Experimental studies in the Ca and O isotopic chains

Evolution of neutron orbits in the Ca isotopic chain

The (d,p) & (p,d) reactions ^{40}Ca and ^{48}Ca nuclei

Evolution of 'SPE', role of neutron-neutron T=1 forces

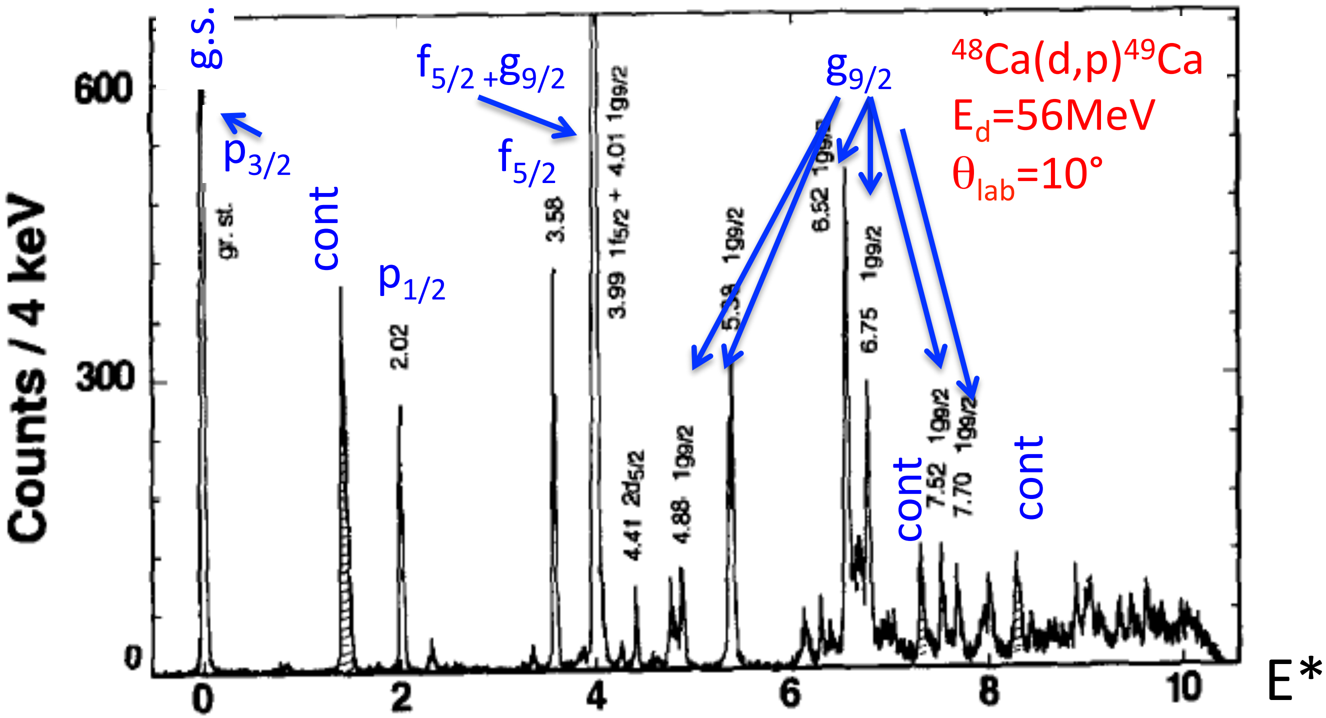
What happens beyond N=28 ?

Valence neutron orbits in ^{48}Ca

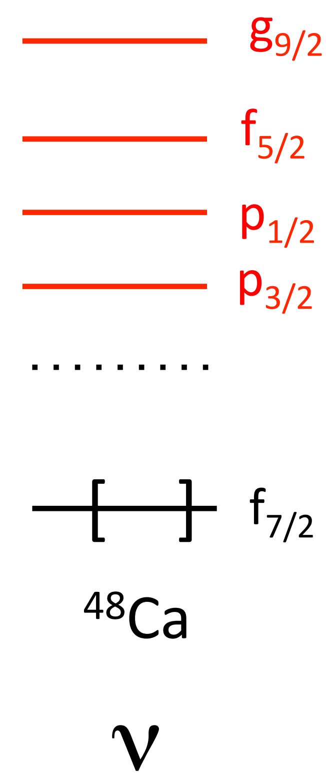
In a (d,p) reaction, we probe the vacancies of the states.

There is no vacancy left for the $f_{7/2}$ orbit → closed ^{48}Ca core

Few fragmentation of the p and f states. The $g_{9/2}$ state is more fragmented.

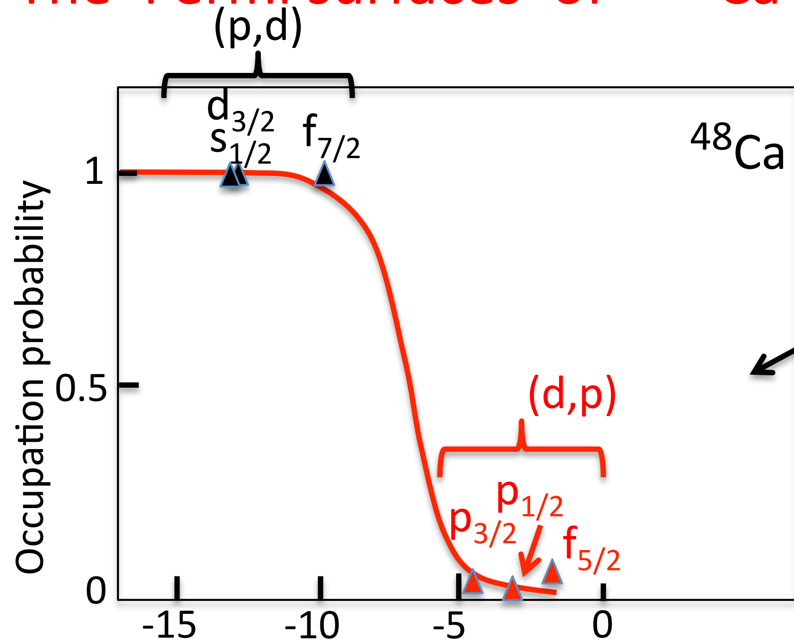


$$\bar{E} = \frac{\sum C^2 S \cdot E_x}{\sum C^2 S}$$

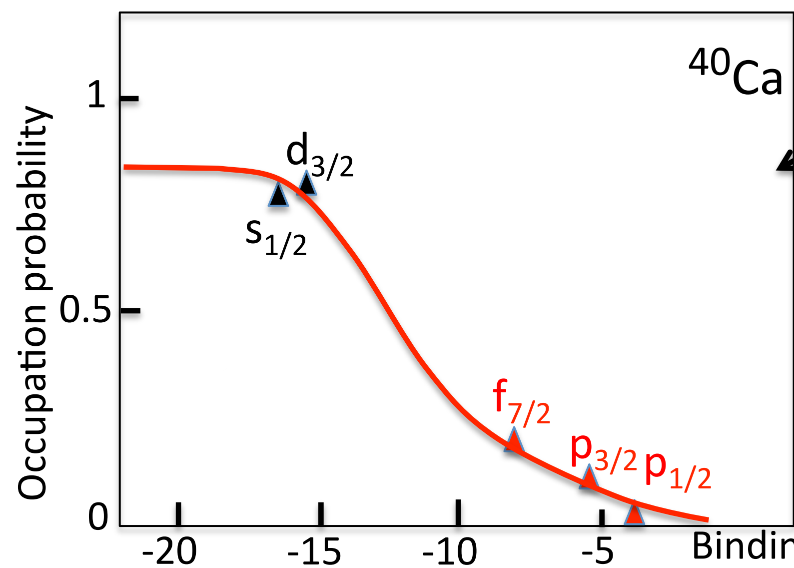


	Vacancy	occupancy	$\bar{E}$(MeV)
$f_{7/2}$	0	1	
$p_{3/2}$	0.97	0.03	g.s.
$p_{1/2}$	1.03	0	2.28
$f_{5/2}$	0.95	0.05	3.945

The 'Fermi surfaces' of ^{40,48}Ca derived from transfer reactions

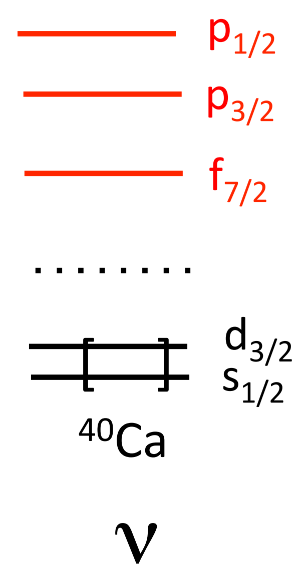


^{48}Ca is a good core nucleus



Binding energy (MeV)

