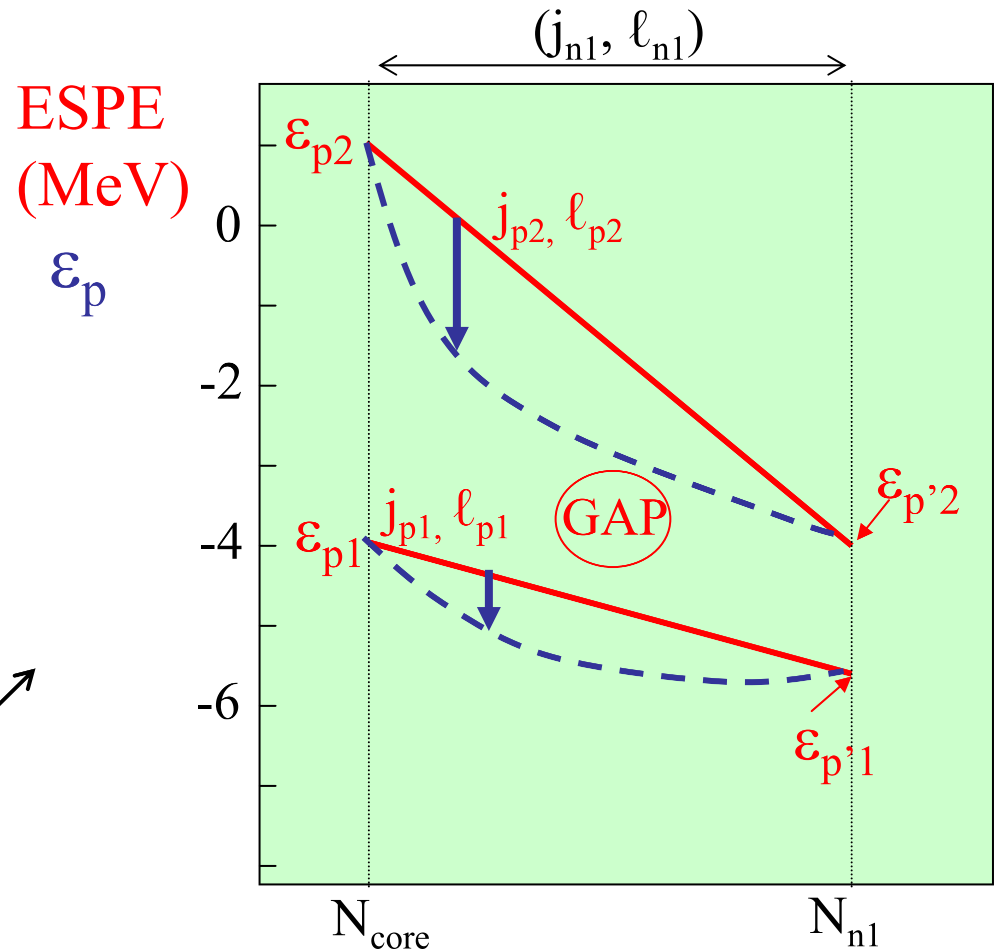
Interaction between unlike nucleons is stronger than with like nucleons in average

Quadrupole energy adds when orbits are not filled completely

The role of correlations in atomic nuclei

$\varepsilon_p = -\,Sp(Z) = [BE(Z-1,N) - BE(Z,N)]\,c^2$





$$\sum S = 1, \forall \varepsilon_p(i)$$

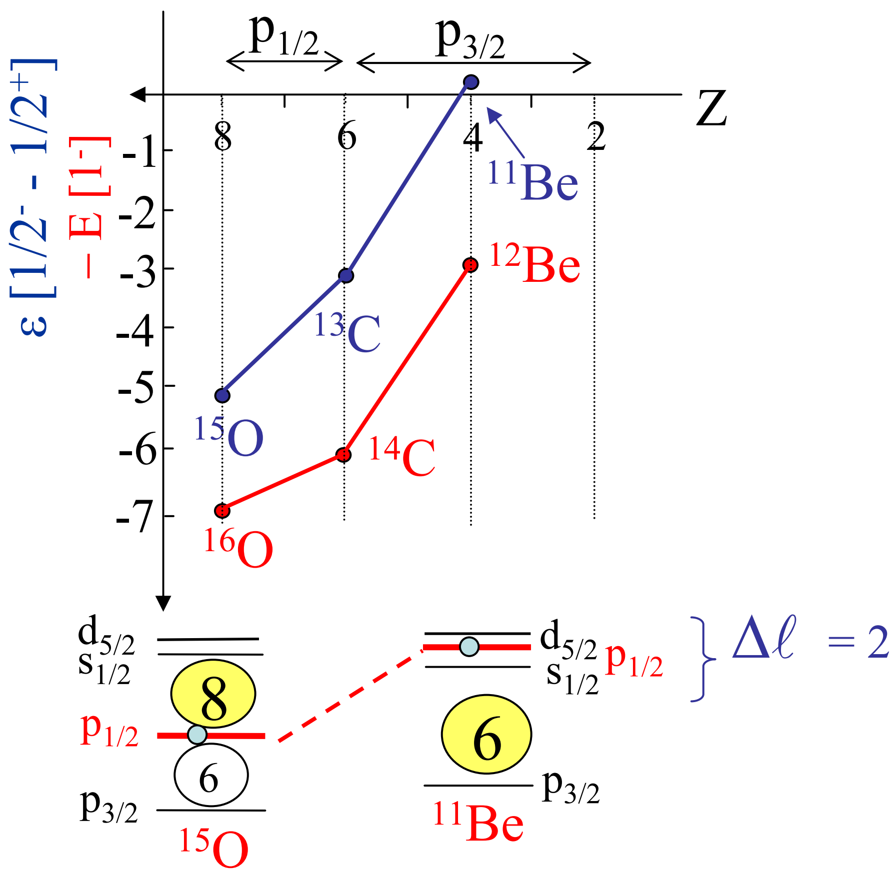
$$\varepsilon_p\ (i) \rightarrow \sum S \times \varepsilon_p(i)$$

