New Trends in the Nuclear Shell Structure

O. Sorlin – GANIL Caen

I . General introduction to the atomic nucleus

Charge density, shell gaps, shell occupancies,
Nuclear forces, empirical monopoles, additivity,
Quadrupole correlations,
Role of 'monopoles', p-n tensor force

II. Study of the N=20 shell closure

Drip line
Spectroscopic properties
Change of shell gap
A new magic number 16

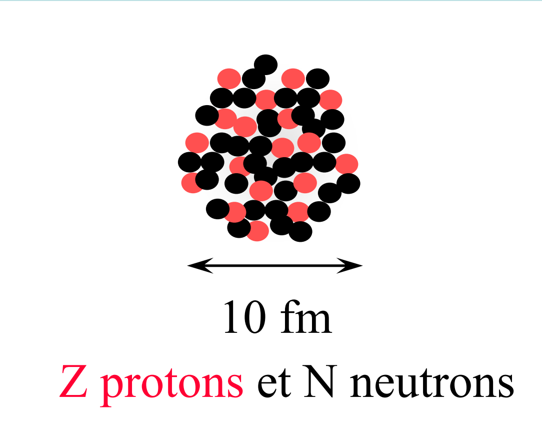
III. Study of the N=28 shell closure
IV. Nuclear astrophysics
V. Perspectives

O. Sorlin and M.-G. Porquet Prog. In Part. Nucl. Phys. 61 (2008)

Ecole Joliot Curie, Maubuisson 2009

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.

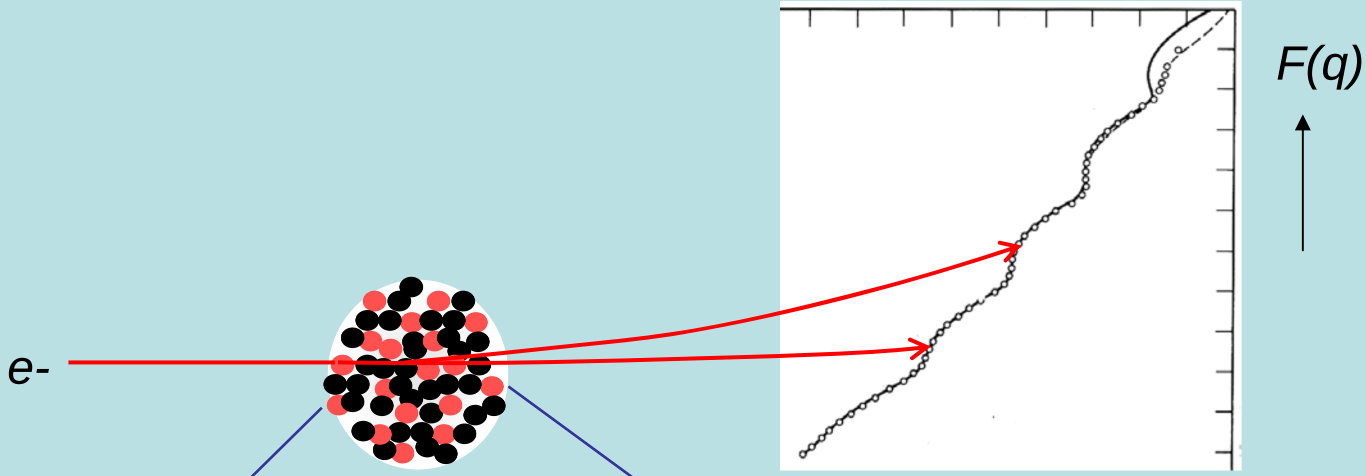
Paradoxically, Mean field approach appropriate for 'heavy' nuclei (Pauli)
Nucleons are self-generating their mean field (contrary to e- in atoms)

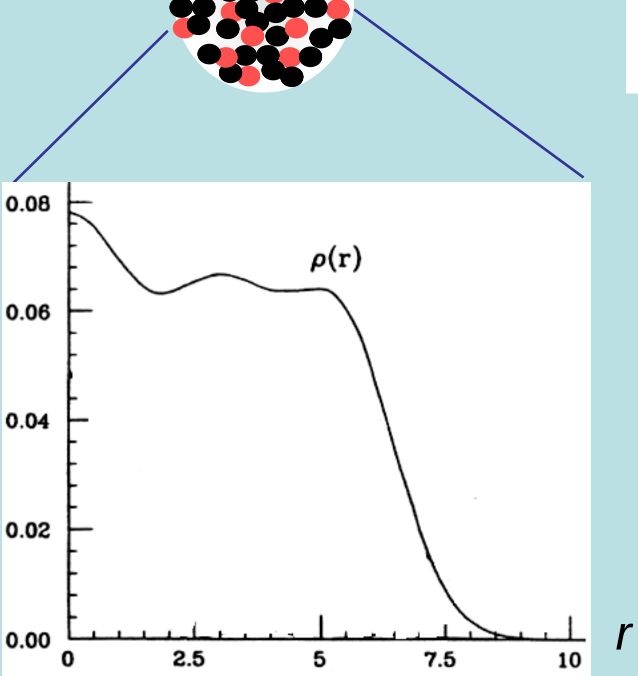
Charge density distribution -> mean field potential
Nucleons arranged on orbits -> irregular spacing gives rise to shell gaps

Shell model approach : Core nucleus on which two body interactions develop
BUT differ from the bare NN forces / to which extent ?

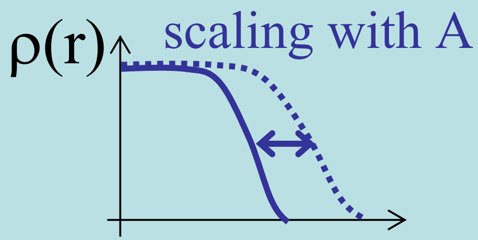
Two quantum 'fluids' ; Vnn (Vpp) ~ 1/3 Vnp due to Pauli principle
-> importance of Vnp for structural changes

Charge density of the nucleus : $\rho(r)$





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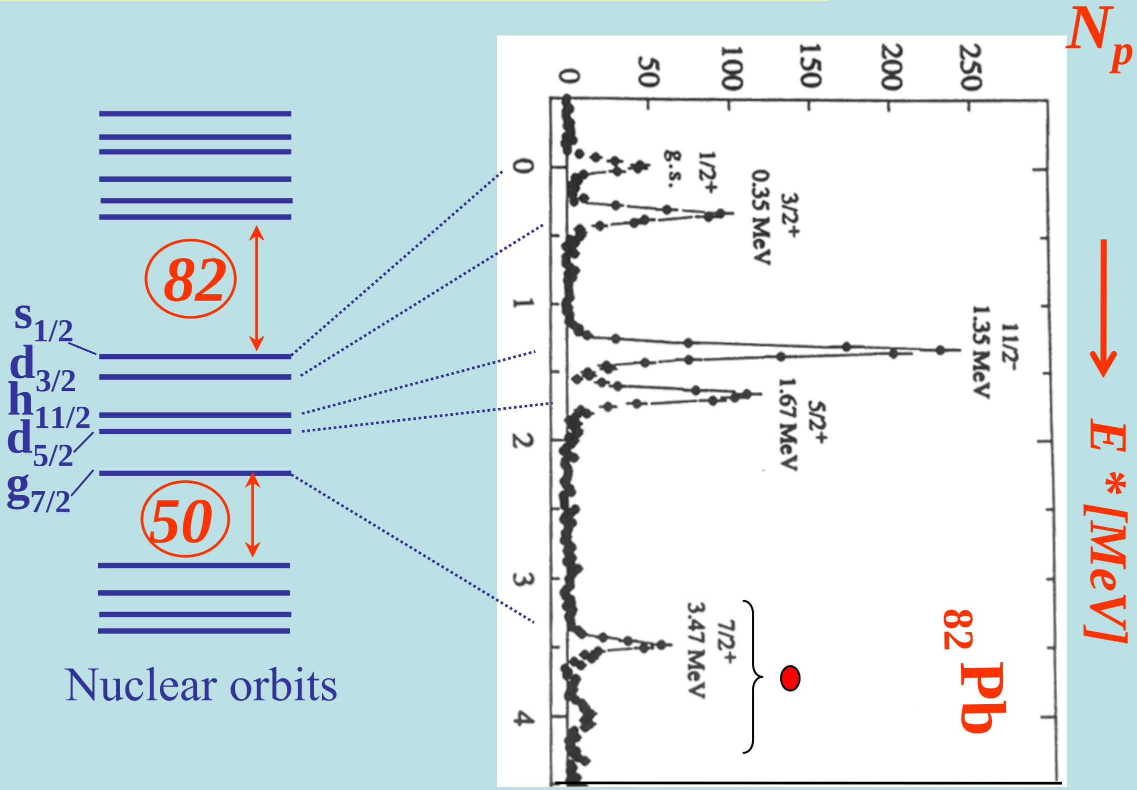
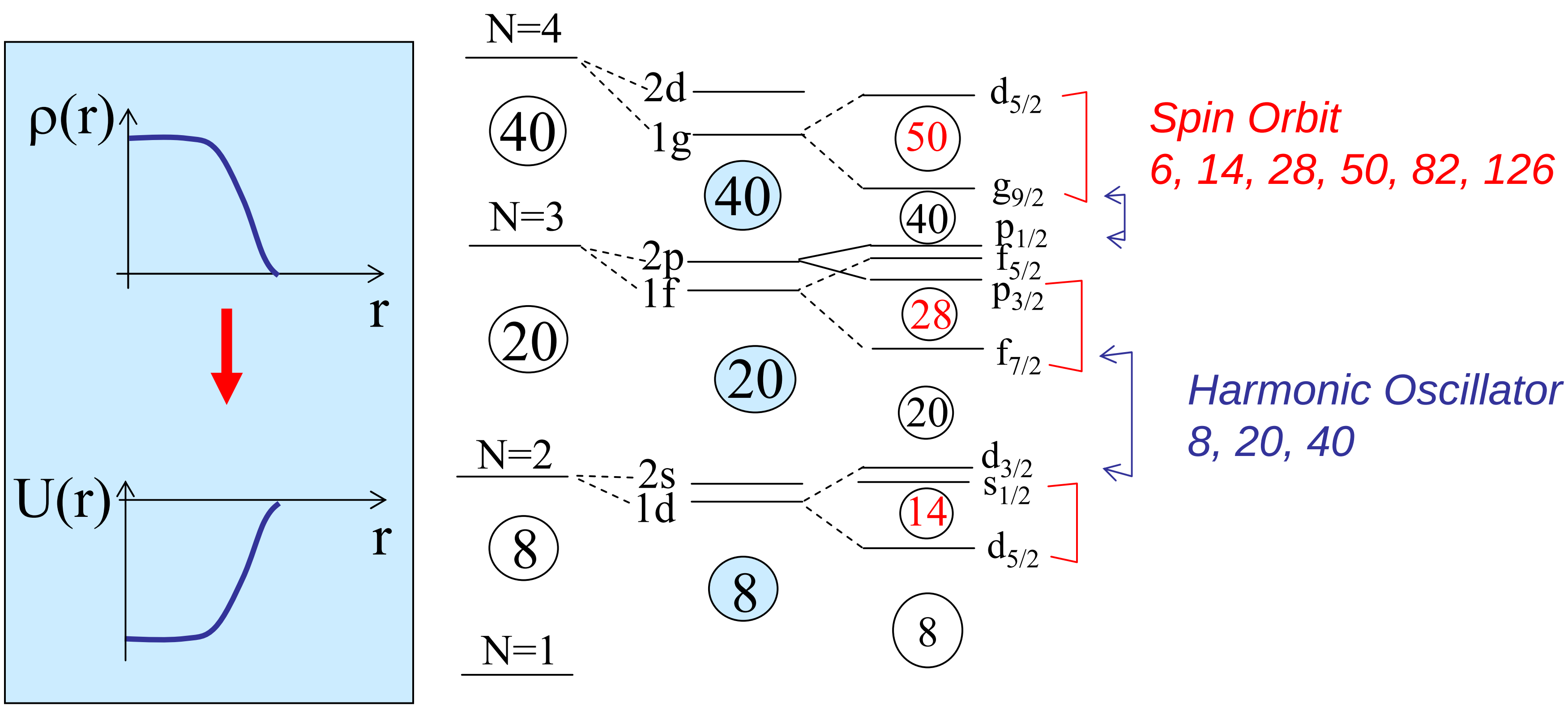
example :
$h_{11/2}$: L=5, J=11/2,
L and s aligned
contains 12 nucleons