The Fermi surface of ^{40}Ca is soft, the nucleus contains significant core excitations

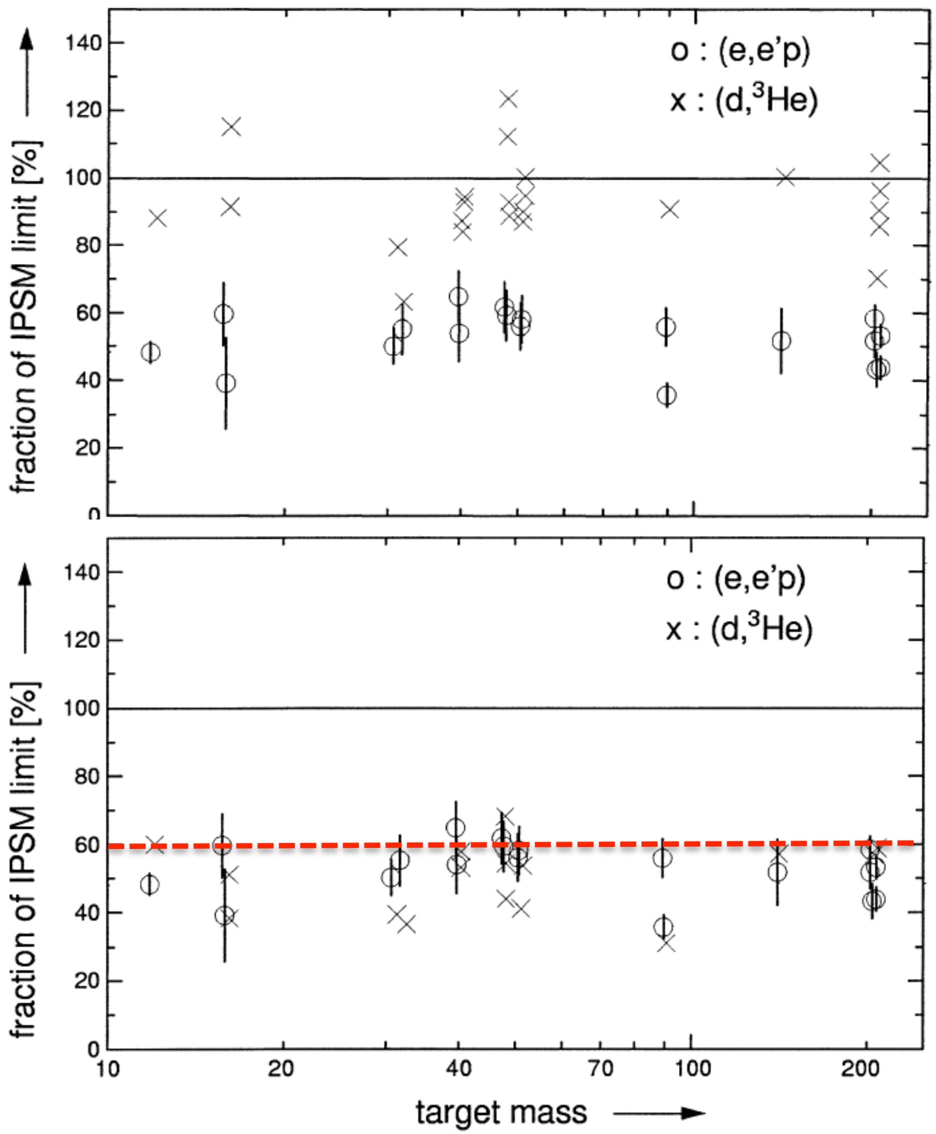


Hole strength (p,d): Martin et al. NPA 185(1972)465

Particle strength (d,p): Uozumi et al. NPA 576 (1994) 123, Uozumi et al. PRC 50 (1994) 263

Quenching of occupancy values

'At any time only 2/3 of the nucleons in the nucleus act as independent particles moving in the nuclear mean field. The remaining third of the nucleons are correlated'
Pandharipande et al. Rev. Mod. Phys. 69 (1997) 981



Comparison of SF's (normalized to 1) obtained in (d,^{3}He) and (e,e',p)

All the strength could NOT be found
Some states above 10MeV !

After reanalysis of the data, a quenching factor of about 60% is found
Kramer et al. NPA 679 (2001) 267

Comes from short range correlations
AND
Coupling to collective resonances
Barbieri et al. PRL 103 (2009) 202502
Duguet et al.

The atomic nucleus is a strongly correlated quantum system

The deduced SPE for all orbits from low-energy spectra are not the correct one
(due to not observed high-energy strength)

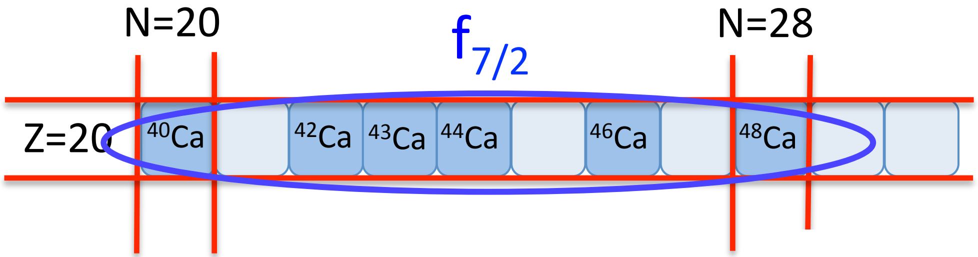
We generally look at relative changes in energies

If we can assume that the high-energy part varies smootly with A
(any calculation of this)

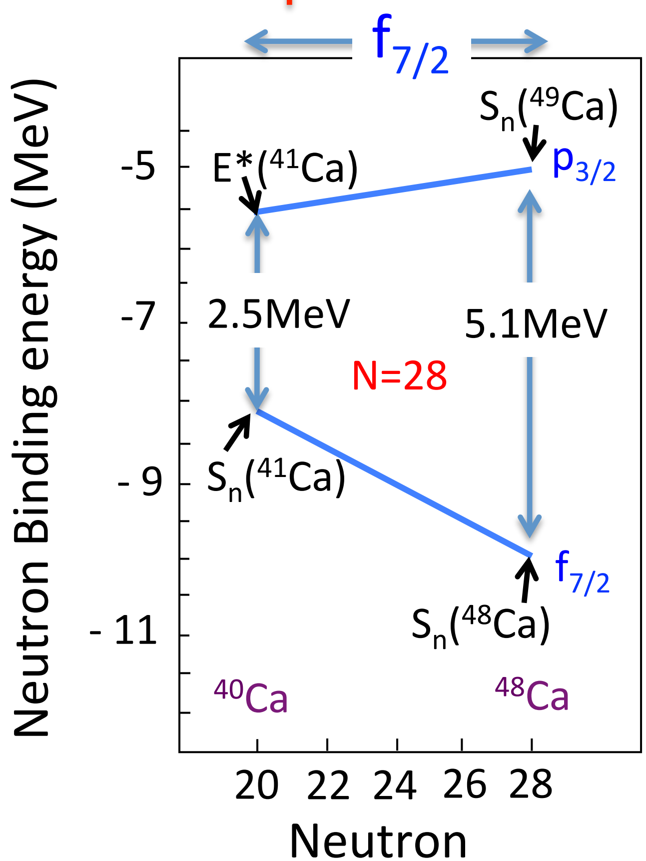
The observation of shell evolution makes sense