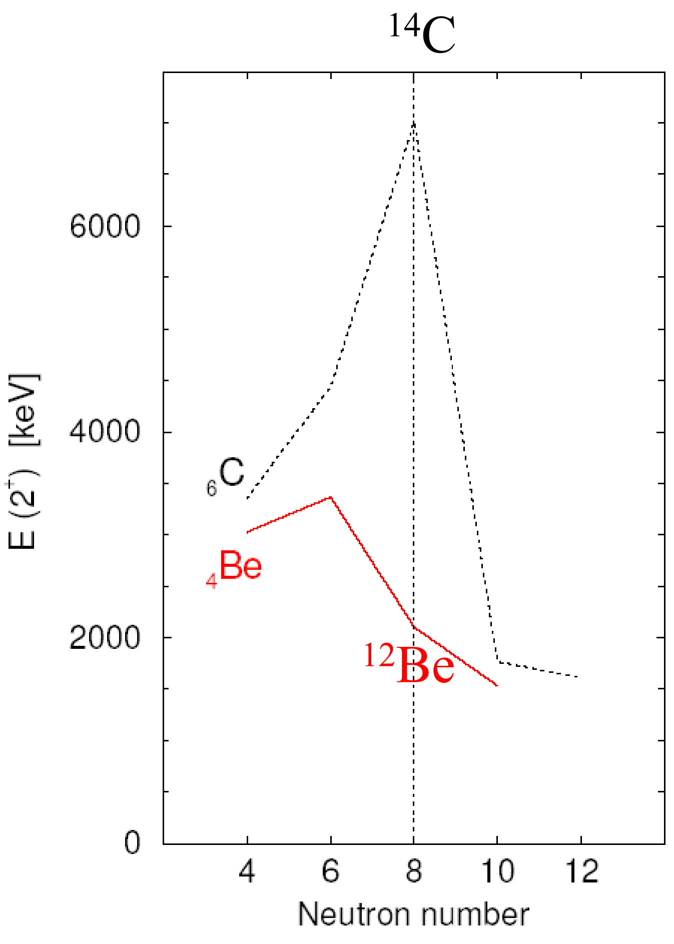
At mid-shell, the strength *S* is spread among several states, e.g. recoupling with 2^+ states

-> Deviation from linear monopole trend

If shell gaps enough reduced -> core excitations can dominate over

Evolution of the N=8 shell closure

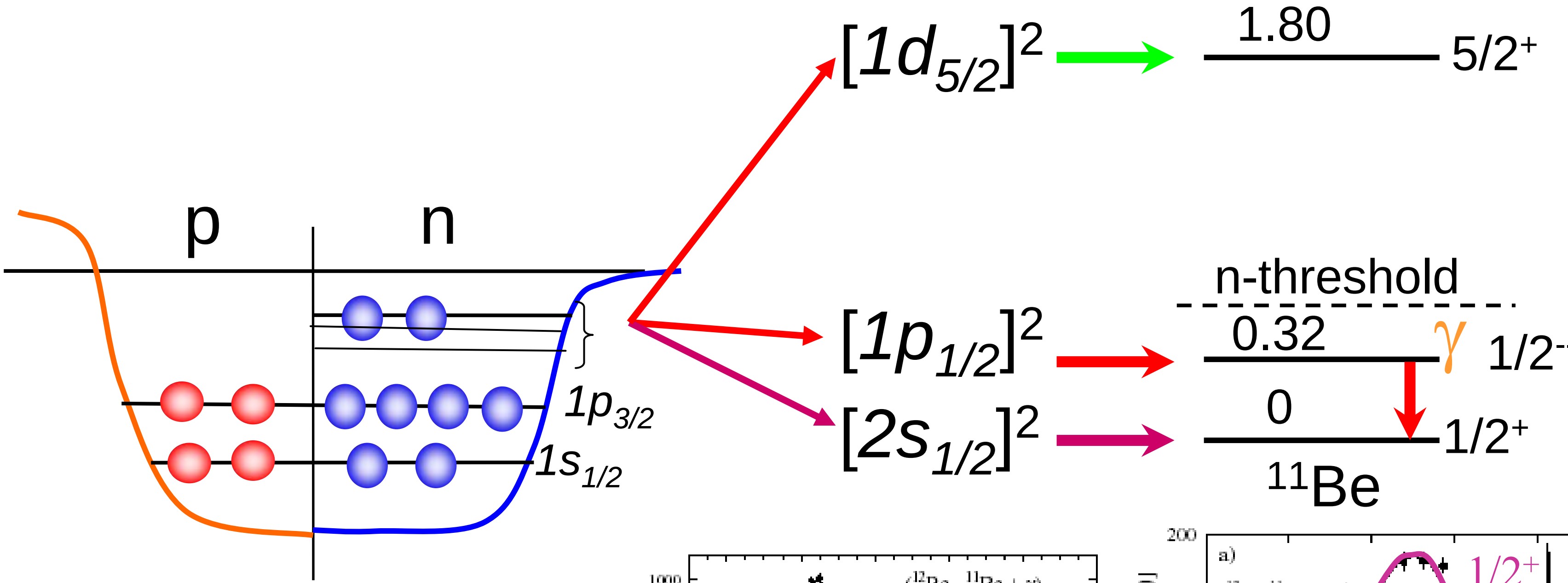




^{12}Be : Iwasaki et al., PLB 481 (2000) 7

Quadrupole excitations favored in Be
First possible island of inversion …
Role of the $\pi p_{3/2}$-$\nu p_{1/2}$ interaction

N=8 shell closure in ^{12}Be ?