->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 (so far) to STABLE nuclei

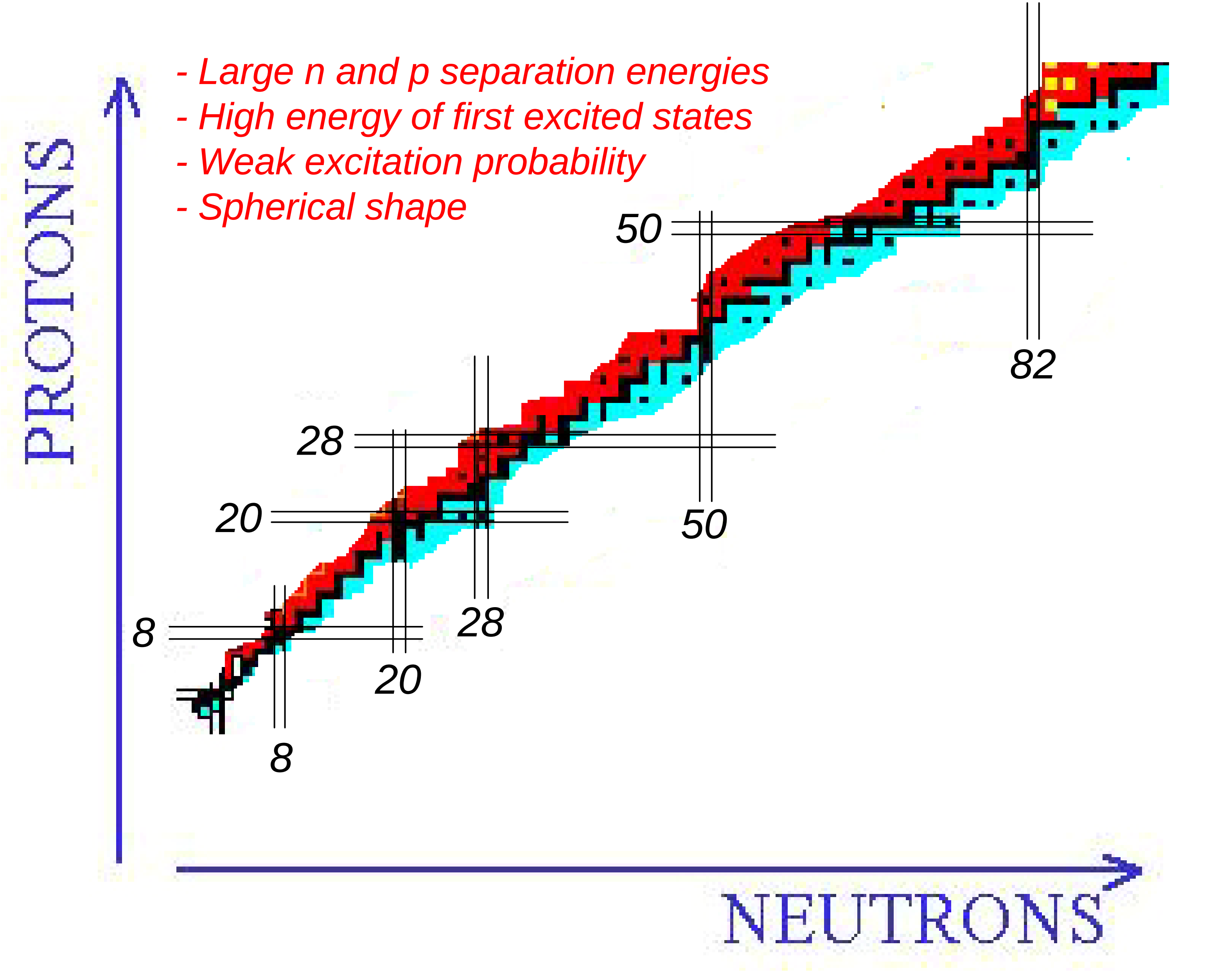
Simplified mean-field approach for atomic nuclei



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

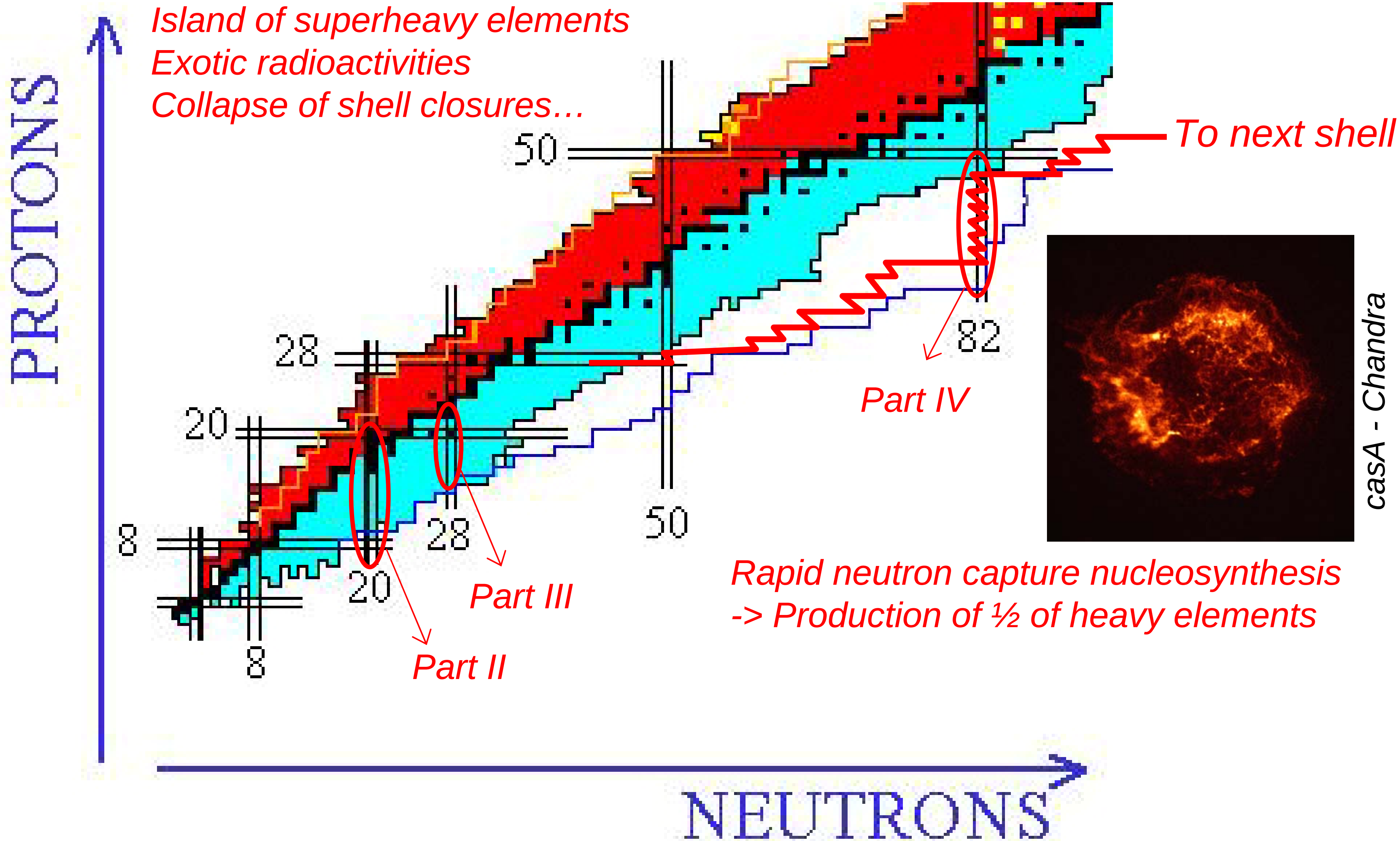
$$U(r) = \int_{vol} \rho(r')v(r,r')d^3r' = \int_{vol} \rho(r')[-v_0\partial(r-r')]d^3r' = -v_0\rho(r)$$

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



Enlarged vision of nuclear structure using worldwide accelerators

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



-> Far from stability, new in-medium forces are explored / i.e. tensor forces

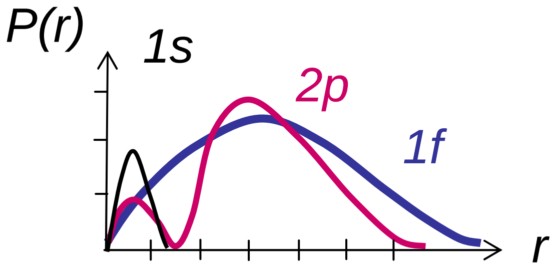
How can magic numbers (or shell gaps)

be modified by nuclear forces ?

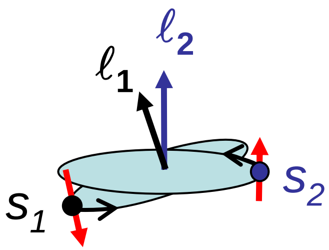
Main features of the in-medium NN interaction

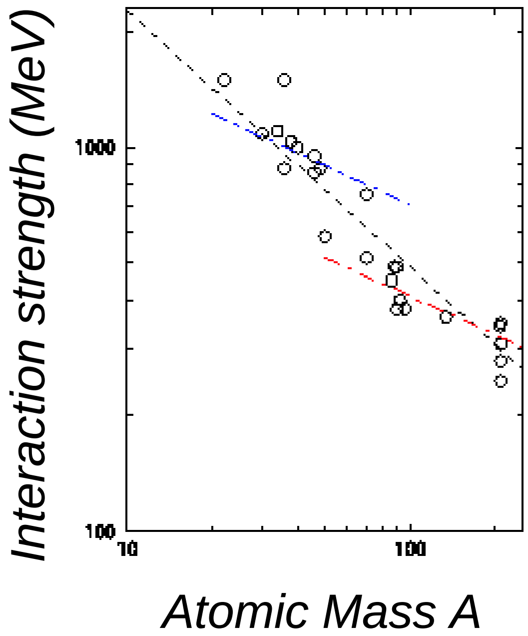
Radial overlap (radial WF) : larger when $n_1=n_2$