Otherwise we should work in another physics domain ☺

Increase of spin orbit (SO) shell gaps in the Ca chain



exp (d,p),(p,d)
from Uozumi et al. NPA 1994, PRC 1994



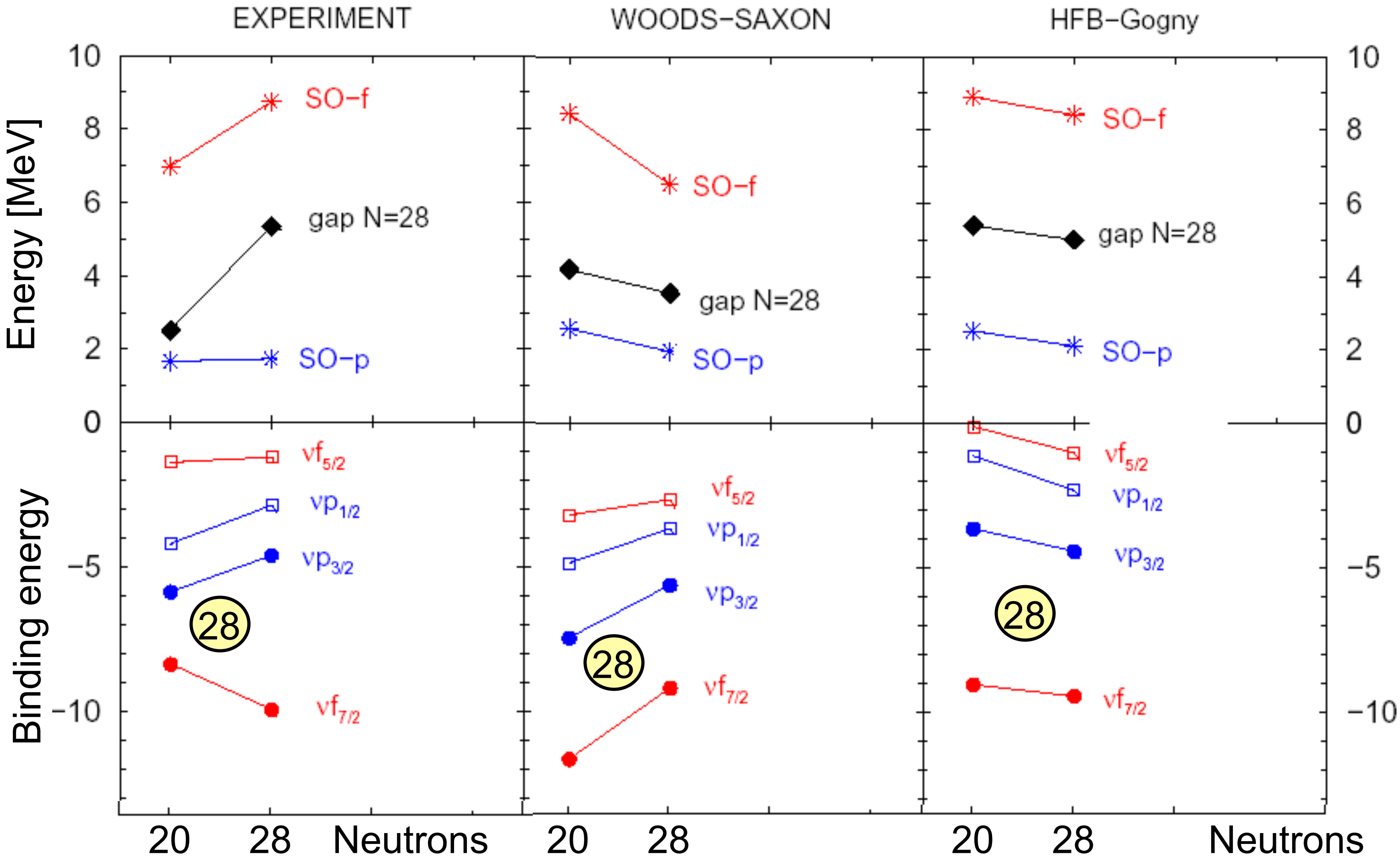
The N=28 gap is created to a large extent by nn interactions

It increases by about 2.7 MeV

$$\delta\varepsilon(1f_{7/2}) \approx 7V^{nn}1f_{7/2}1f_{7/2}$$

$$\delta\varepsilon(1p_{3/2}) \approx 8V^{nn}1f_{7/2}2p_{3/2}$$

Evolution of neutron SPE in the Ca isotopic chain



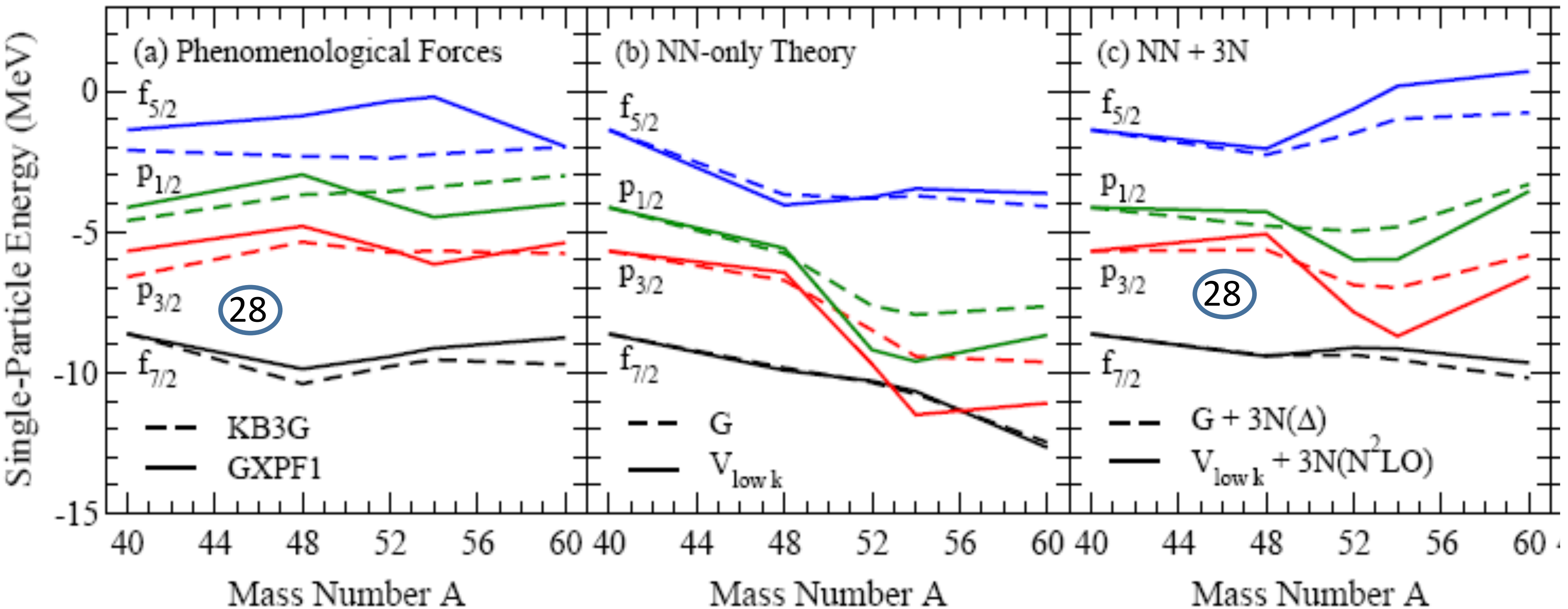
Courtesy M.G Porquet

No increase of the N=28 shell gap when $\nu f_{7/2}$ is filled

Same conclusion found with realistic V_{lowK} interaction

The role of three body forces to create SO shell gaps

J. Holt et al., 2012 J. Phys. G. 39 085111



Significant increase of the N=28 gap between N=20 and N=28

Realistic two-body forces could not account for the increase of SO shell gaps at N=28

Almost constant N=32 SO 'gap'
Almost constant N=34 'gap' when using proper T=1 TBME
What happens towards ^{60}Ca ? Strongly repulsive three body force ?
The d5 and g9 neutron orbits become almost degenerate (inferred from ^{68}Ni)

Some remarks about the N=32 and N=34 shells in Ca ….

Evolution of neutron orbits in the O isotopic chain

Experimental results in the O isotopic chain ($^{21-25}O$)

Systematics of ESPE derived from experimental Sn values

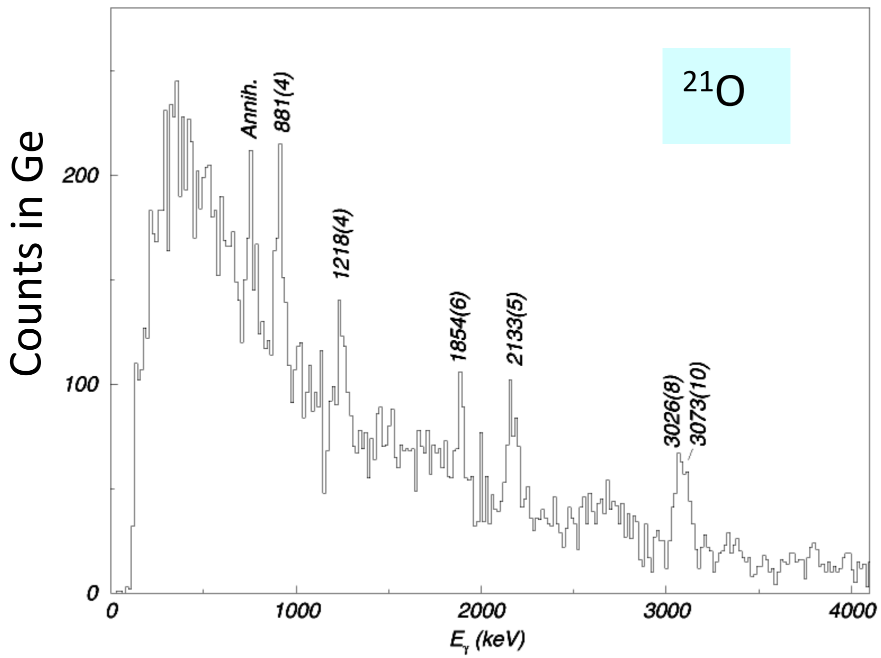
What happens when approaching the continuum ?