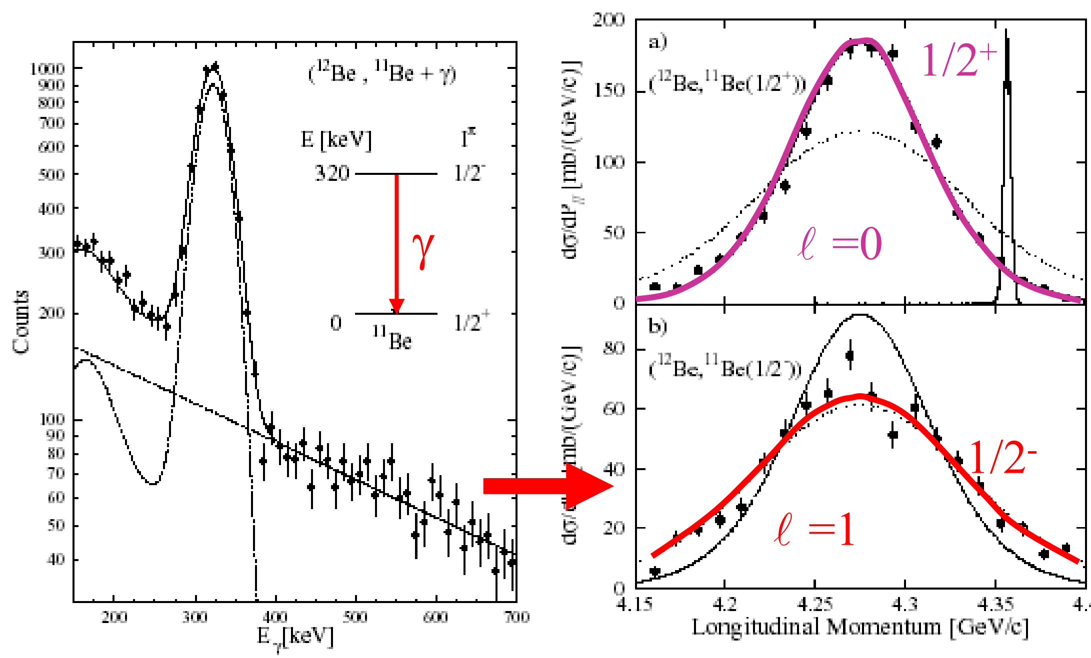


psd-shell ordering in ^{12}Be?

Knock-out reaction ^{12}Be(-1n) to probe g.s. composition of ^{12}Be

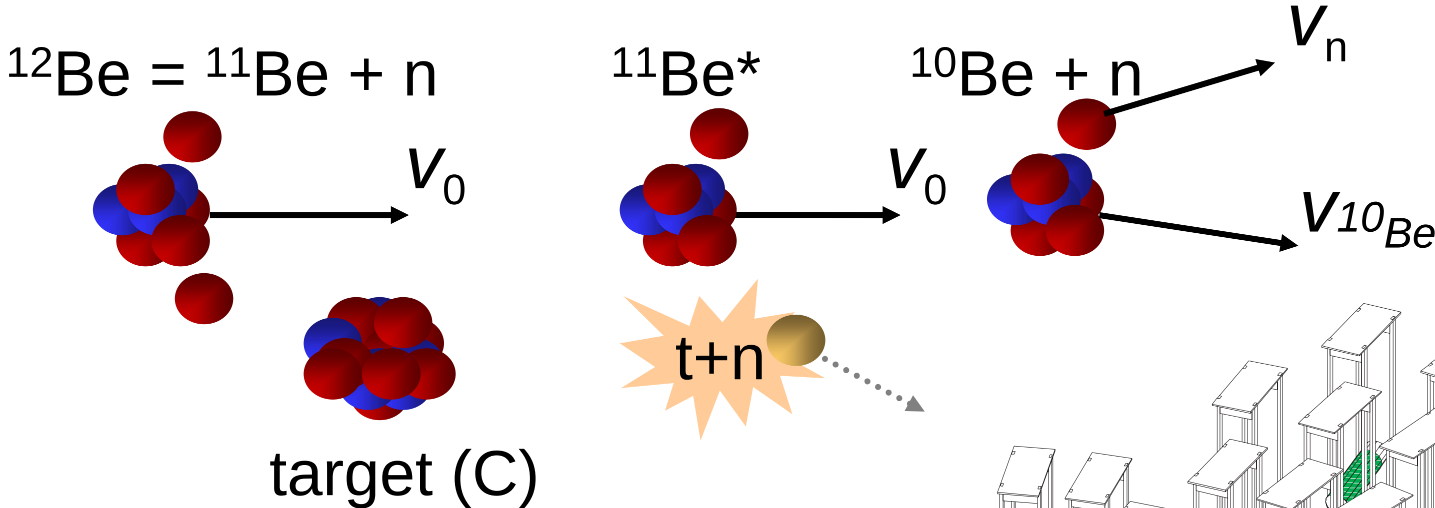
~Equal p and s composition

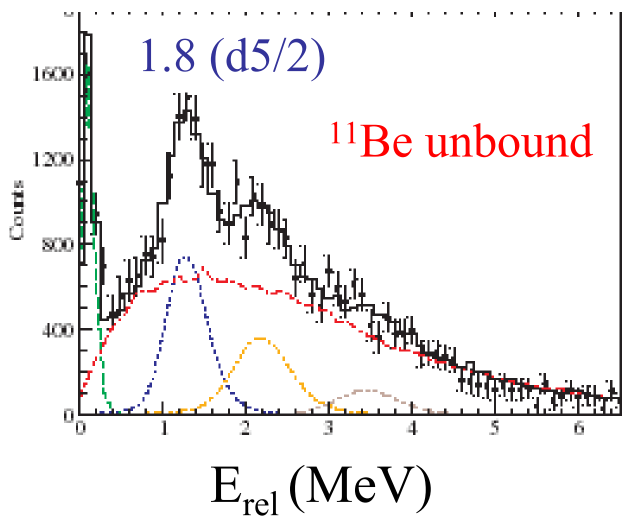
What about d5/2 strength ?