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



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

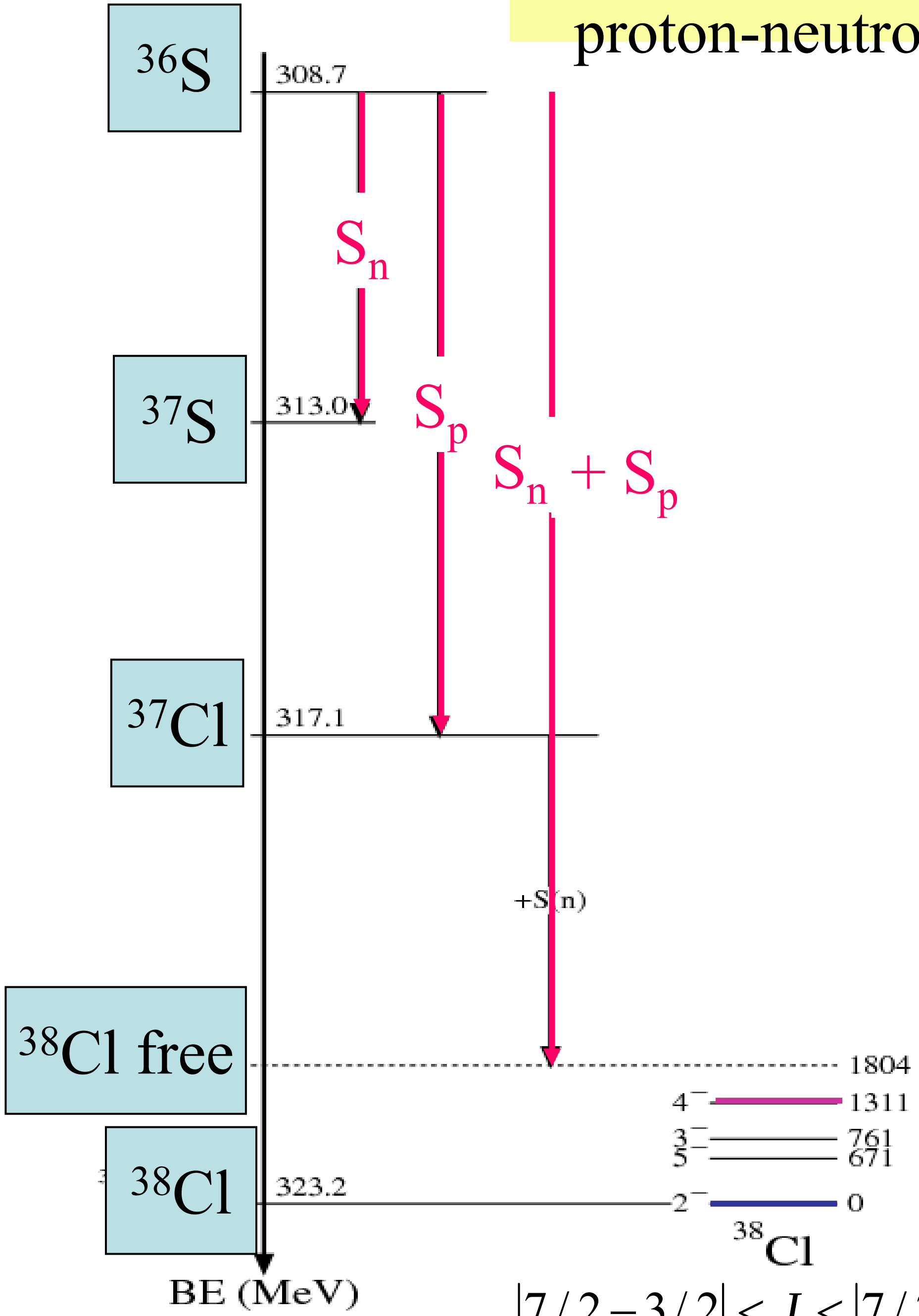




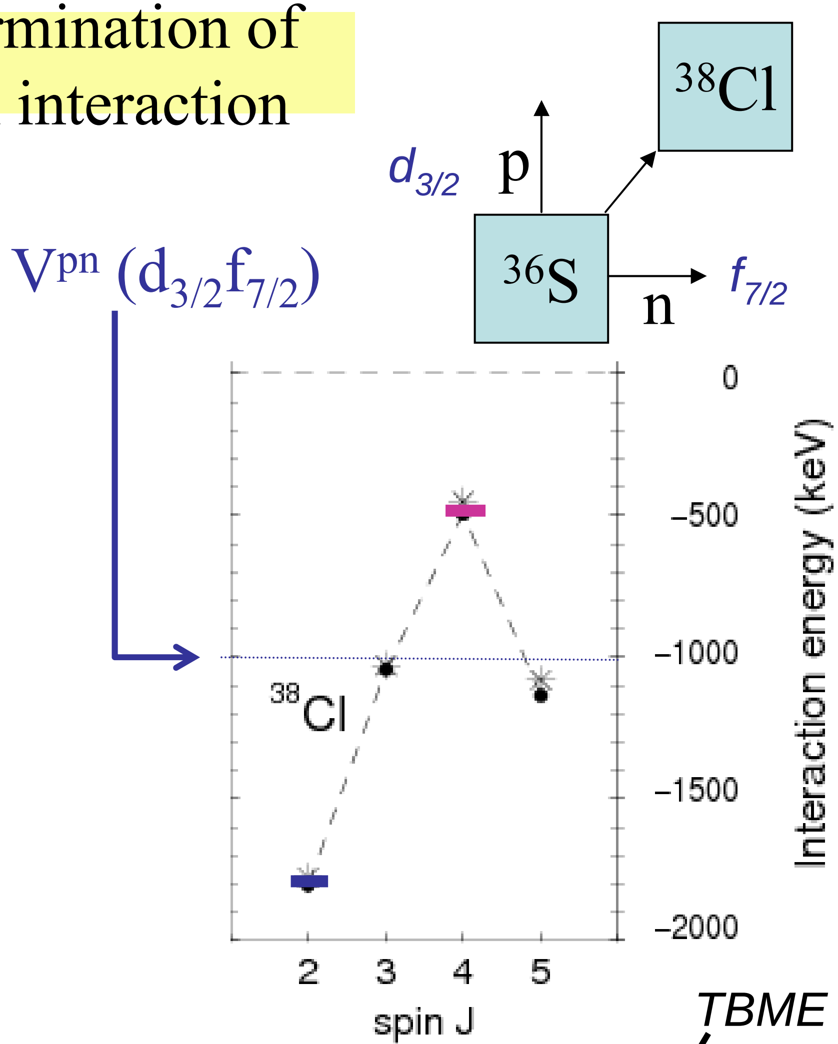
Radius of the orbits (scales with 1/r or $A^{-1/3}$)

smoother changes in structure of heavy nuclei

Empirical determination of proton-neutron interaction



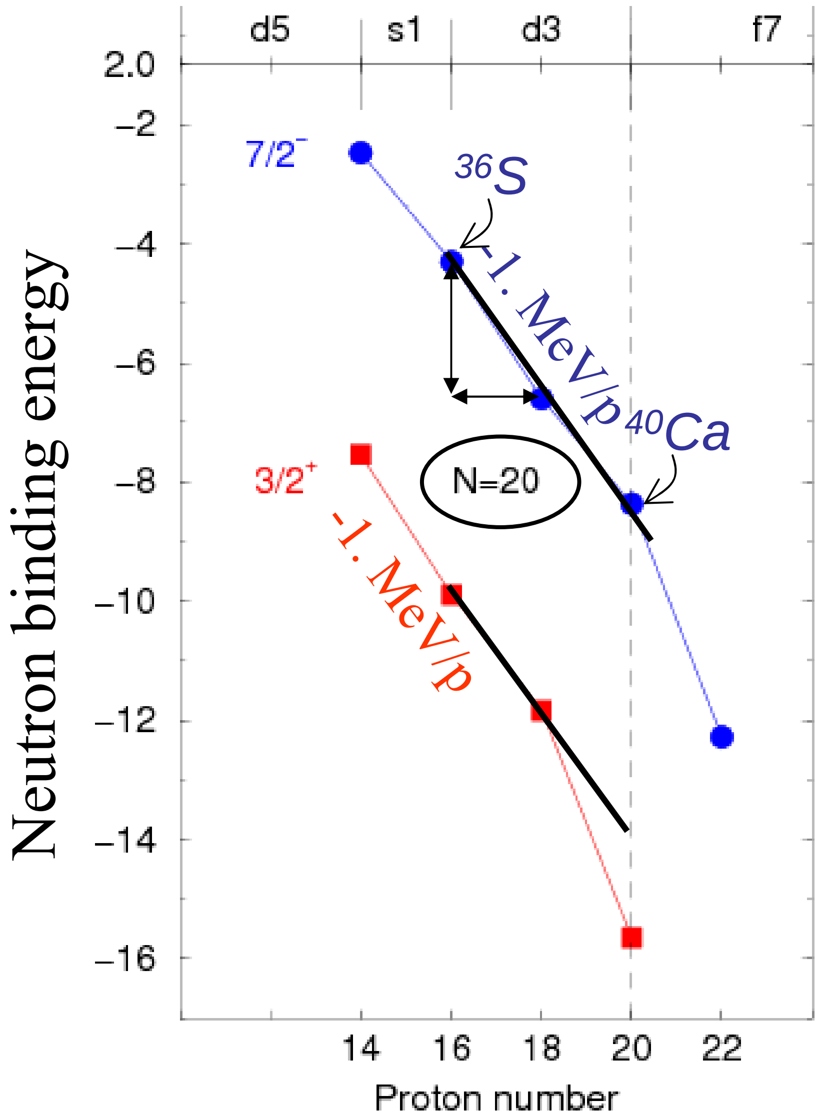
$$|7/2-3/2| < J < |7/2+3/2|$$



TBME

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

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



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

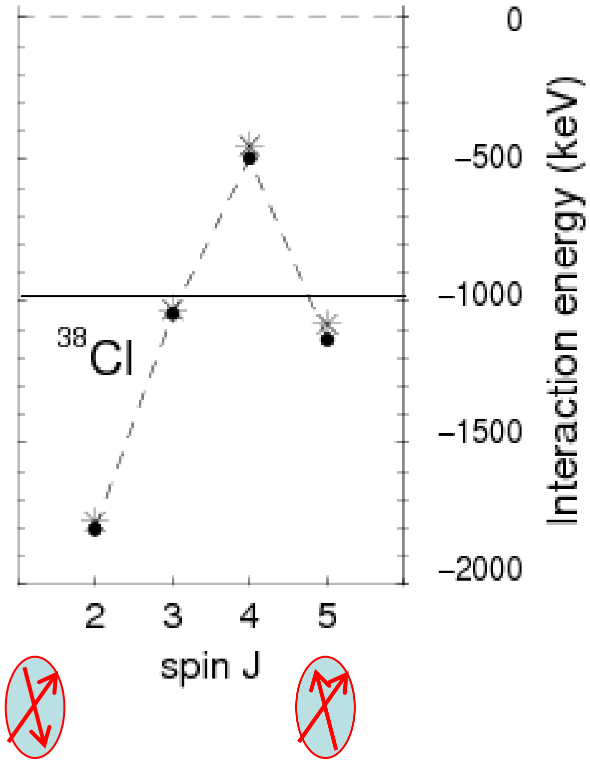
$$\Delta(20) = \underbrace{(2j_p+1)}_{4}\,(V^{pn}_{d3/2\,f7/2} - V^{pn}_{d3/2\,d3/2})$$