What makes the C and O chains so different ?

The T=1 $d_{3/2}$-$d_{3/2}$ force in Ca and O chains

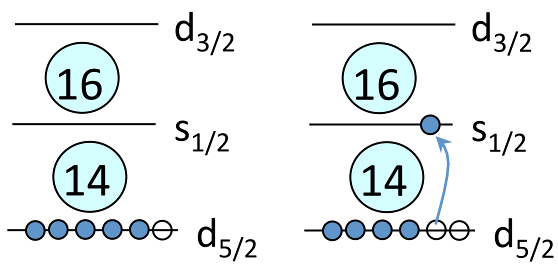
Generalization of the role of T=1 forces in O, Ca and Ni

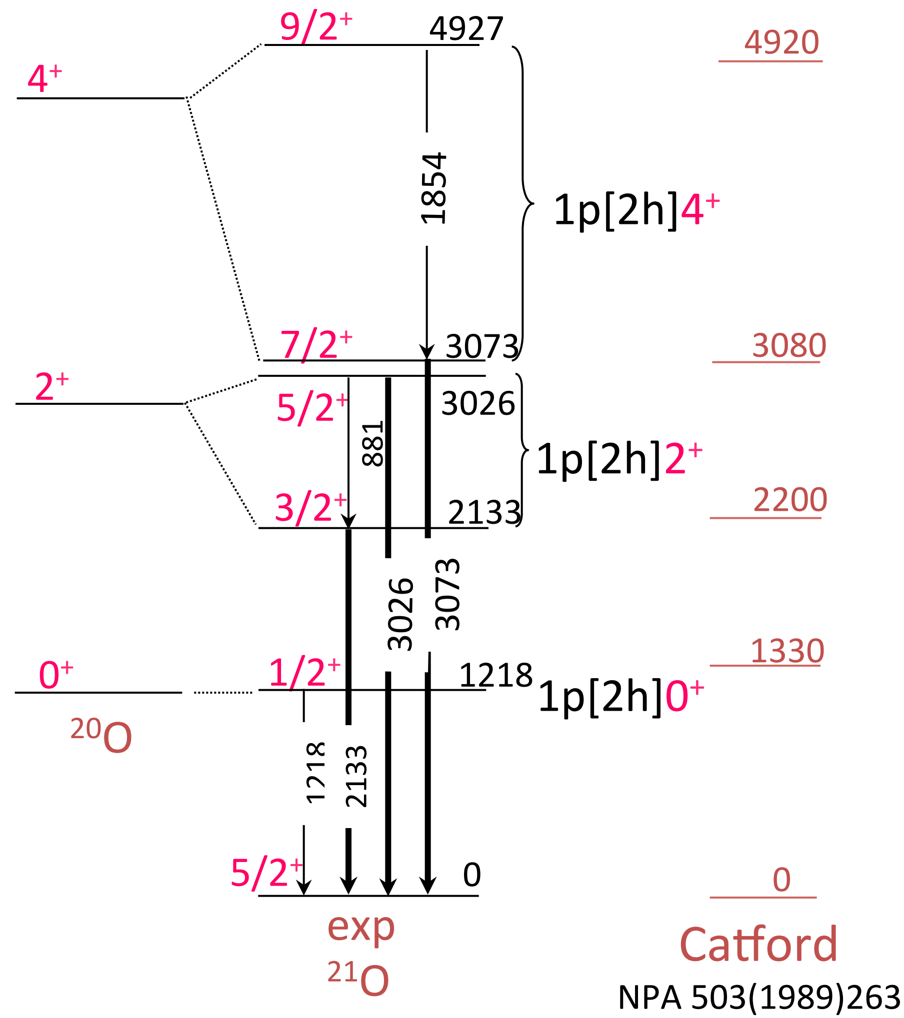
Oxygen Isotopes A=20, 21



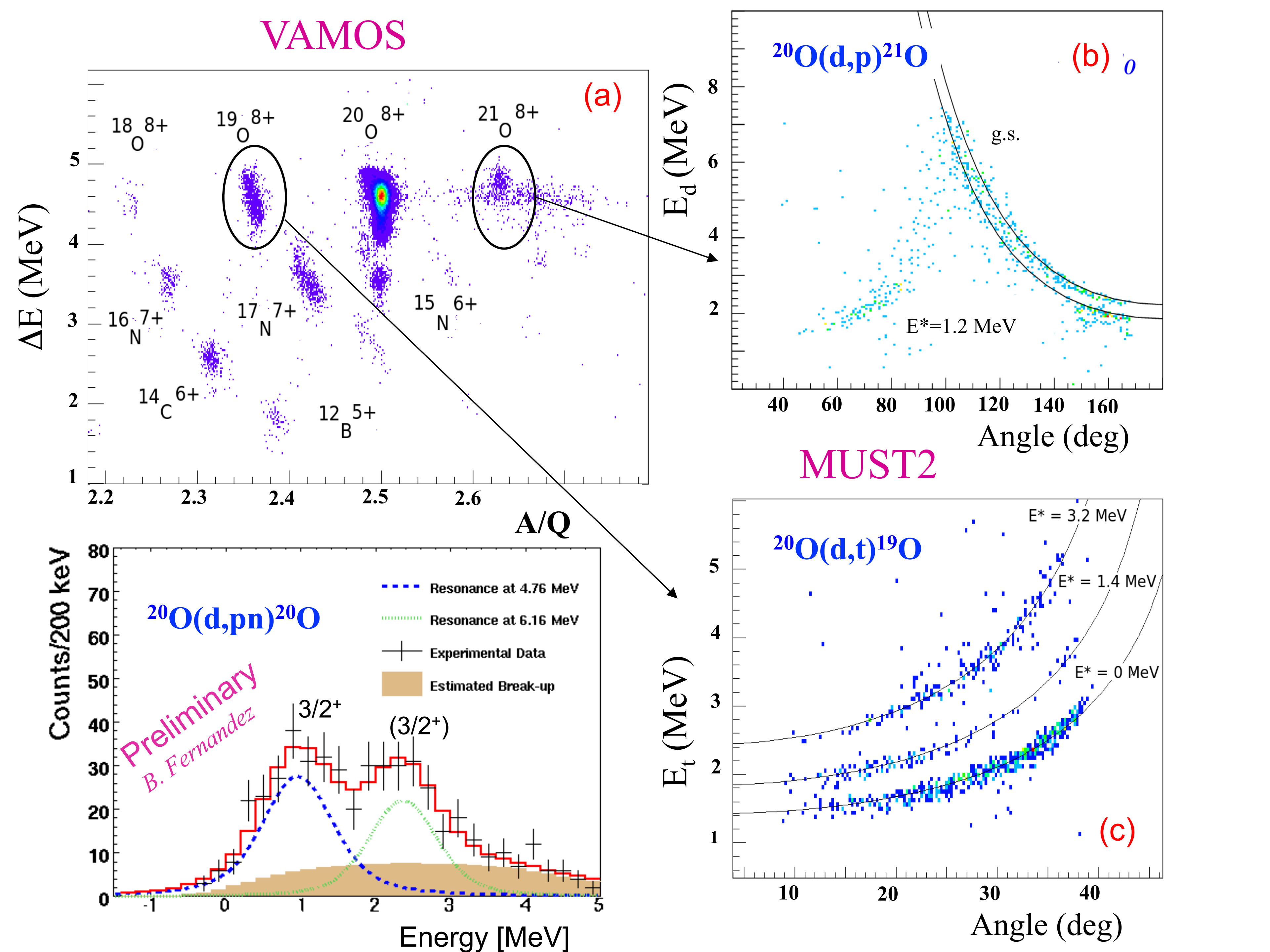
^{21}O description from an ^{22}O core

$E(1/2^+) = E(N=14) - E([2h]\ d_{5/2})$



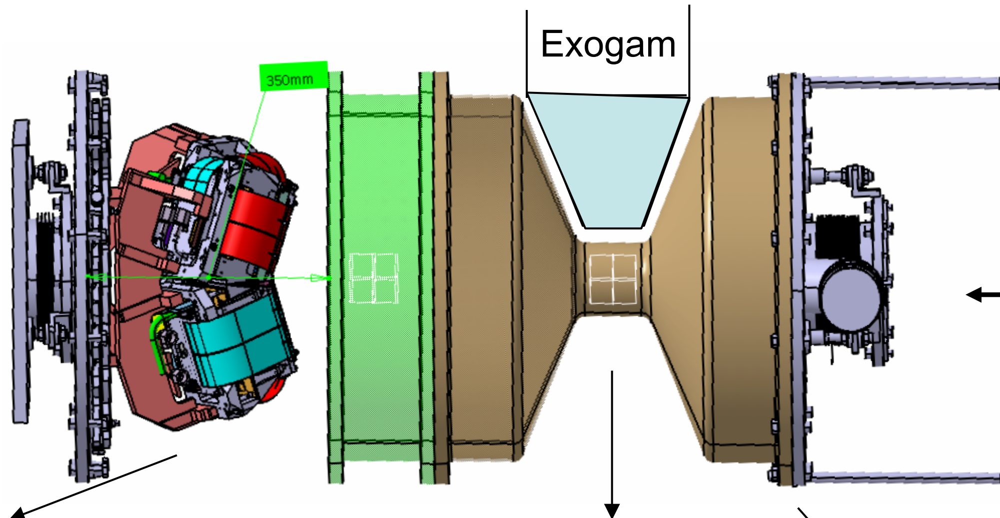


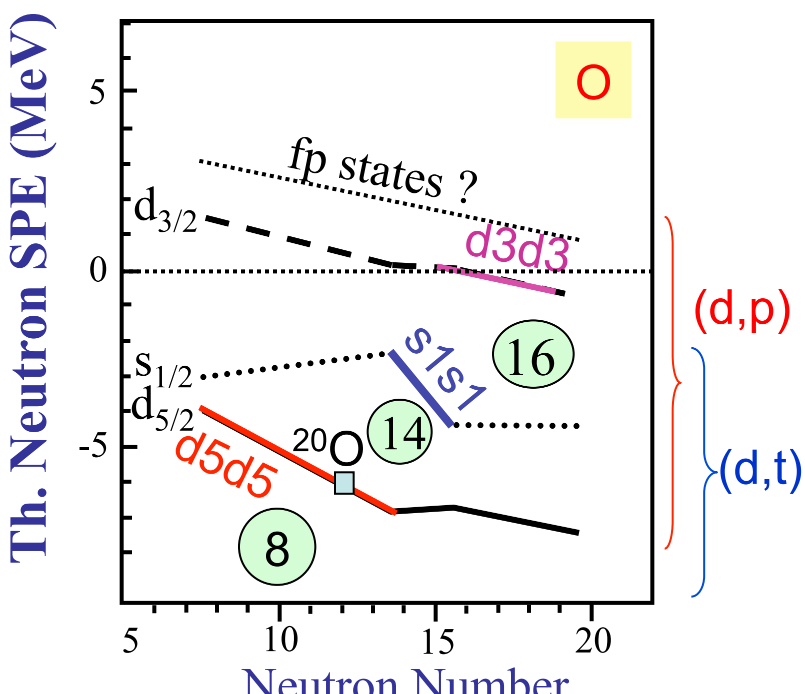
Agreement with Brown's USD calculations.