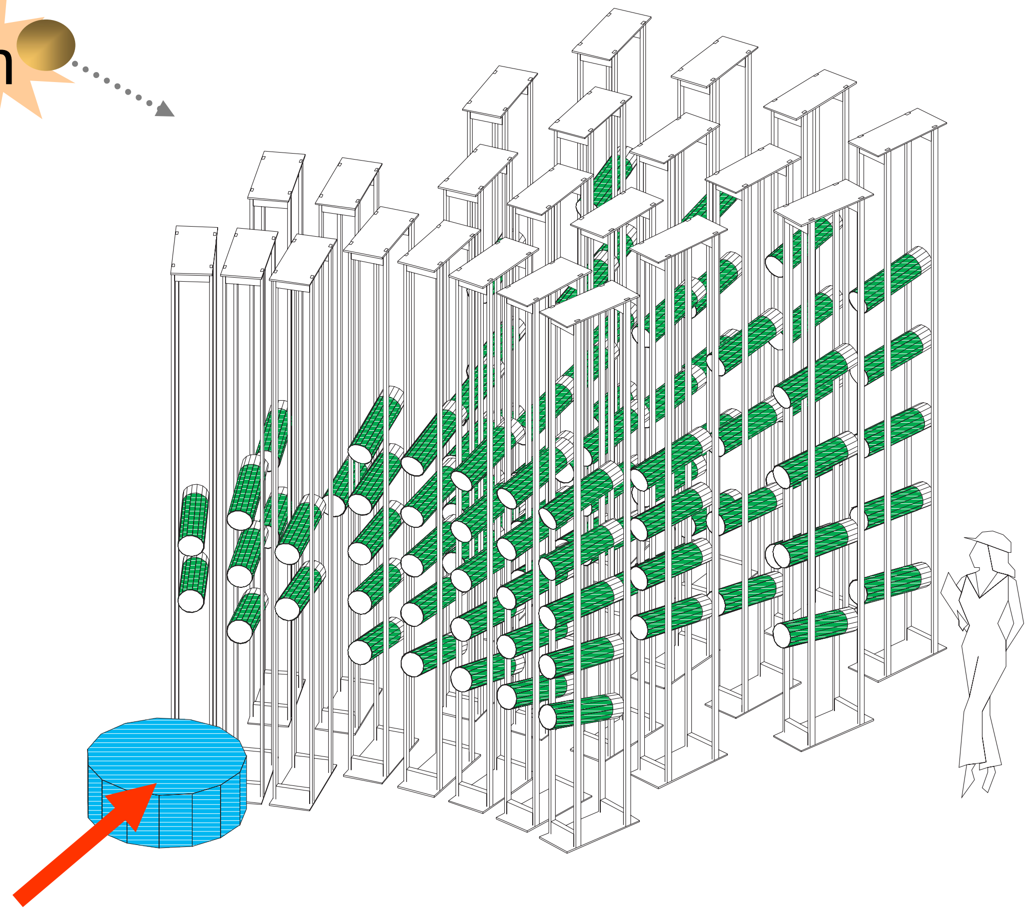


Navin et al., PRL 85 (2000) 2

Study of unbound states produced by ^{12}Be knock-out reaction





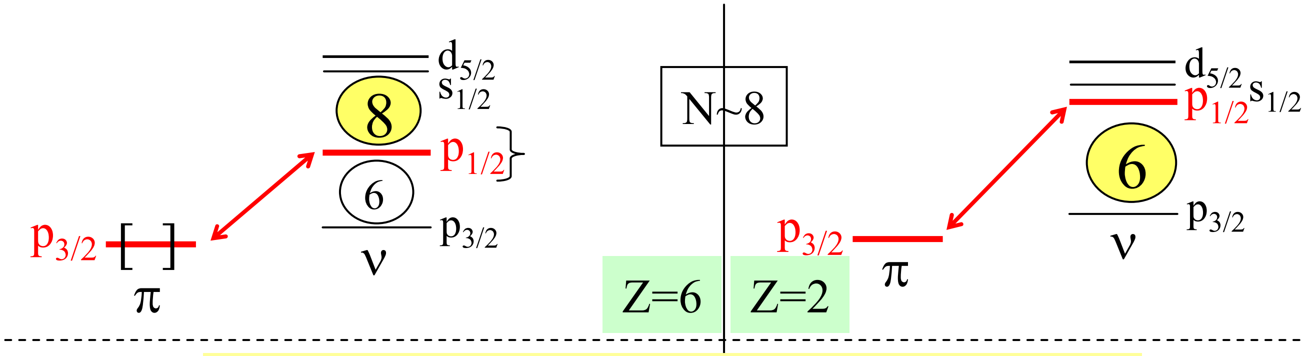


Equal admixtures of states:
s (0.56) , p (0.44) and d (0.48)