$Vpn\,(d_{3/2}d_{3/2}) \sim -1$ MeV per proton

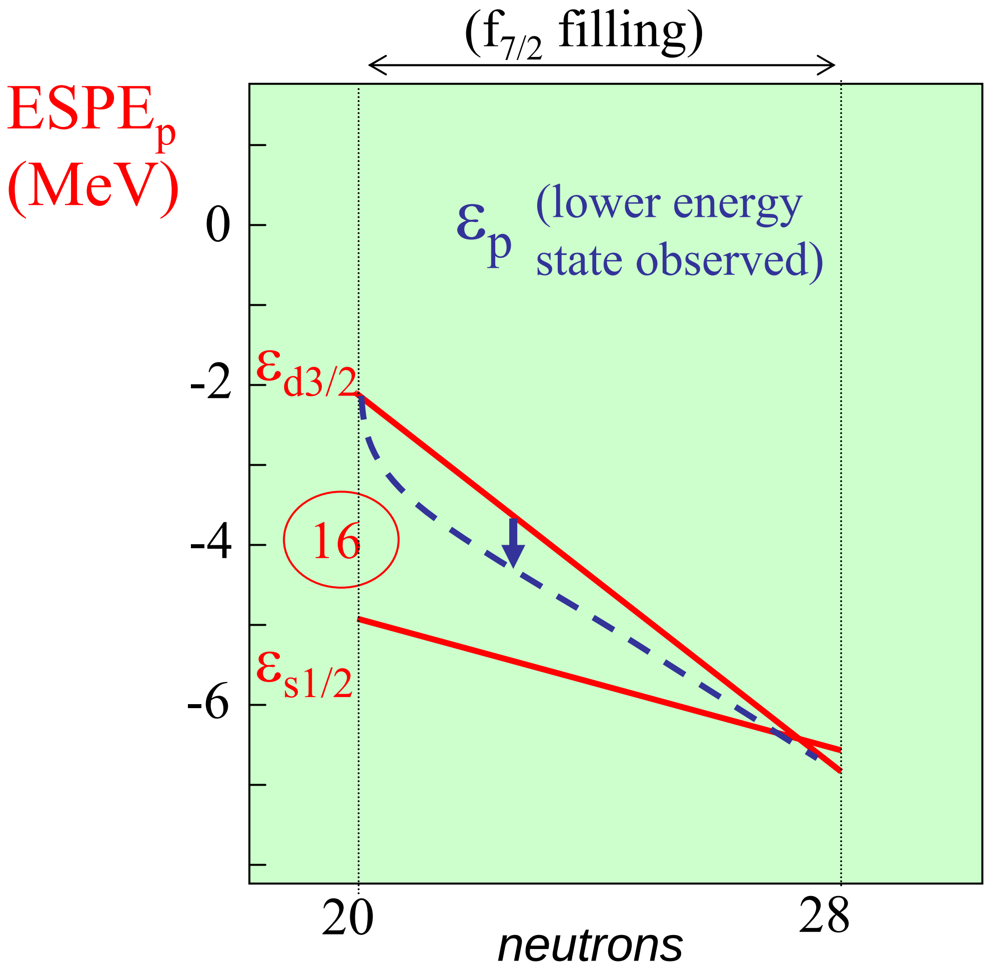
The N=20 shell gap is unchanged !

The role of quadrupole correlations in atomic nuclei

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



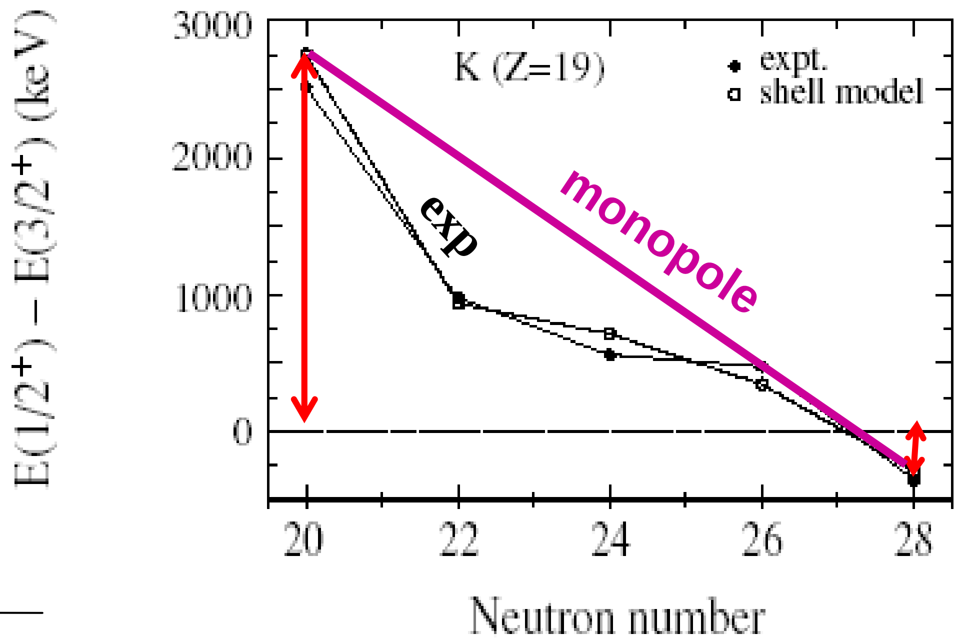
Quadrupole energy can be gained for certain orientations of particles



$$\Delta(Z=16) = 8\,(V^{pn}_{d3/2\,f7/2} - V^{pn}_{s1/2\,f7/2})$$

At mid-shell, deviation from linear monopole trend
-> correlations / coupling to excitations of the neutron core

Evolution of proton configurations in the K chain

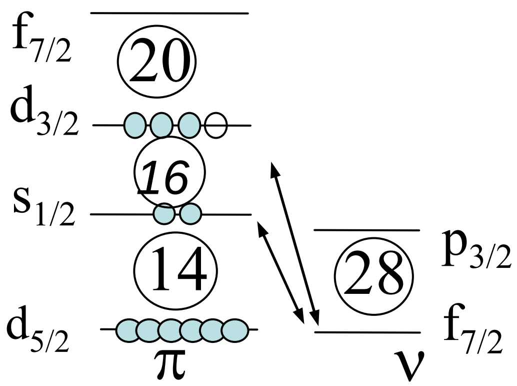


Exp :(d,3He) or ee'p.
[Doll 76, Banks 85, Kramer01]

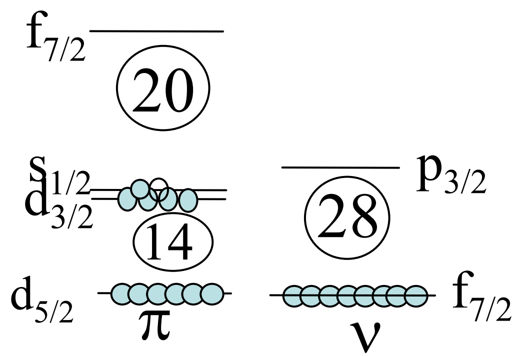
Role of pn monopole force

$Vd_3f_7 >> Vs_1f_7$

No info on tensor !



Z=19 *K* **N=20**

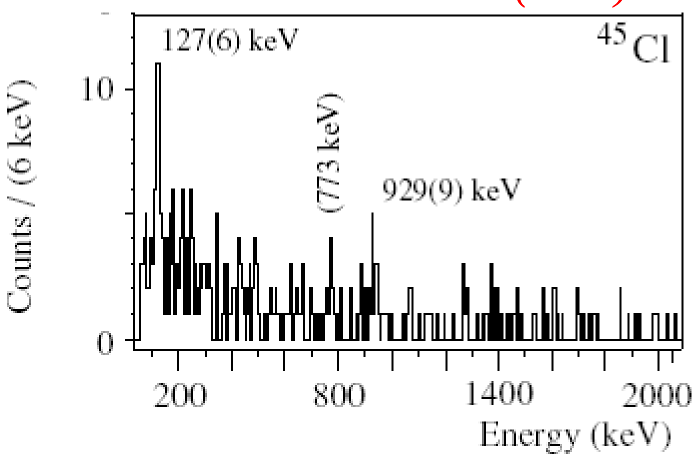


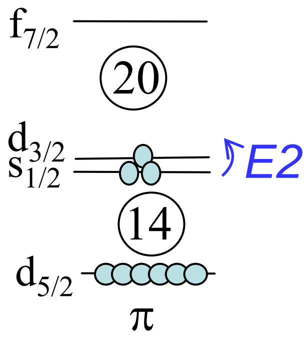
Z=19 *K* **N=28**

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

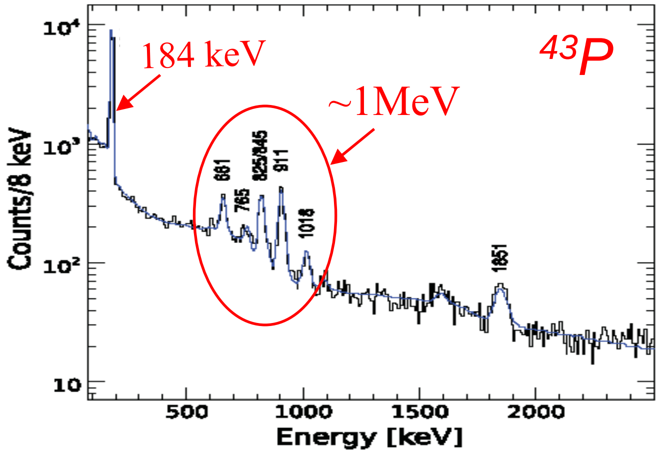
Predictive power : Evolution of sd proton states towards N=28 below Ca (Z=20)

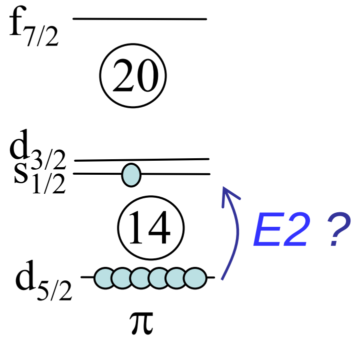
Gade et al. PRC 74 (2006)

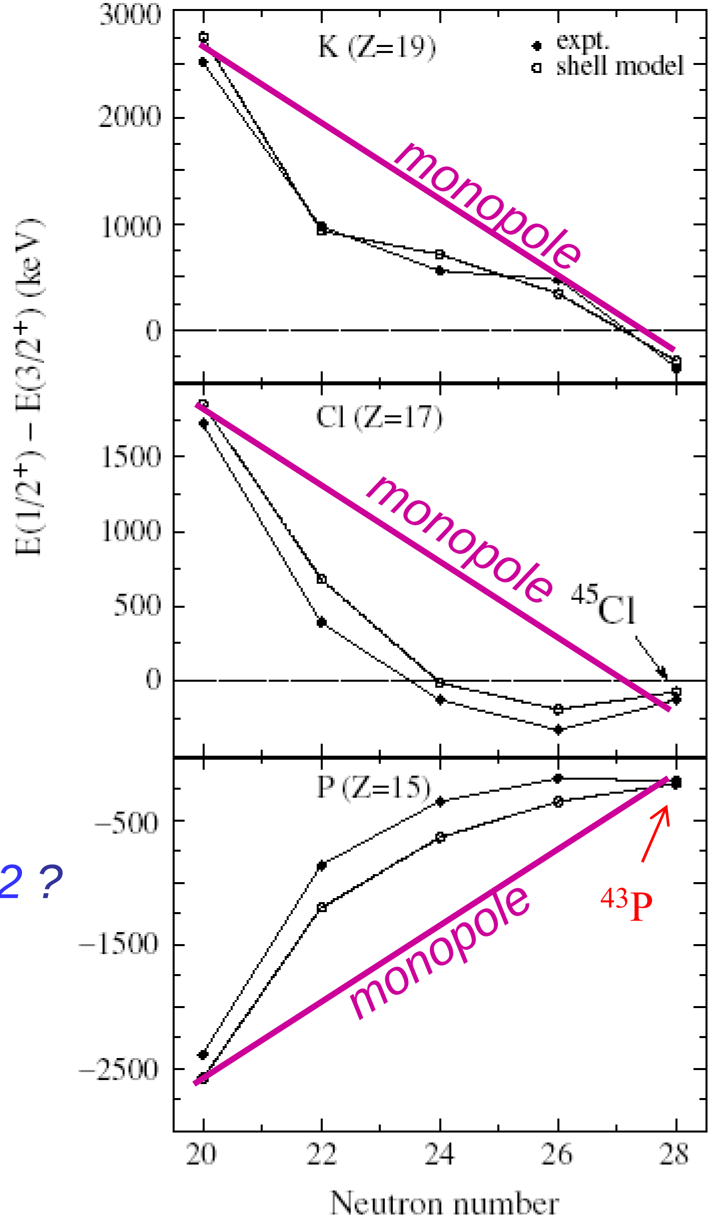




Riley et al. PRC 78 (2008)