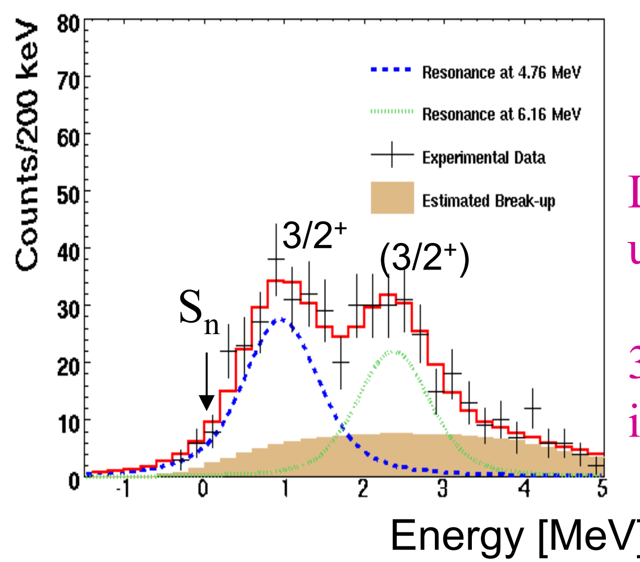

VAMOS
(a)
ΔE (MeV)
A/Q
18 O 8+
19 O 8+
20 O 8+
21 O 8+
16 N 7+
17 N 7+
15 N 6+
14 C 6+
12 B 5+
(b)
20O(d,p)21O
E_d (MeV)
Angle (deg)
g.s.
E*=1.2 MeV
MUST2
(c)
20O(d,t)19O
E_t (MeV)
Angle (deg)
E* = 3.2 MeV
E* = 1.4 MeV
E* = 0 MeV
20O(d,pn)20O
Counts/200 keV
Energy [MeV]
Resonance at 4.76 MeV
Resonance at 6.16 MeV
Experimental Data
Estimated Break-up
3/2+
(3/2+)
Preliminary
B. Fernandez

Evolution of shell gaps using (d,p) and (d,t) with ^{20}O and ^{26}Ne beams at SPIRAL