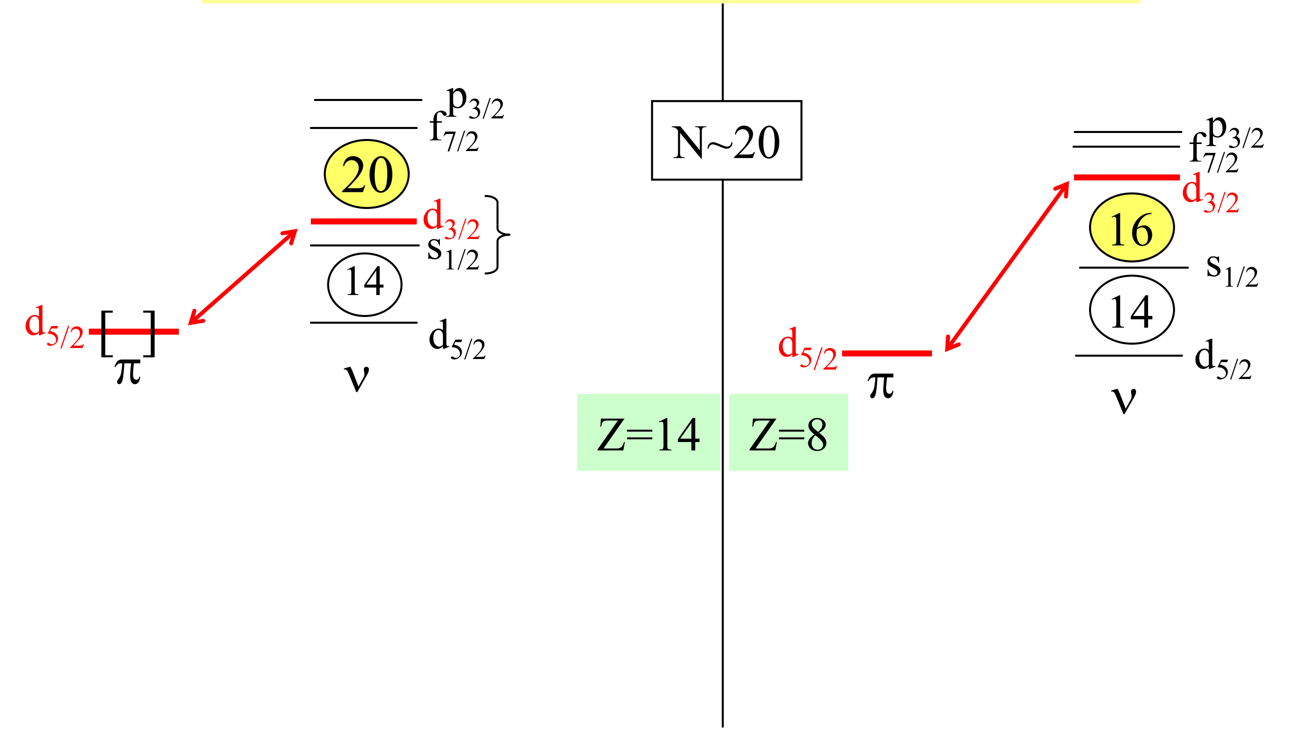
Pain et al., PRL 96 (2006) 032502

Confirms that the N=8 gap has collapsed

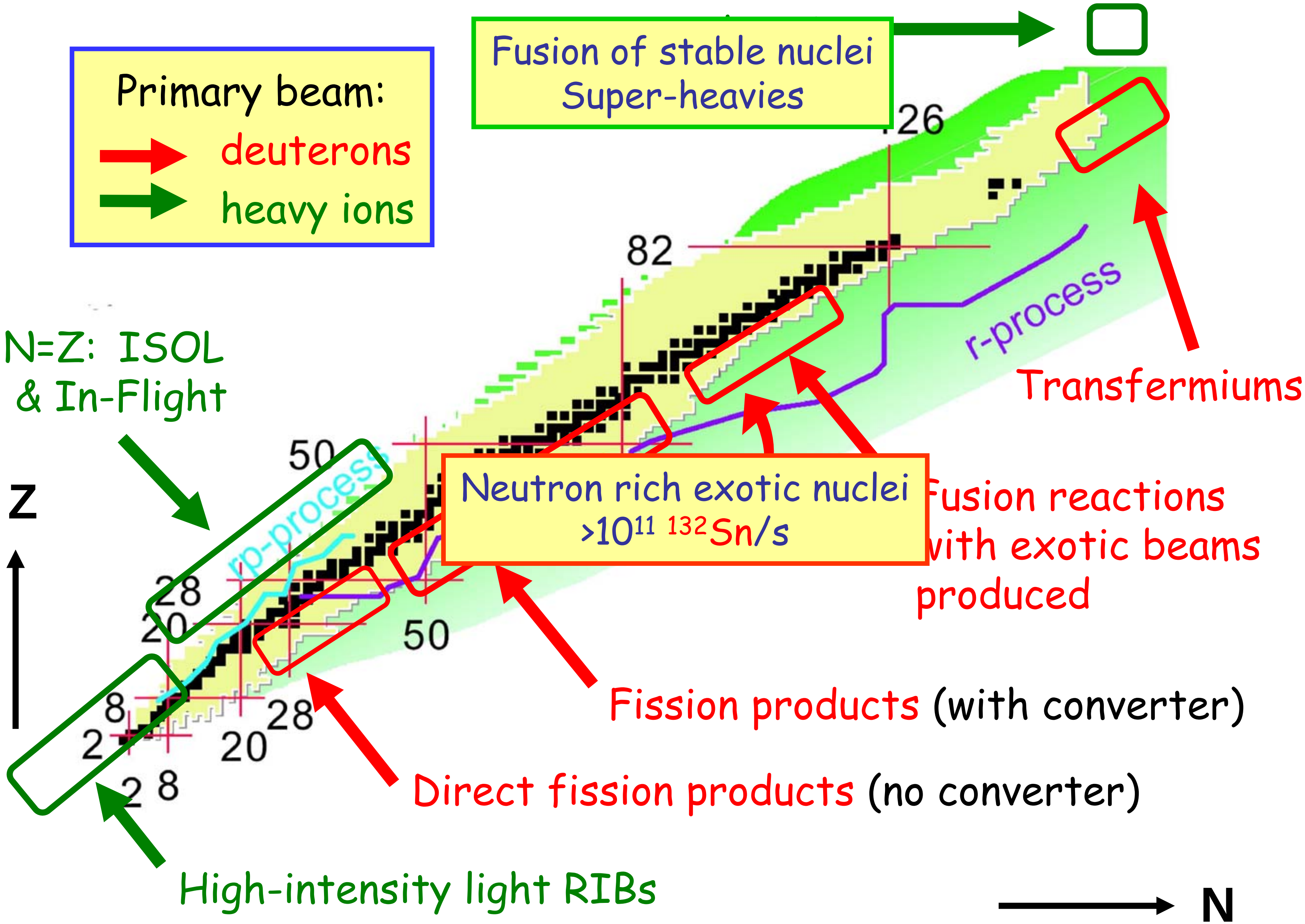
Evolution of Harmonic Oscillator shell closures