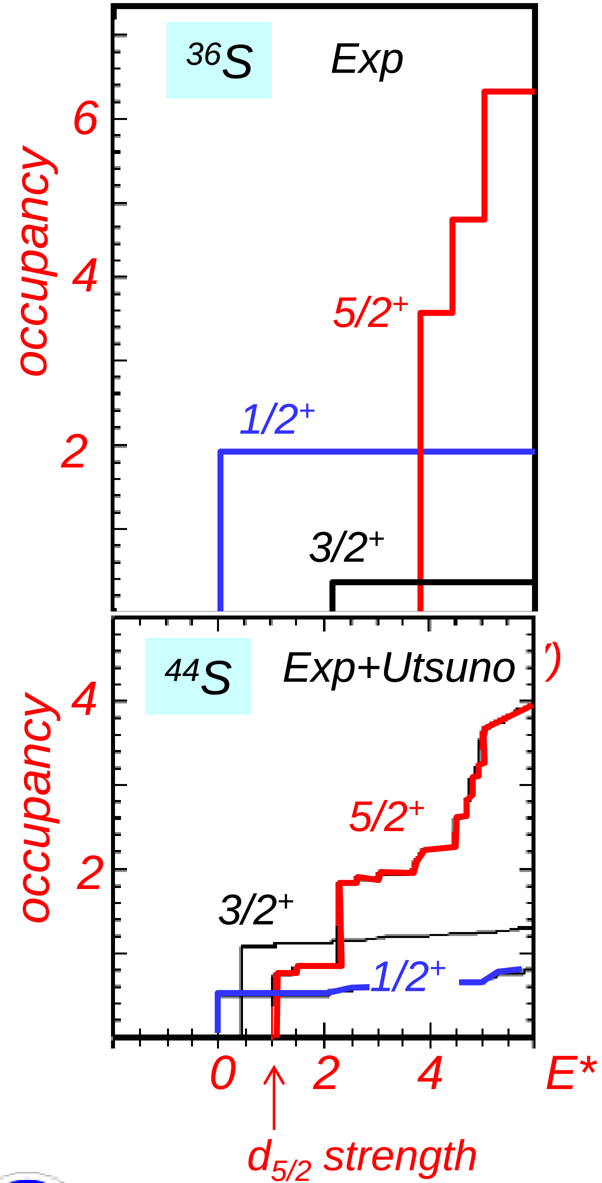
From Gade PRC74 (2006)
Fridmann et al. PRC 74 (2006)

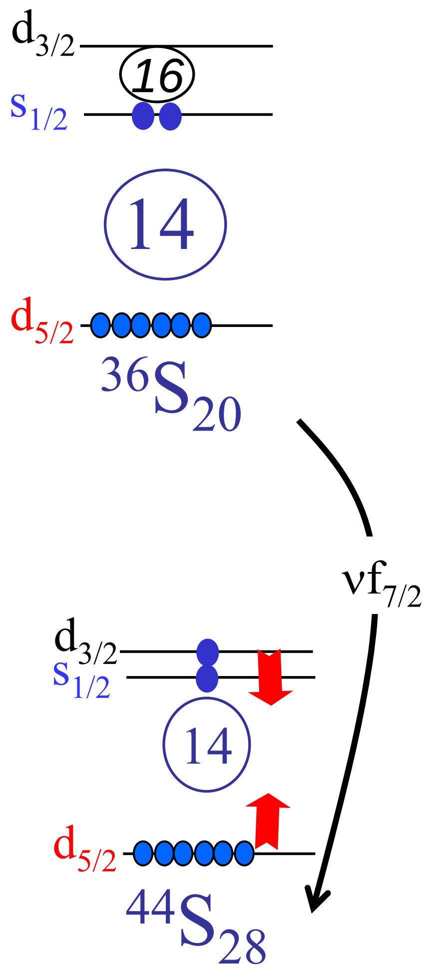
Degeneracy of proton $s_{1/2}$ and $d_{3/2}$ orbits **preserved**

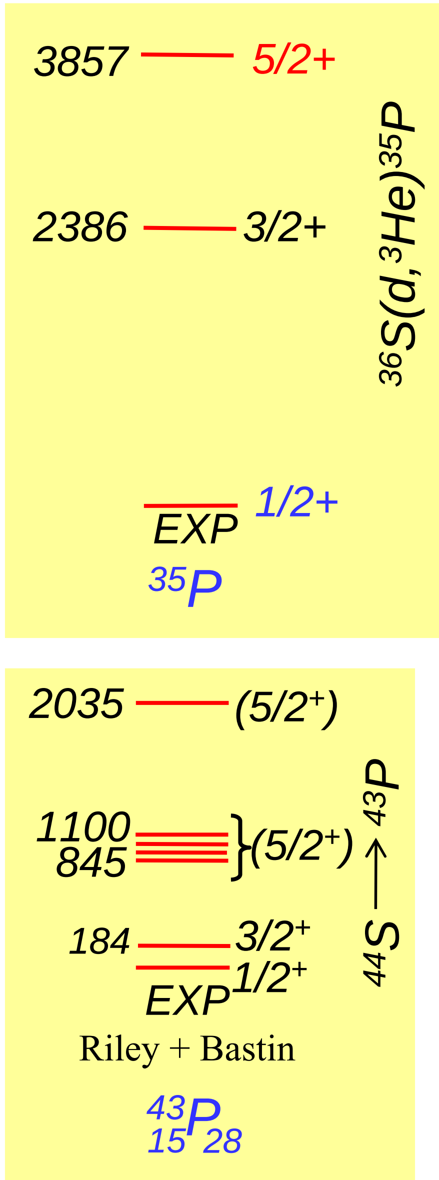
Role of monopole interactions **similar**

How is the $d_{5/2}$ changed, tensor force ? Change of Z=14 gap ?

Evolution of the Z=14 shell gap – A way to constraint tensor interaction



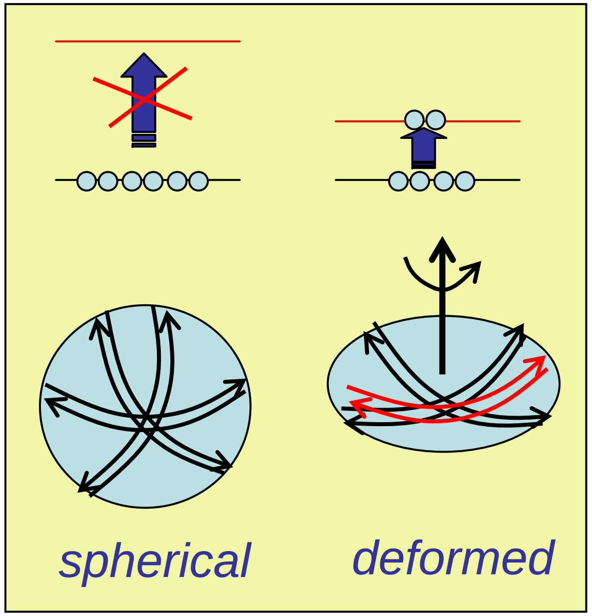


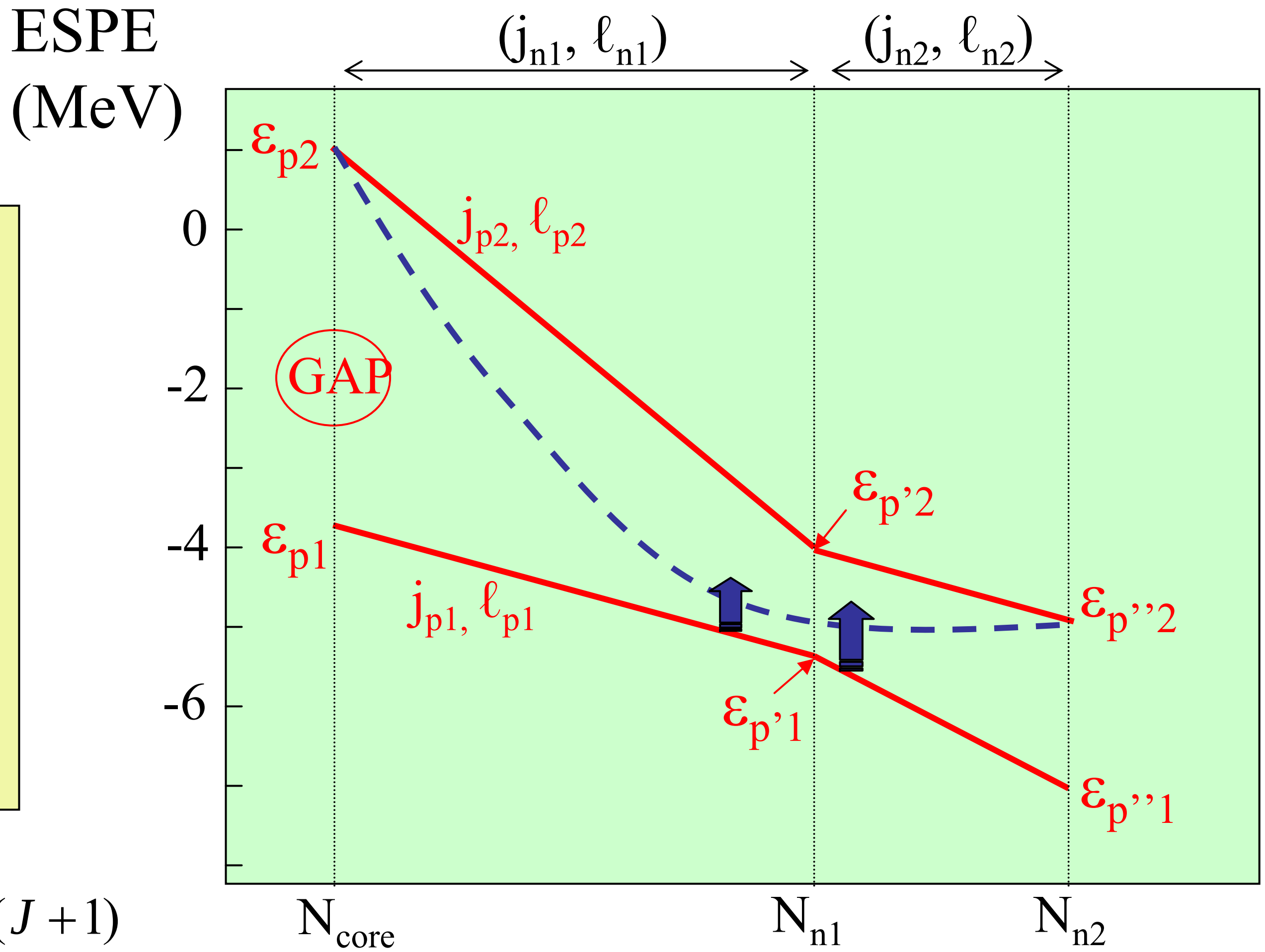


From N=20 to N=28, the proton $d_{5/2}$ is shifted at lower E* and is more fragmented