TIARA-MUST2-EXOGAM-VAMOS COLLABORATION





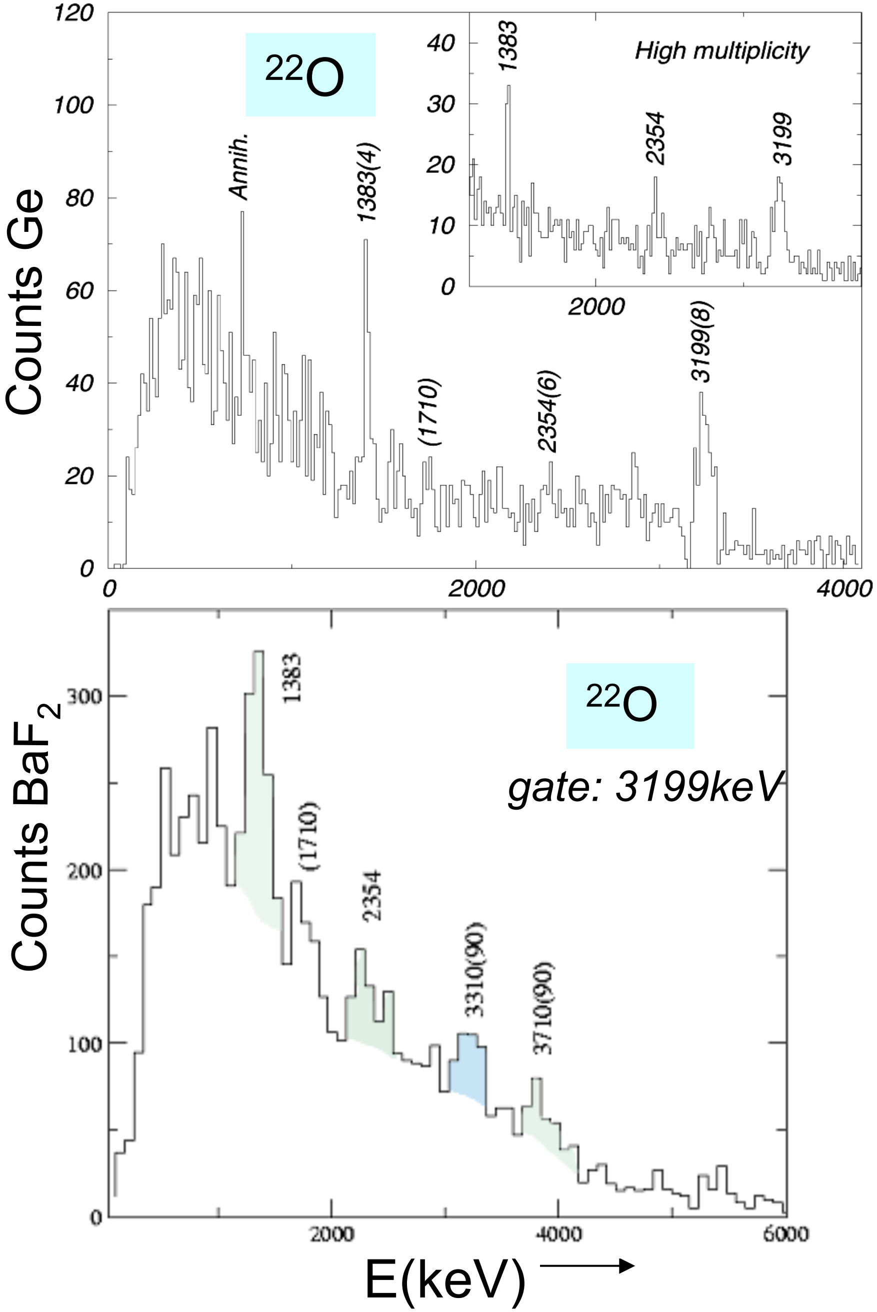


Location of the unbound $d_{3/2}$ orbit

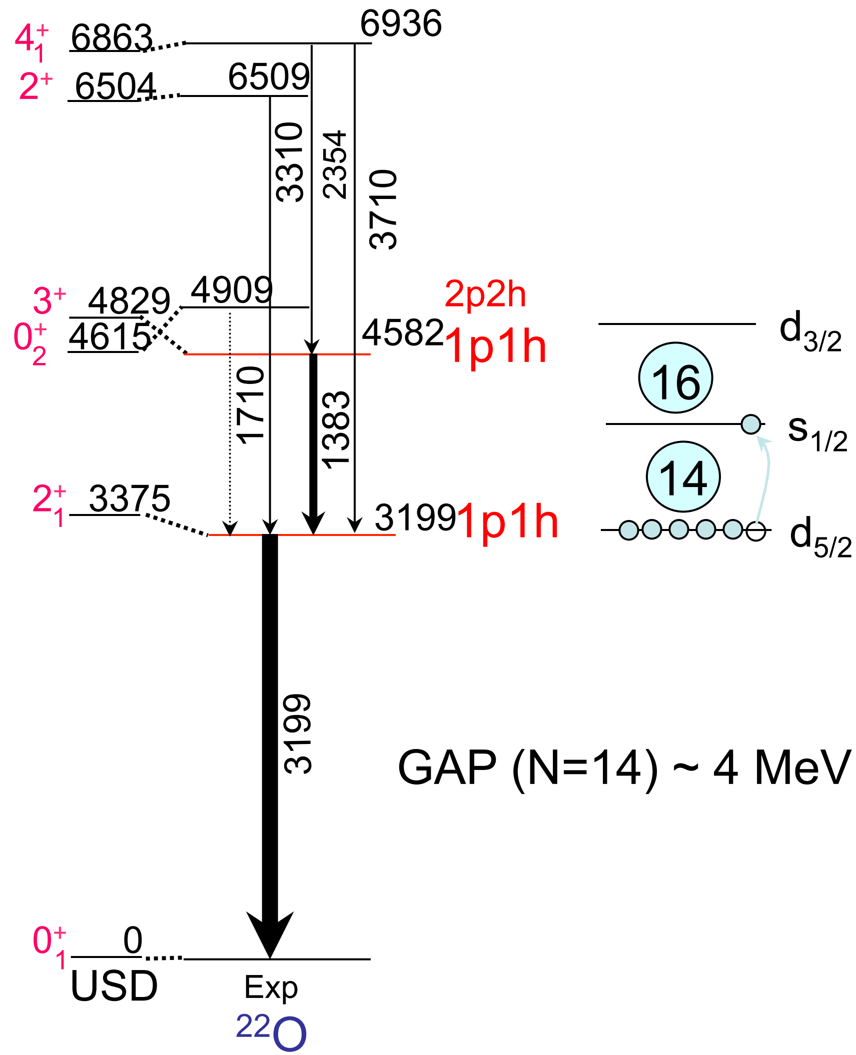
$3/2^+_2$ state decays to 2^+ in ^{20}O

UK labs + IPN Orsay, GANIL, LPC Caen from IN2P3

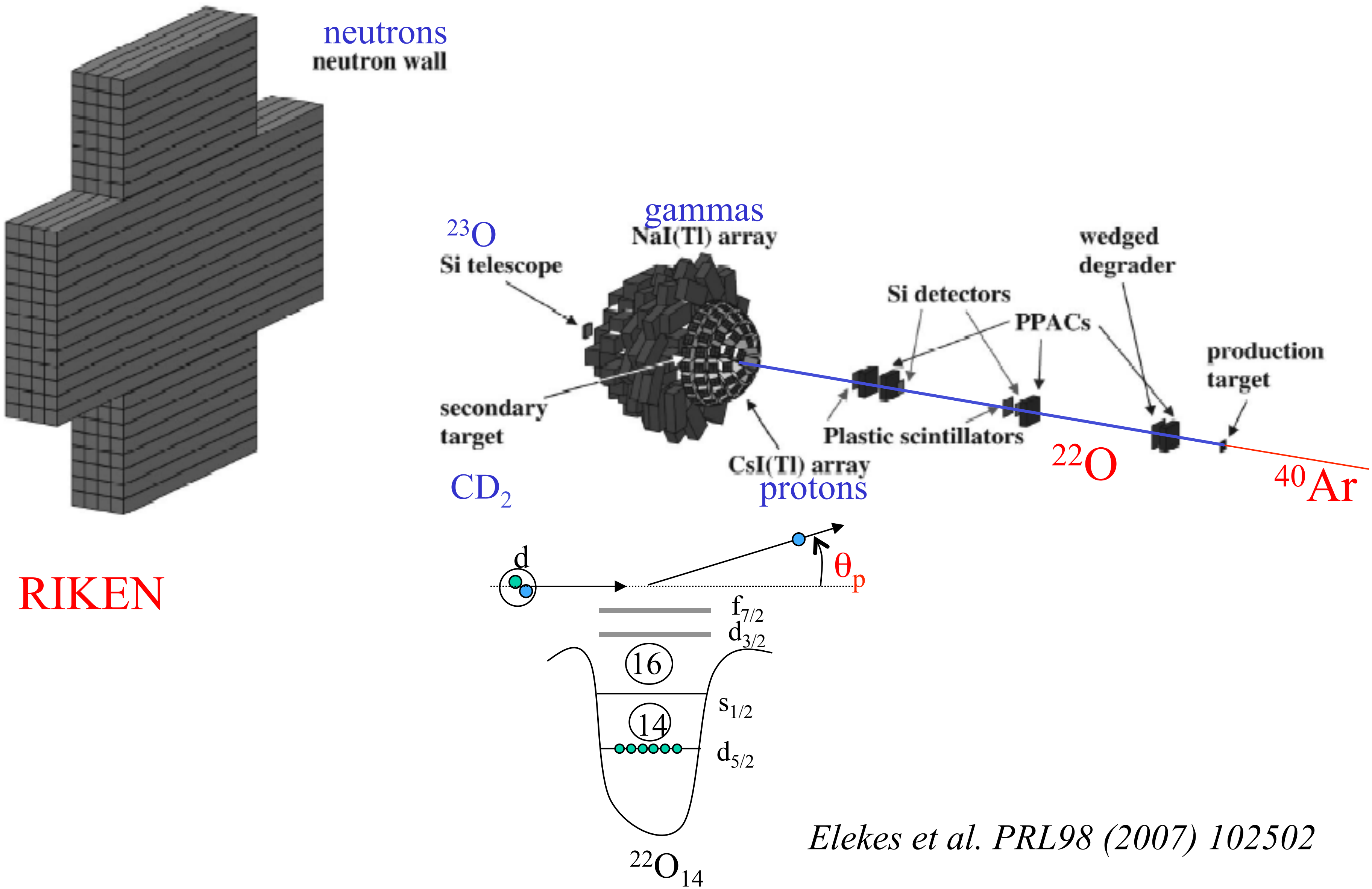
Oxygen Isotope A=22



Stanoiu et al. PRC (2004)