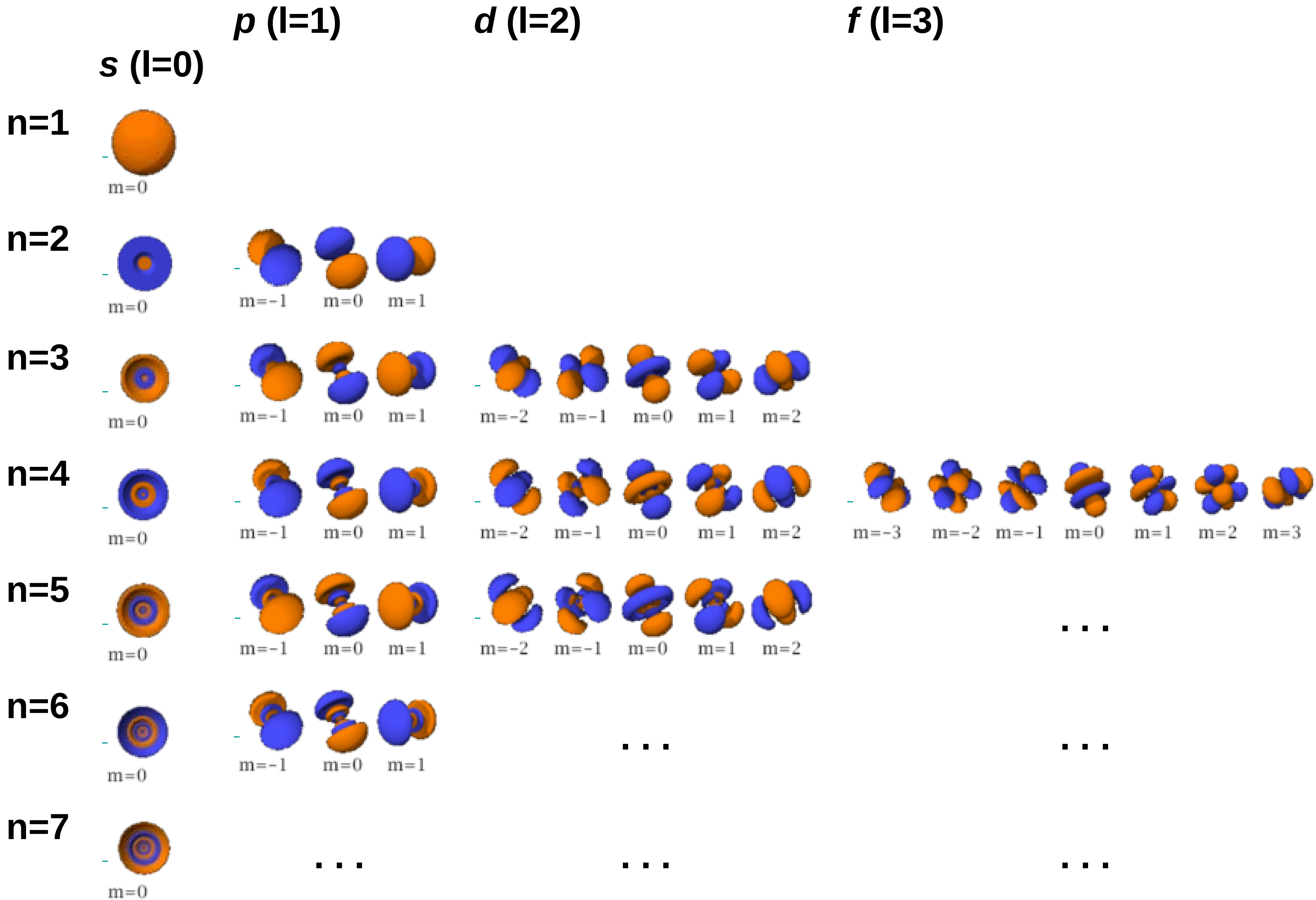


Role of the $\pi\ p_{3/2}$- $\nu\ p_{1/2}$ interaction

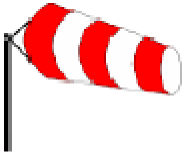


The SPIRAL2 facility





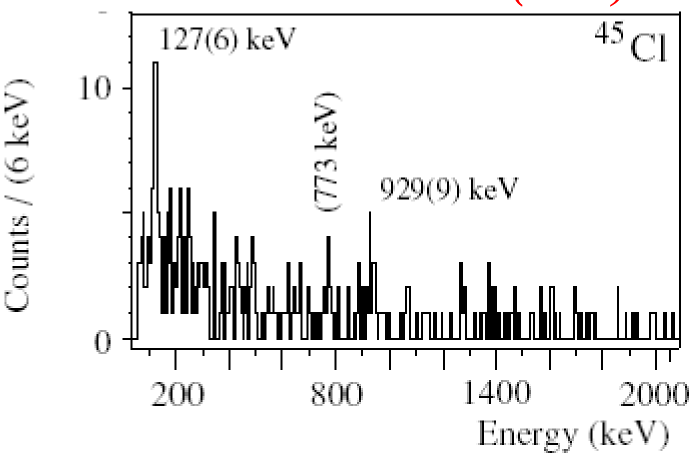
s (l=0)
p (l=1)
d (l=2)
f (l=3)
n=1
m=0
n=2
m=0
m=-1 m=0 m=1
n=3
m=0
m=-1 m=0 m=1
m=-2 m=-1 m=0 m=1 m=2
n=4
m=0
m=-1 m=0 m=1
m=-2 m=-1 m=0 m=1 m=2
m=-3 m=-2 m=-1 m=0 m=1 m=2 m=3
n=5
m=0
m=-1 m=0 m=1
m=-2 m=-1 m=0 m=1 m=2
. . .
n=6
m=0
m=-1 m=0 m=1
. . .
. . .
n=7
m=0
. . .
. . .
. . .