Consistent picture with proton-neutron tensor forces

From spherical to deformed nuclei





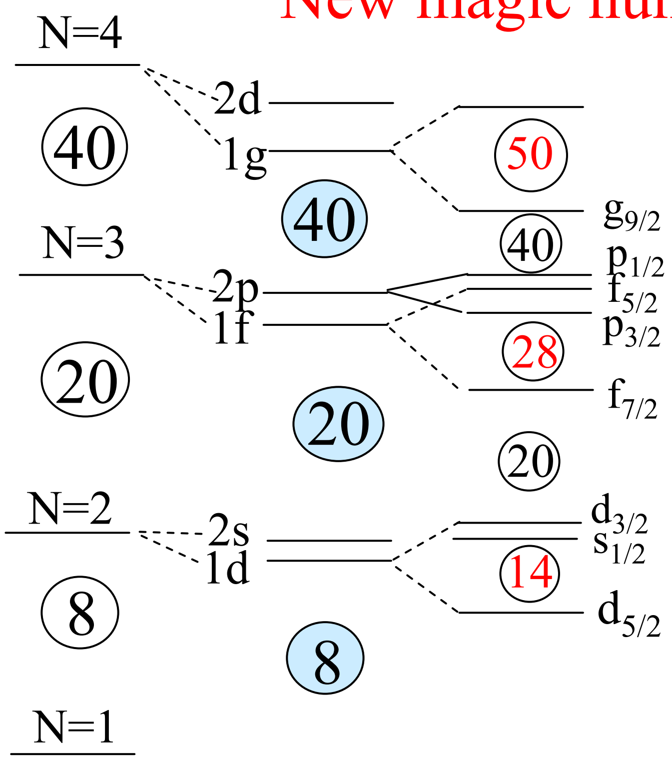
$$E(J) = \frac{\hbar^2}{2\Im} J(J+1)$$

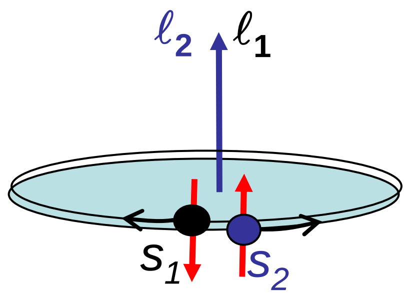
When a spherical gap weakens, cross shell excitations can develop
Quadrupole energy gain can bring the nucleus to deform
If large deformation : low 2^+ energy, large B(E2) value

From two-body short-range interactions to collective motion

II . The N=20 shell closure

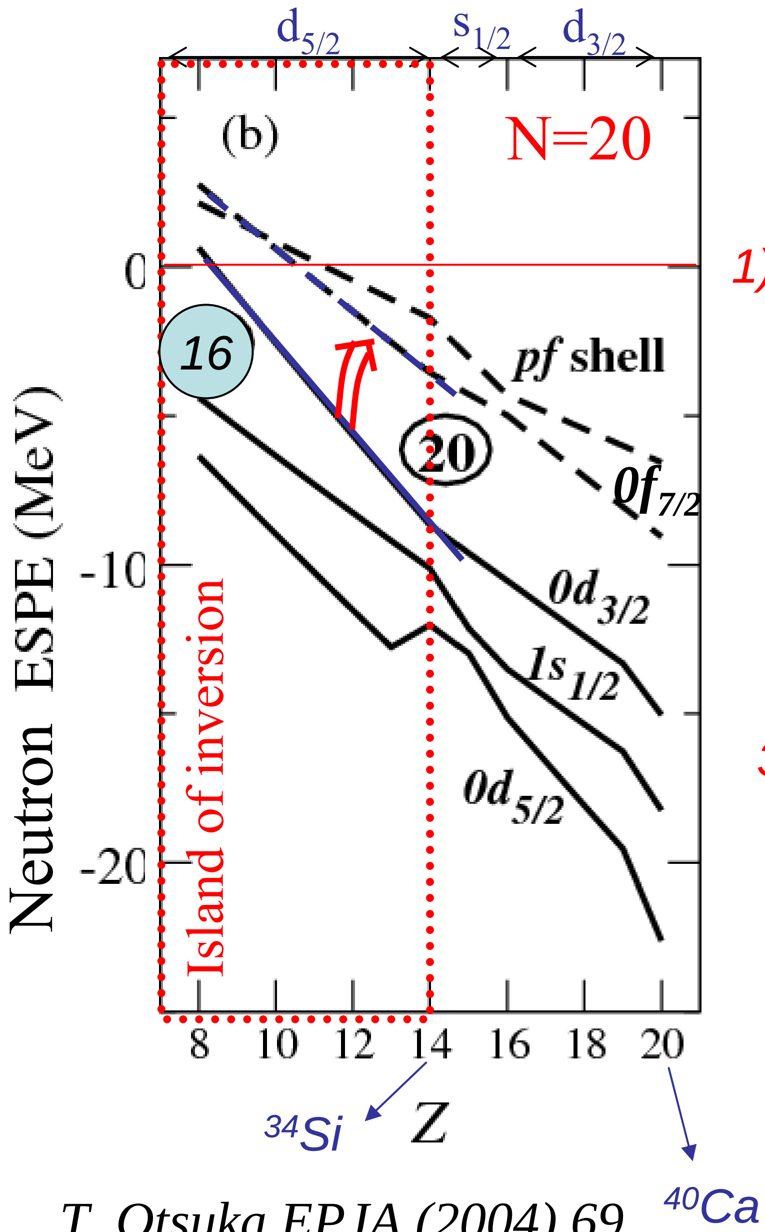
Role of proton-neutron interaction $\pi d_{5/2}$-$\nu d_{3/2}$?
Collapse of shell closure
New magic number





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

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)