$^{22}O(d,p)^{23}O$ reaction to probe the neutron N=16, 20 shell closures

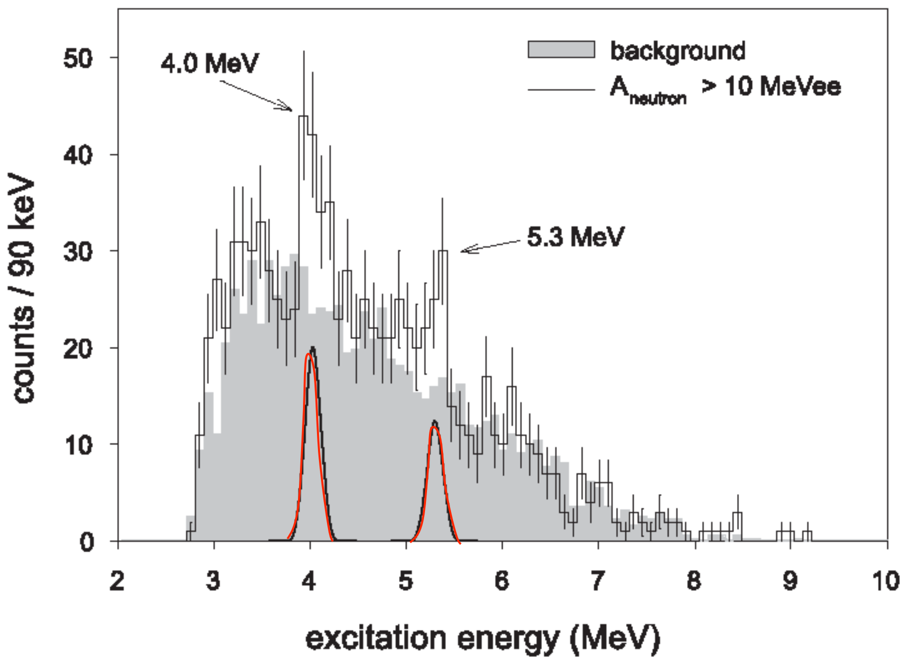


Elekes et al. PRL98 (2007) 102502

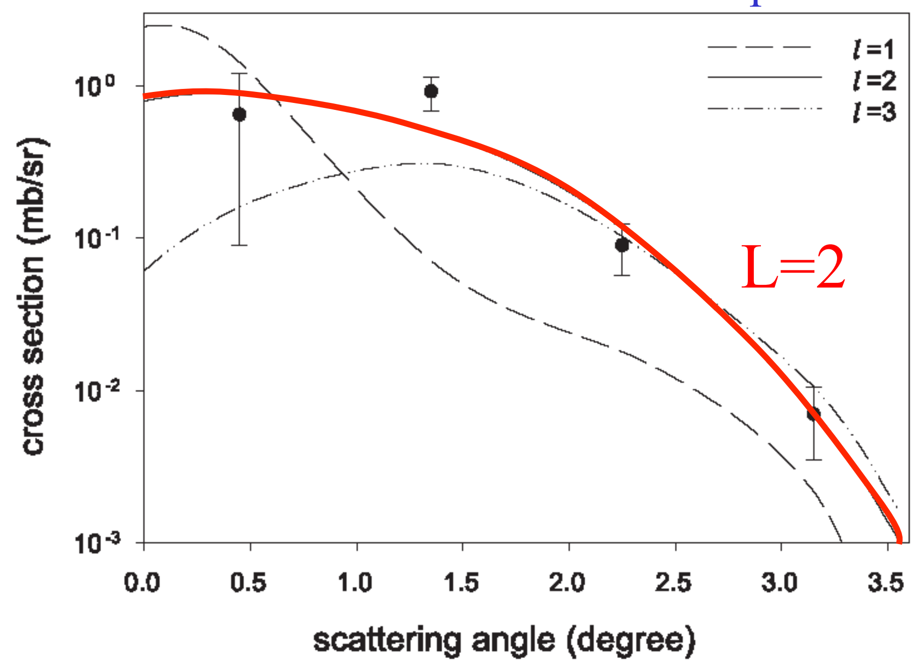
The ‘sizes’ of the N=20 and N=16 gaps in Oxygen (RIKEN)

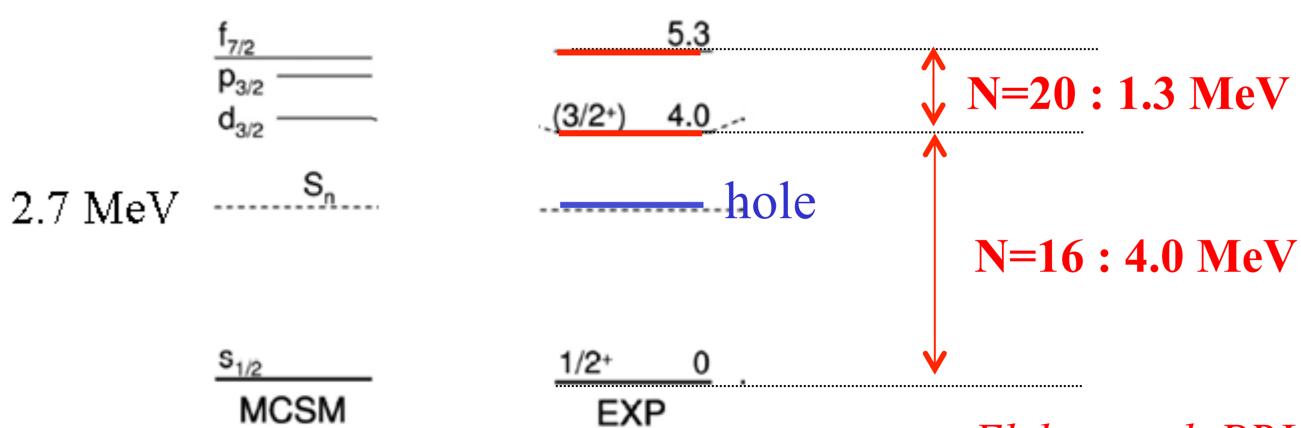
$^{22}O(d,p)^{23}O$ reaction to probe the neutron N=16, 20 shell closures

Gated on neutrons



Gated on 4 MeV neutron peak





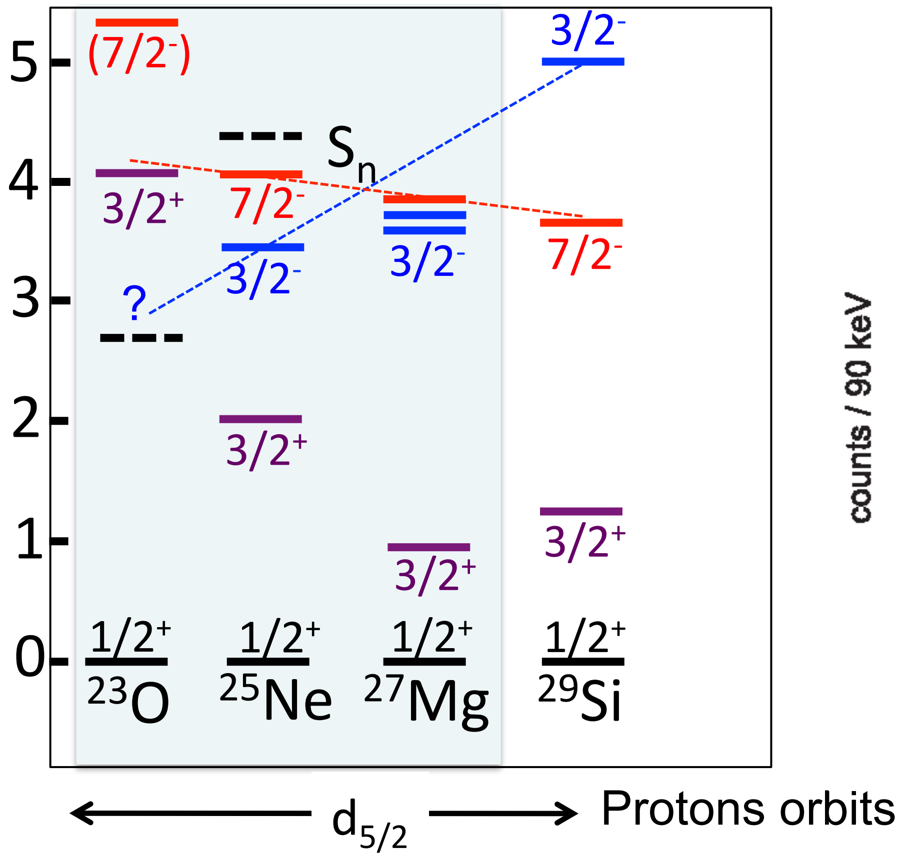
^{23}O

Elekes et al. PRL98 (2007) 102502

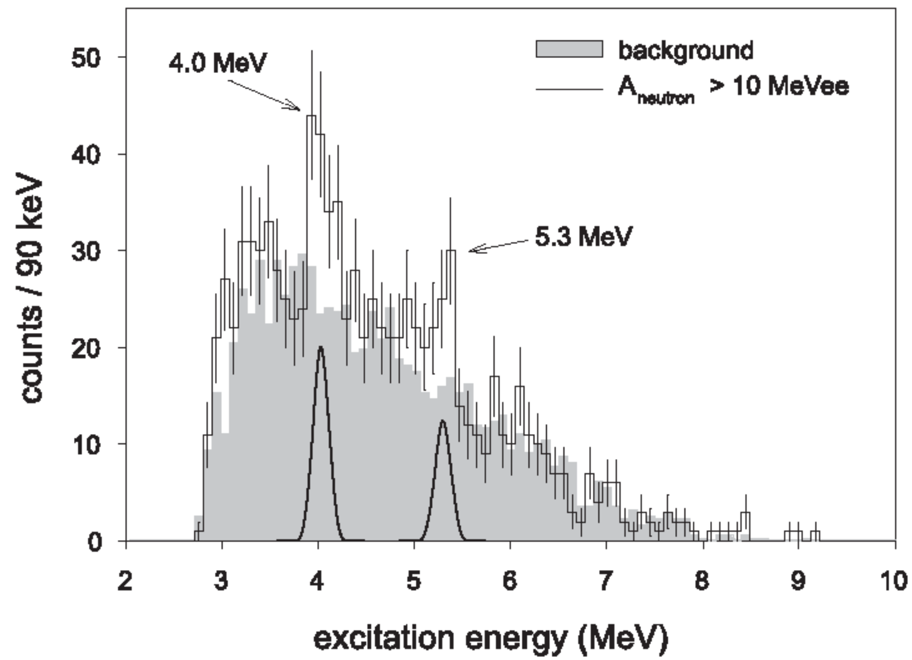
$5/2^+$ observed PRL99 (2007)

Proposal – O.S.