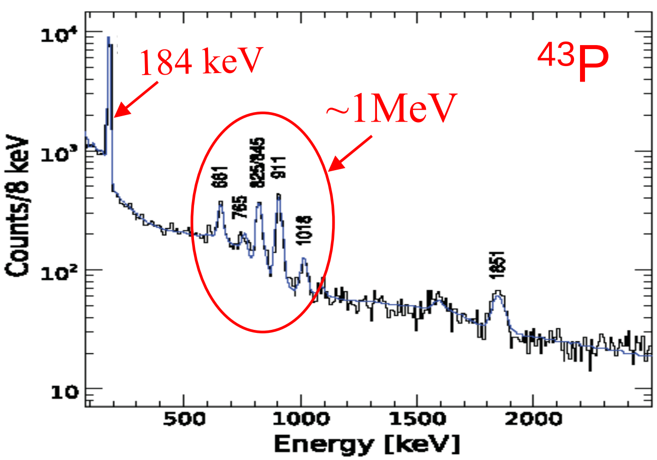
1- Evolution of proton orbits between N=20 and N=28

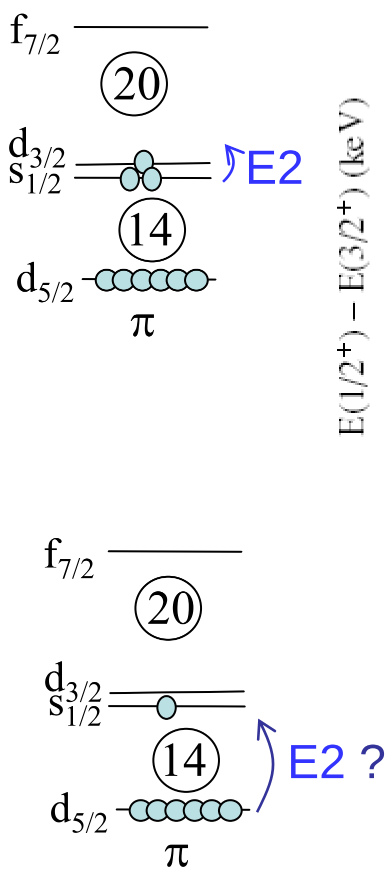
Evolution of sd proton states towards N=28 below Ca (Z=20)

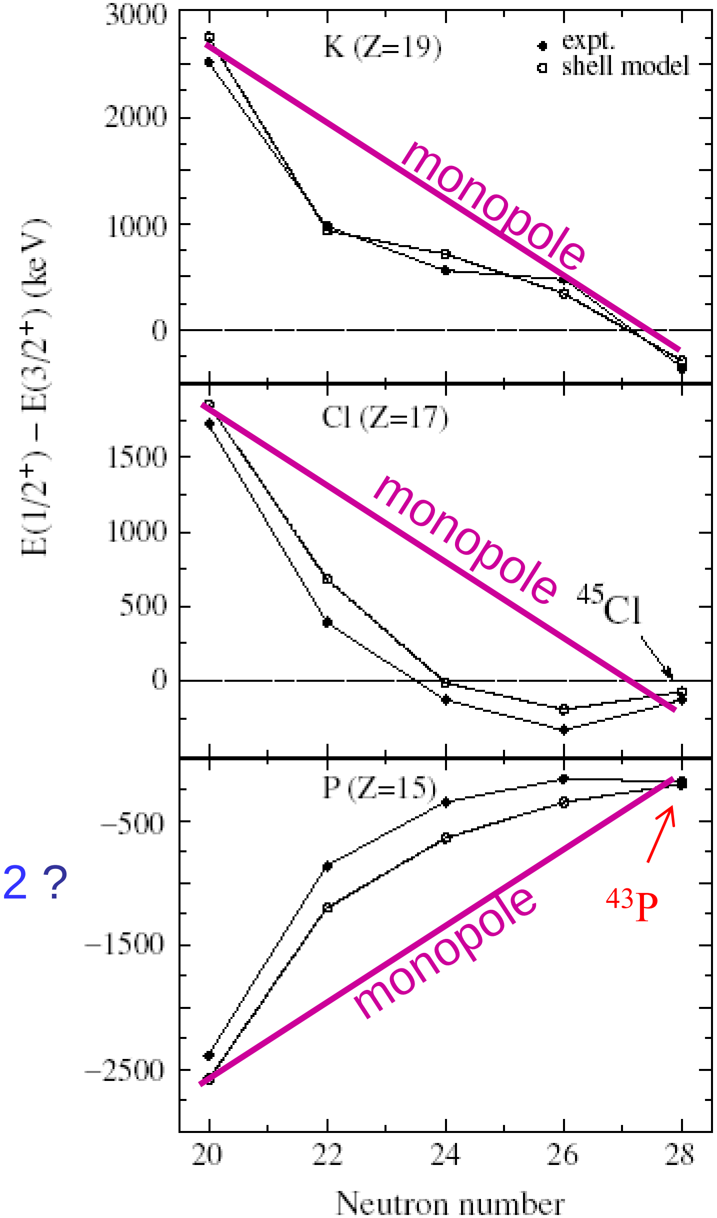
Gade et al. PRC 74 (2006)



Riley et al. PRC 78 (2008)







From Gade PRC74 (2006)

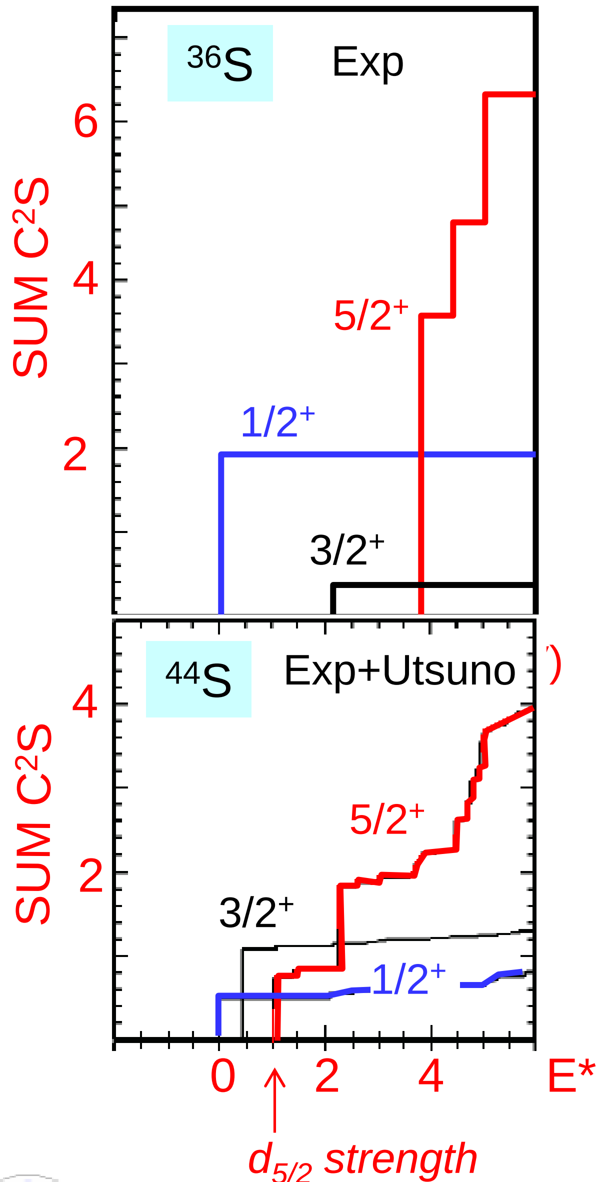
Fridmann et al. PRC 74 (2006)