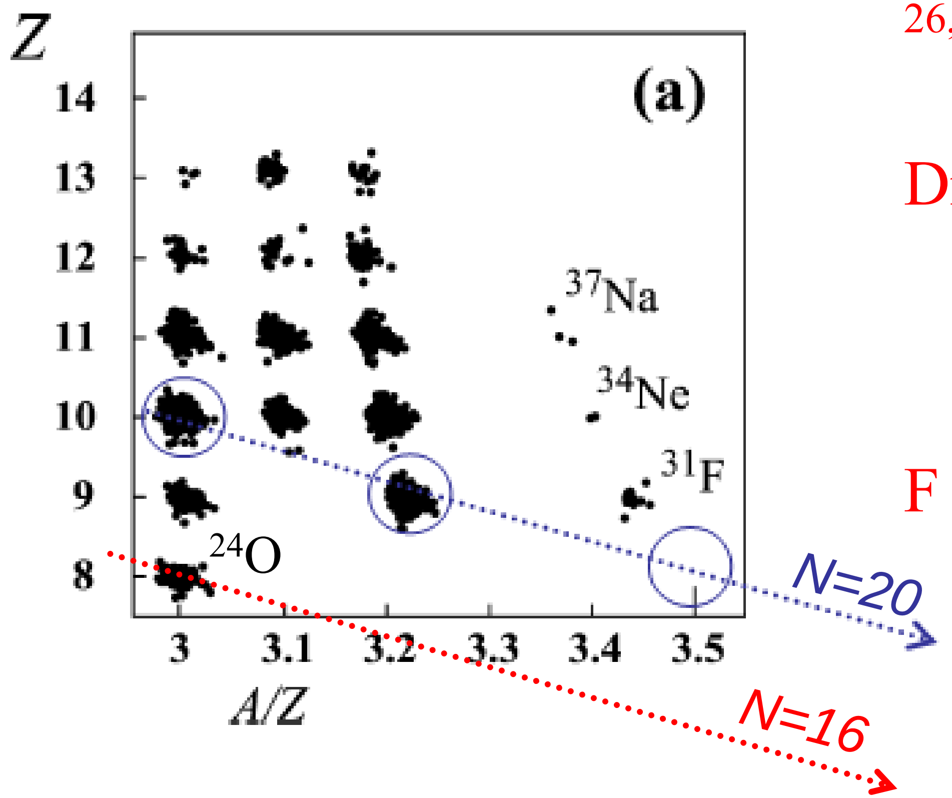
3) Birth of a new magic number at N=16

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

Notami et al., PLB B542 (2002) 49

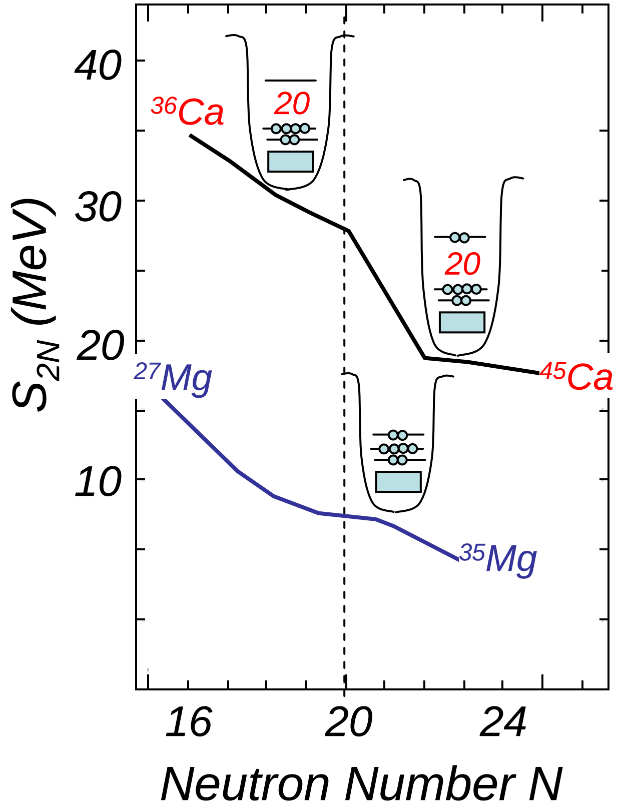


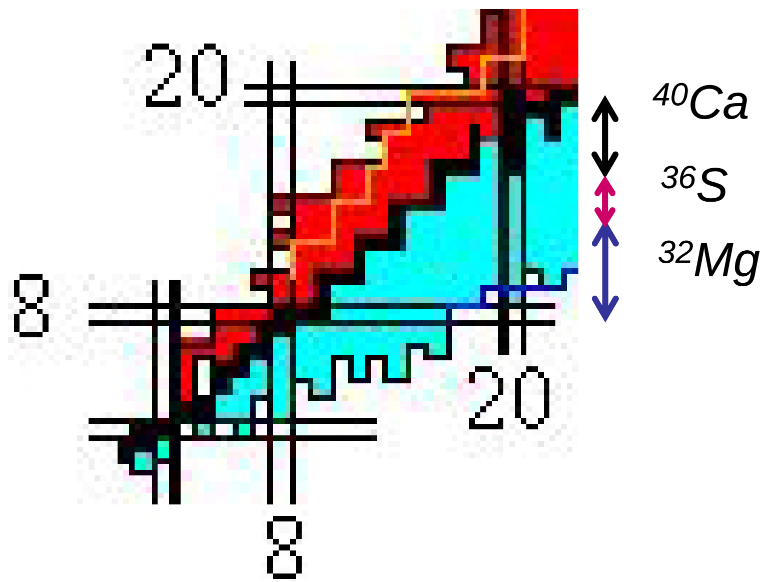
^{26,28}O nuclei unbound

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

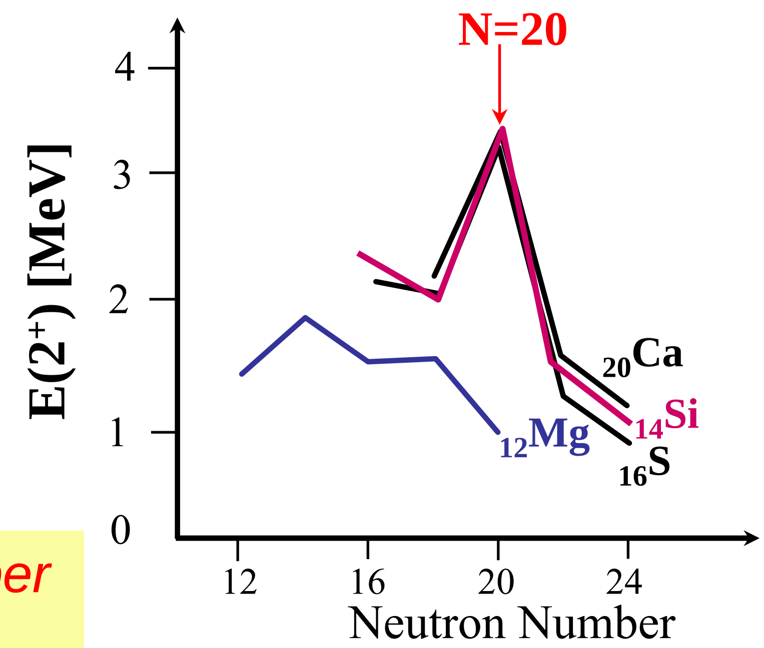
F and Ne are bound up to N=22, 24

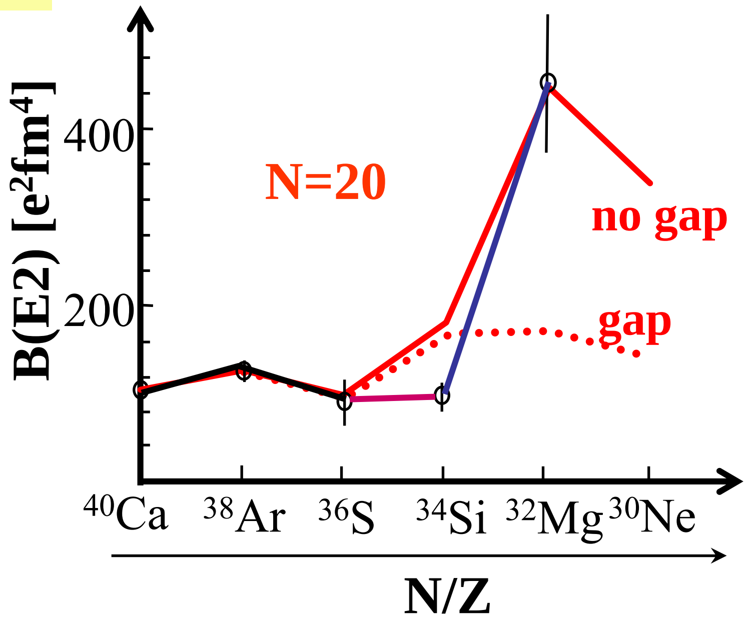
Adding one SINGLE proton in $d_{5/2}$ enables to bind SIX neutrons !



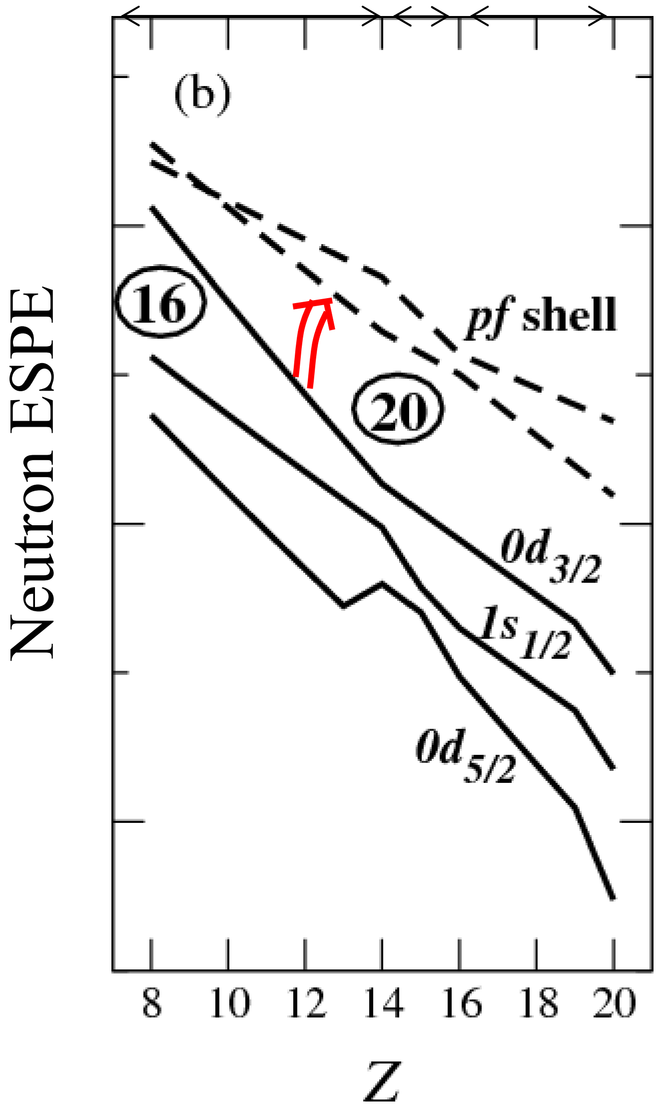


N=20 magic number Disappears !

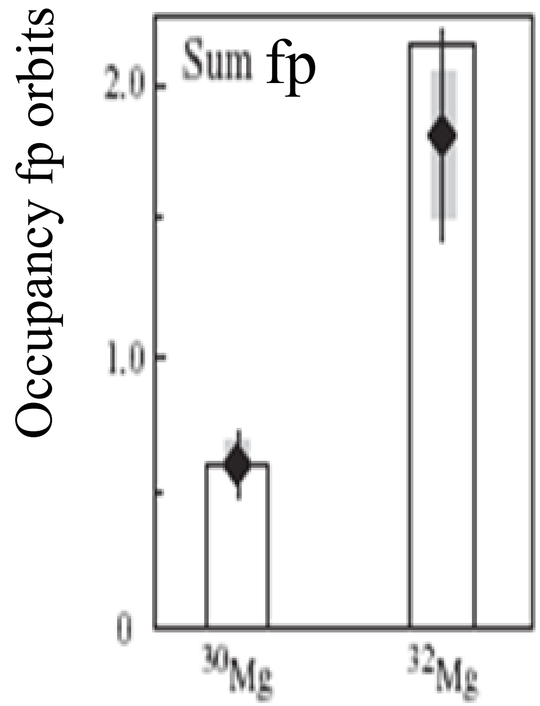




Large occupancy of fp shells at N=20 ! 2p2h mechanism



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

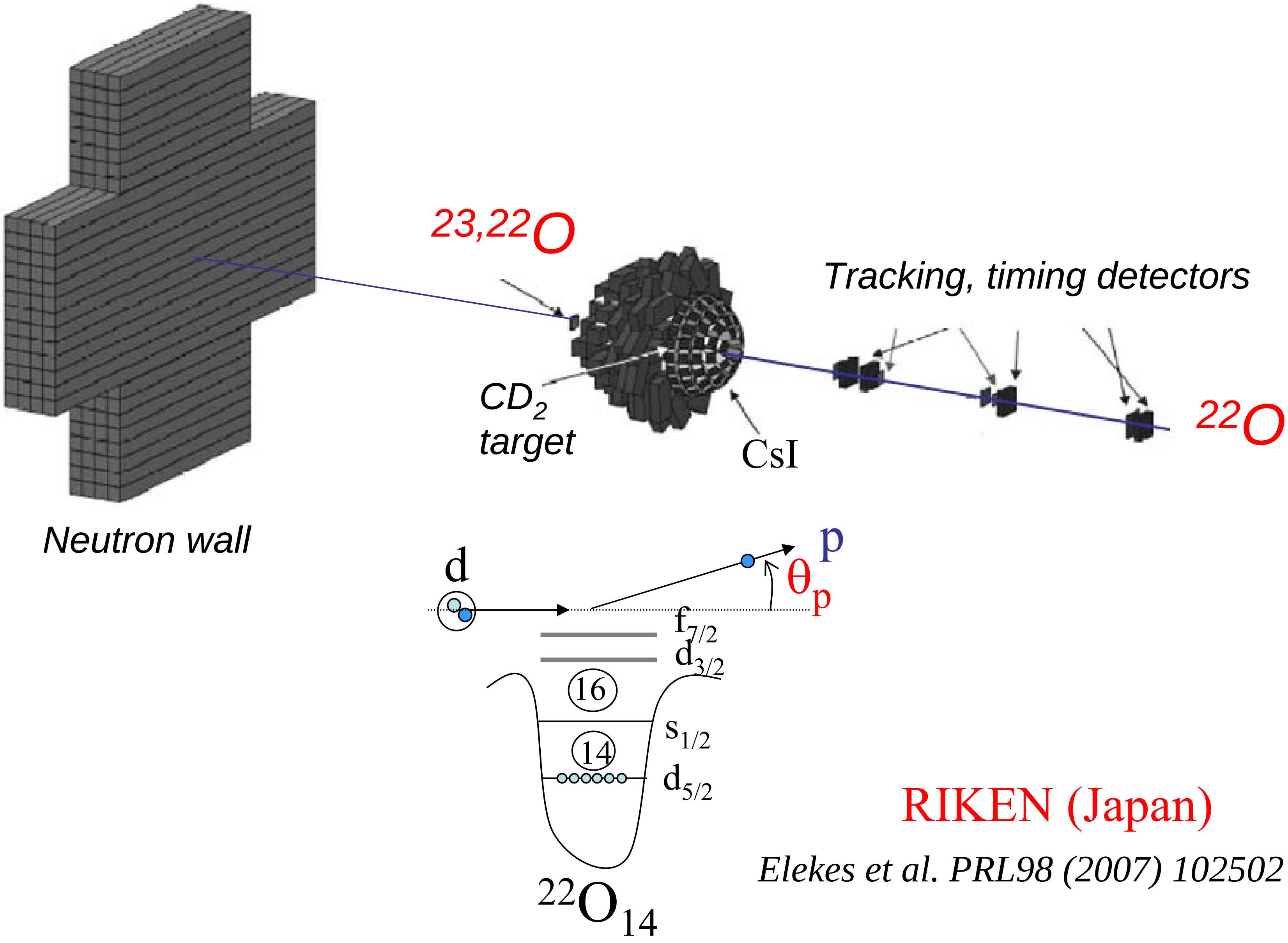


J. R. Terry et al., PRC 77 (2008) 014316.

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

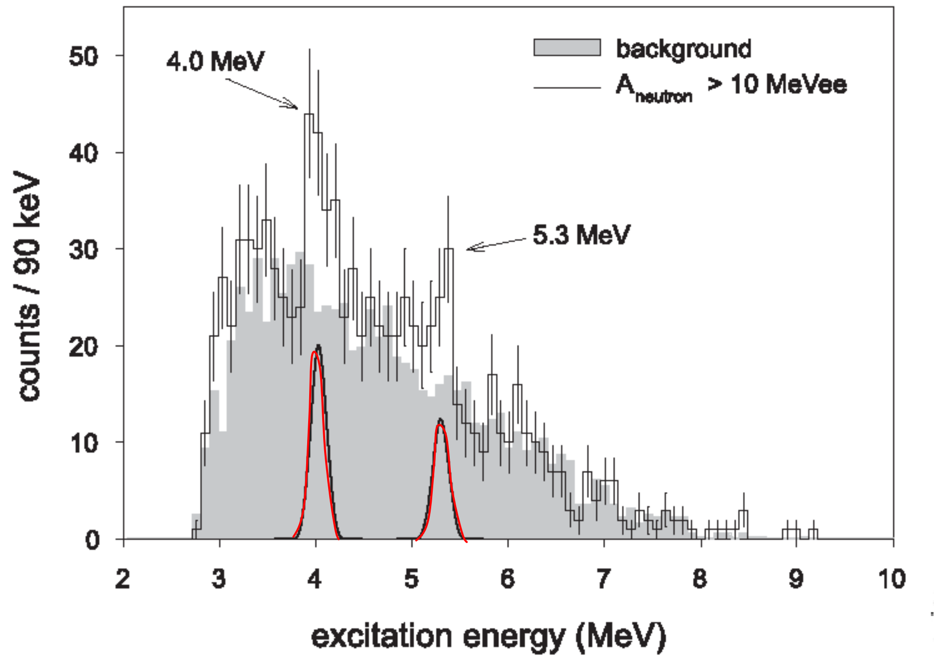


RIKEN (Japan)