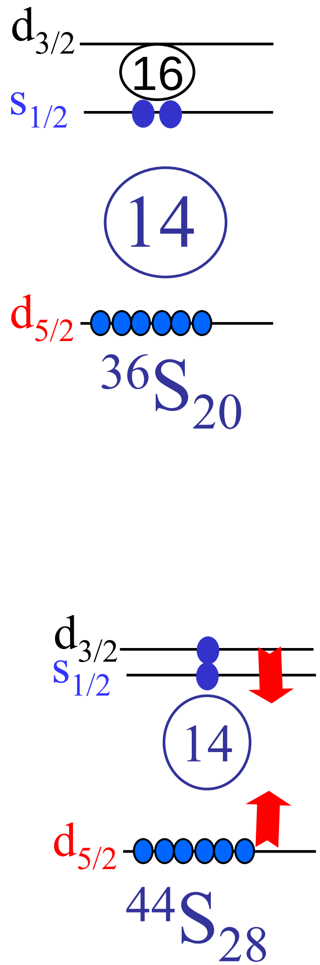
Degeneracy of proton $s_{1/2}$ and $d_{3/2}$ orbits **preserved**

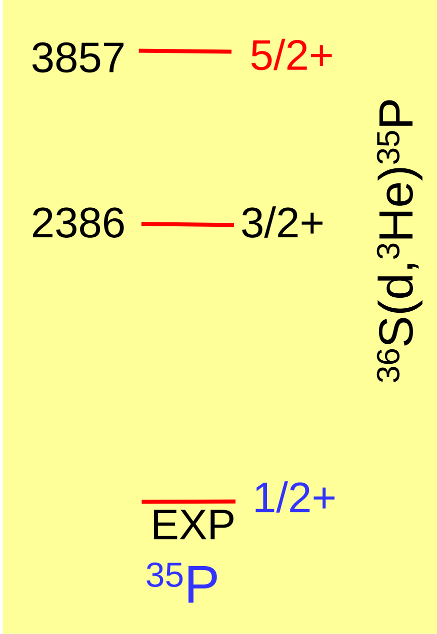
Role of monopole interactions **similar**

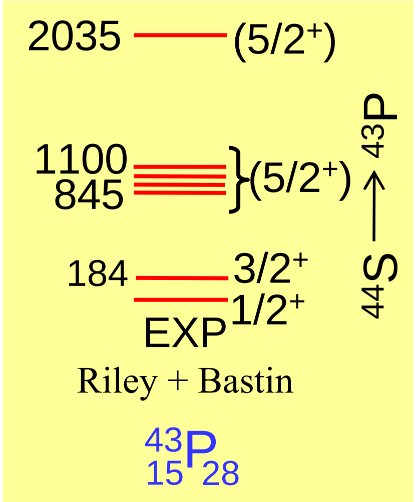
Proton E2 collectivity **favoured** at N=28 / depends on Z=14 gap

Evolution of the Z=14 shell gap – The role of nuclear interactions





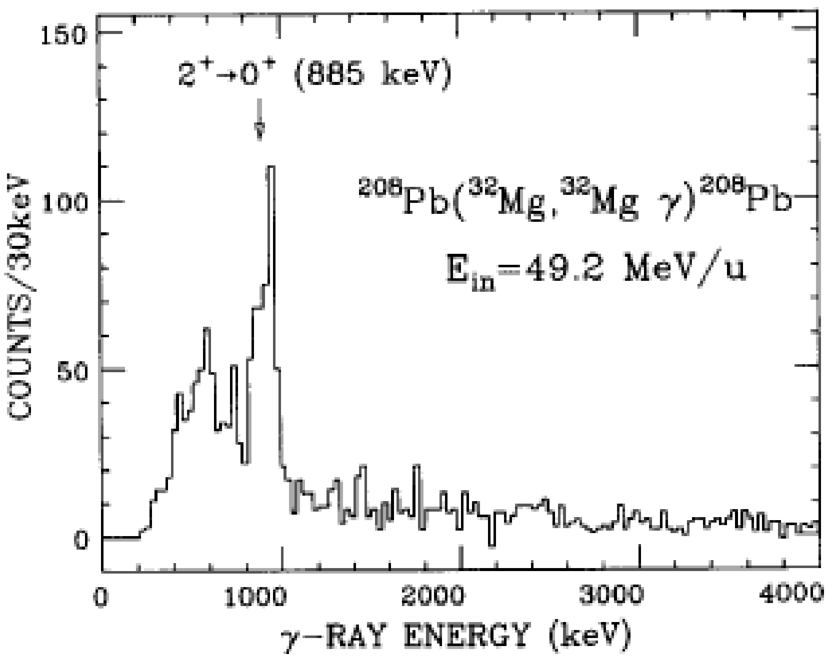




From N=20 to N=28, the proton $d_{5/2}$ is shifted at lower E* and is more fragmented

Consistent picture with proton-neutron tensor forces

2) Enhanced cross shell excitations -> Large quadrupole deformation



Motobayashi et al., PLB 346 (1995)