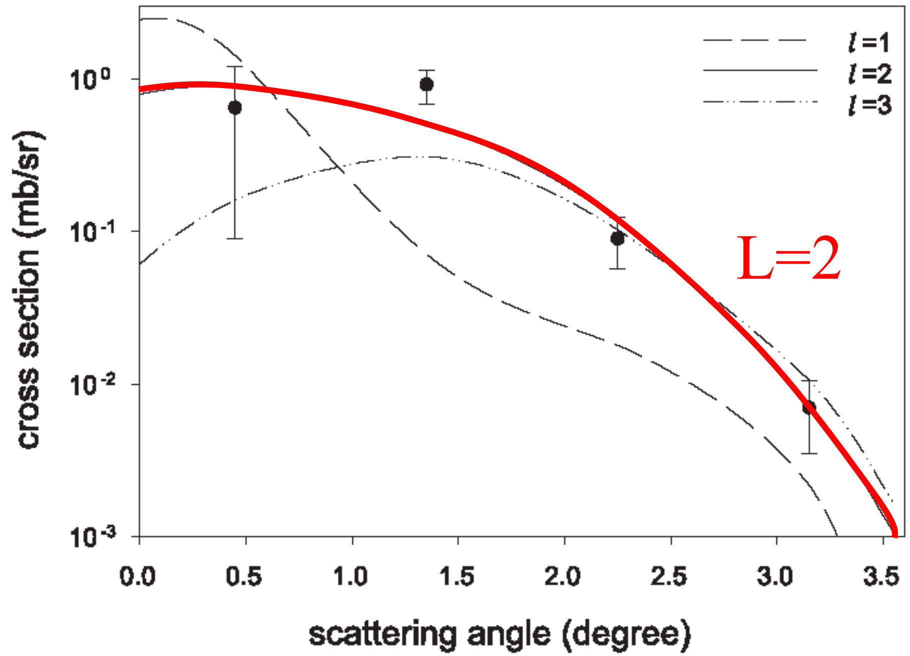
Elekes et al. PRL98 (2007) 102502

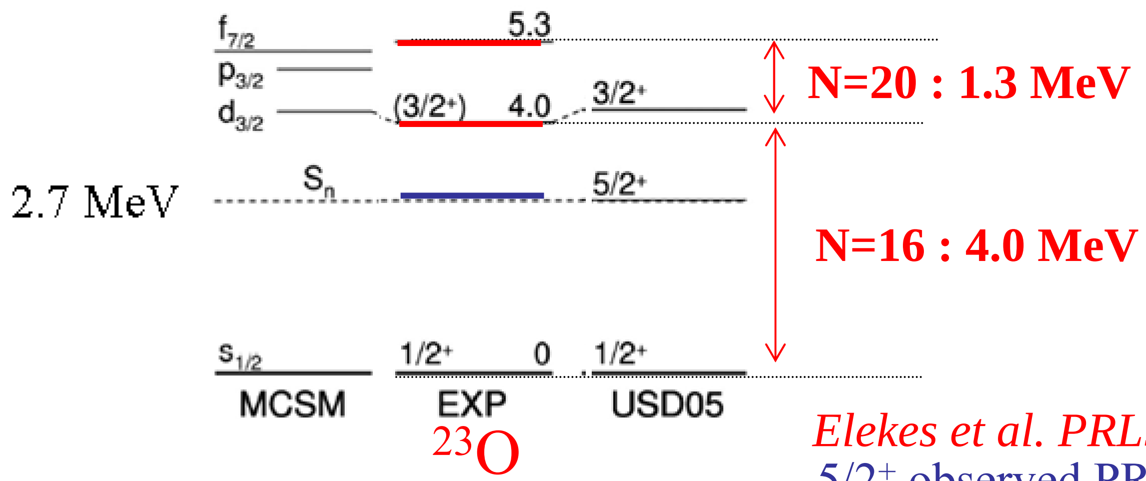
The ‘sizes’ of the N=20 and N=16 gaps in Oxygen

Gated on neutrons



Gated on 4 MeV neutron peak

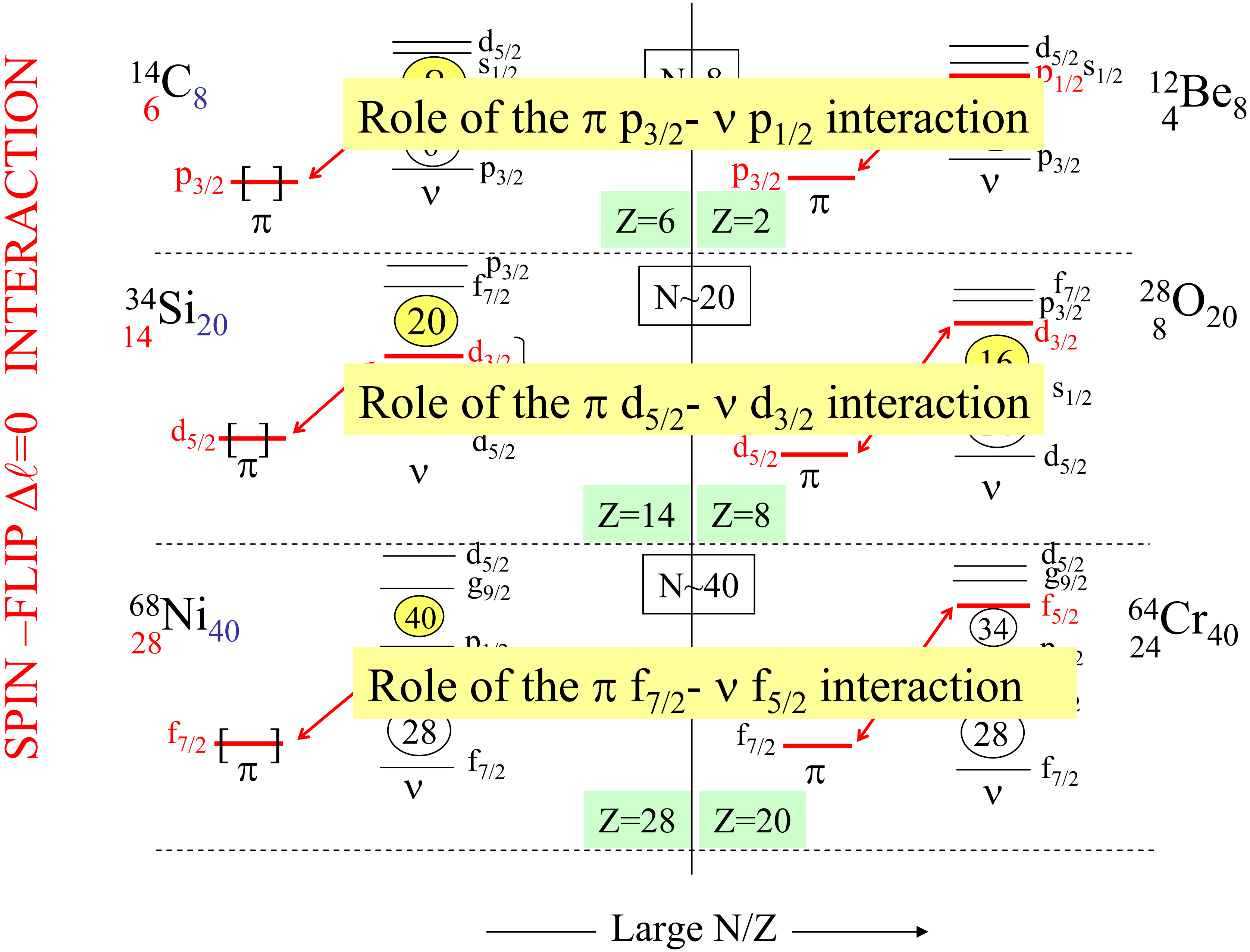




Elekes et al. PRL98 (2007) 102502

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

Evolution of Harmonic Oscillator shell closures

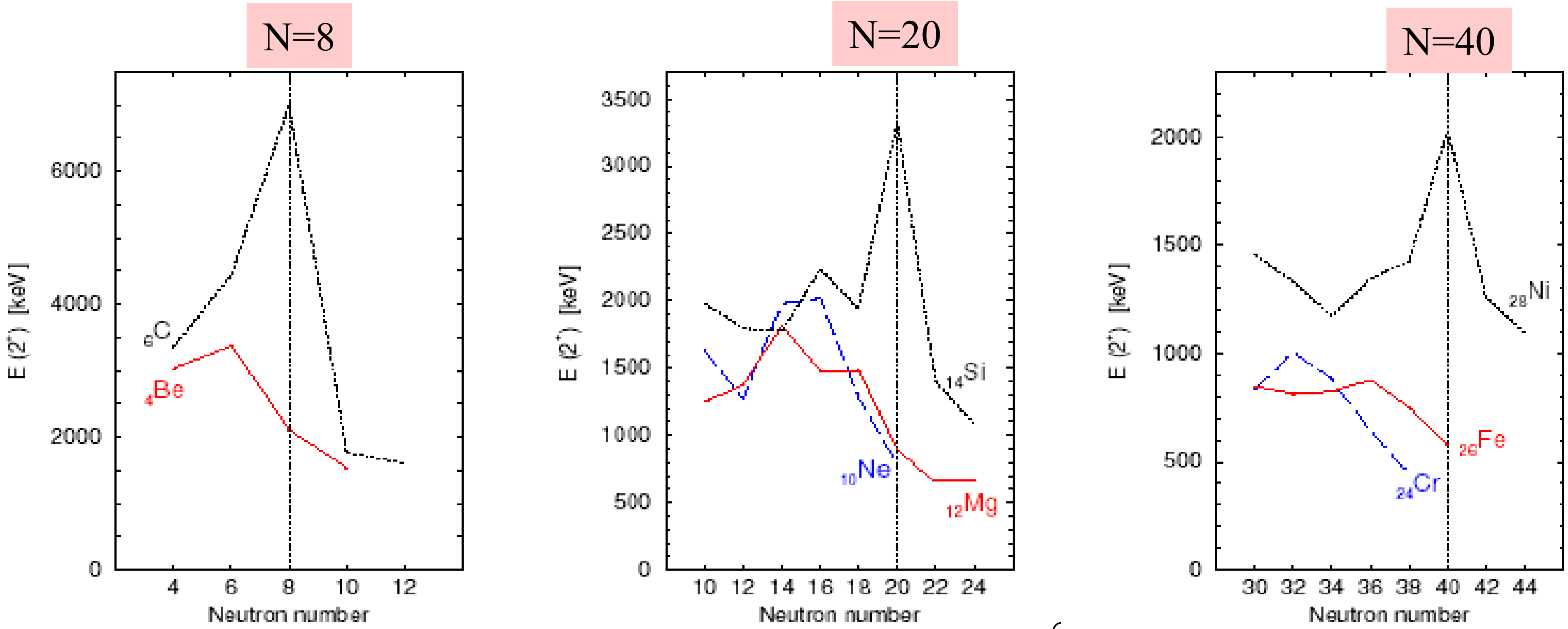


Role of the π $p_{3/2}$- ν $p_{1/2}$ interaction

Role of the π $d_{5/2}$- ν $d_{3/2}$ interaction

Role of the π $f_{7/2}$- ν $f_{5/2}$ interaction

Great similarity between the three cases of HO shell numbers



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 !

Take away messages :

Monopole term Very powerfull to predict structural evolution,
Important role of correlations at mid-shells-> deformation
Robust effect of NN forces to change HO shell gaps

Too much monopole can cause severe damages !!!