Shell evolution viewed from N=15 systematics



$^{22}O(d,p)\,^{23}O$ at 34 Mev/A @RIKEN



Swaping between the $f_{7/2}$ and $p_{3/2}$ orbits (N=28) below Z=14

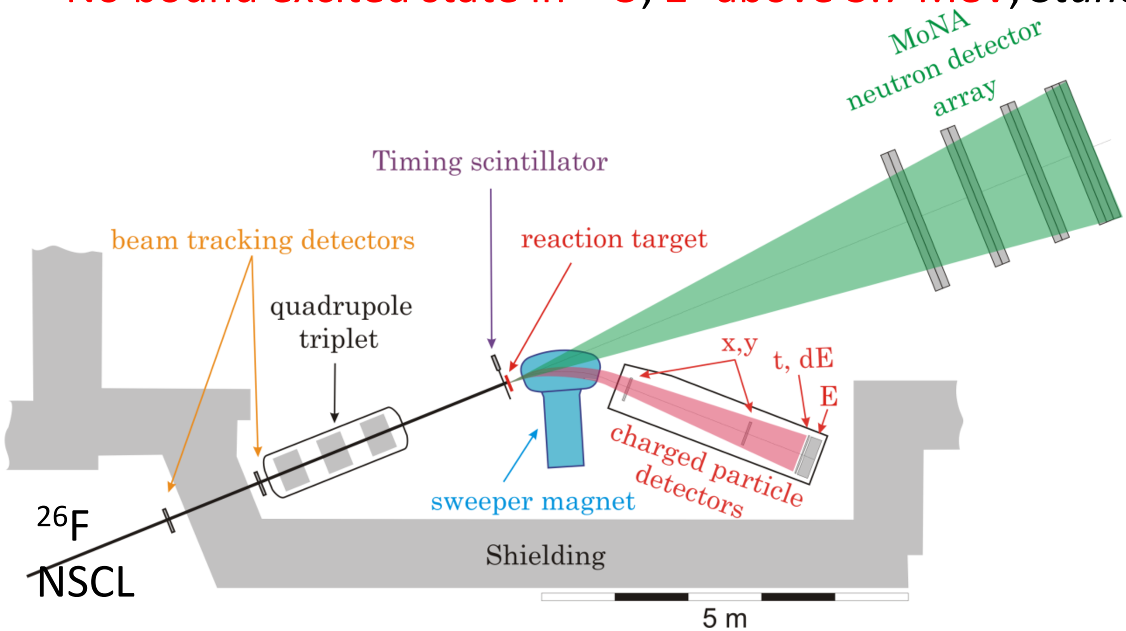
$3/2^-$ state not observed in ^{23}O -> statistics ? Energy matching ?

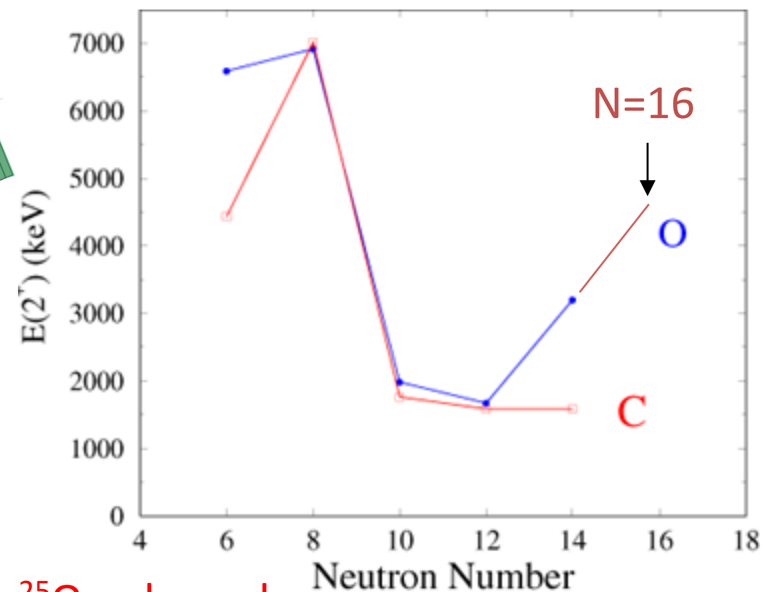
Study of $^{22}O(d,p)\,^{23}O$ at about 10 A.MeV with ACTAR

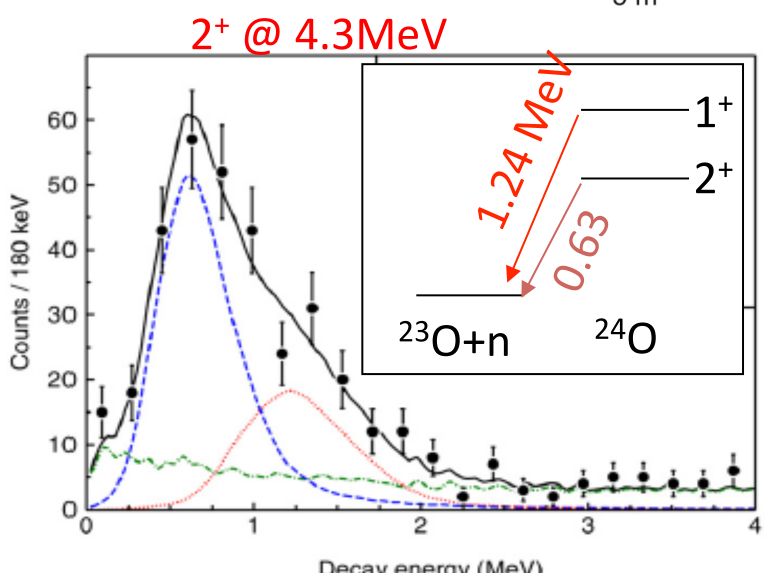
^{22,24}O: good core nuclei ?

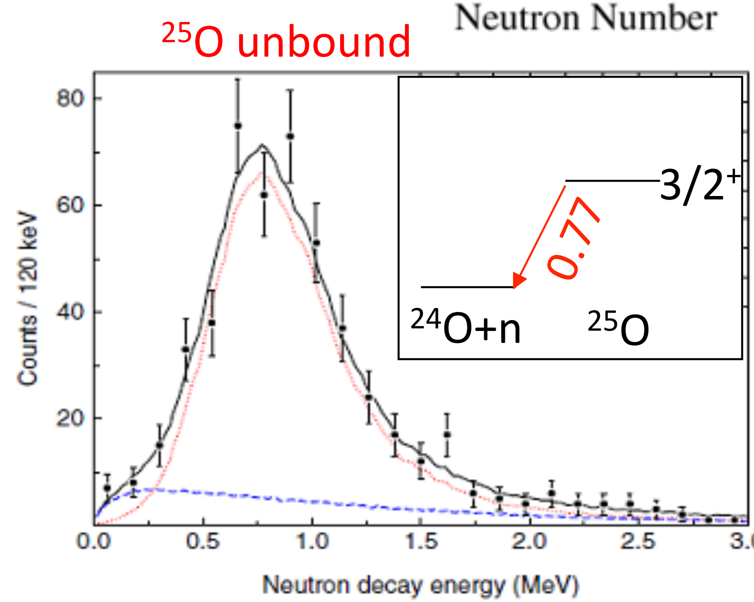
Changing slope in neutron separation energies *Ozawa et al. PRL 84 (2000)*

No bound excited state in ^{24}O, 2^+ above 3.7 MeV, *Stanoiu et al. PRC 69 (2004)*



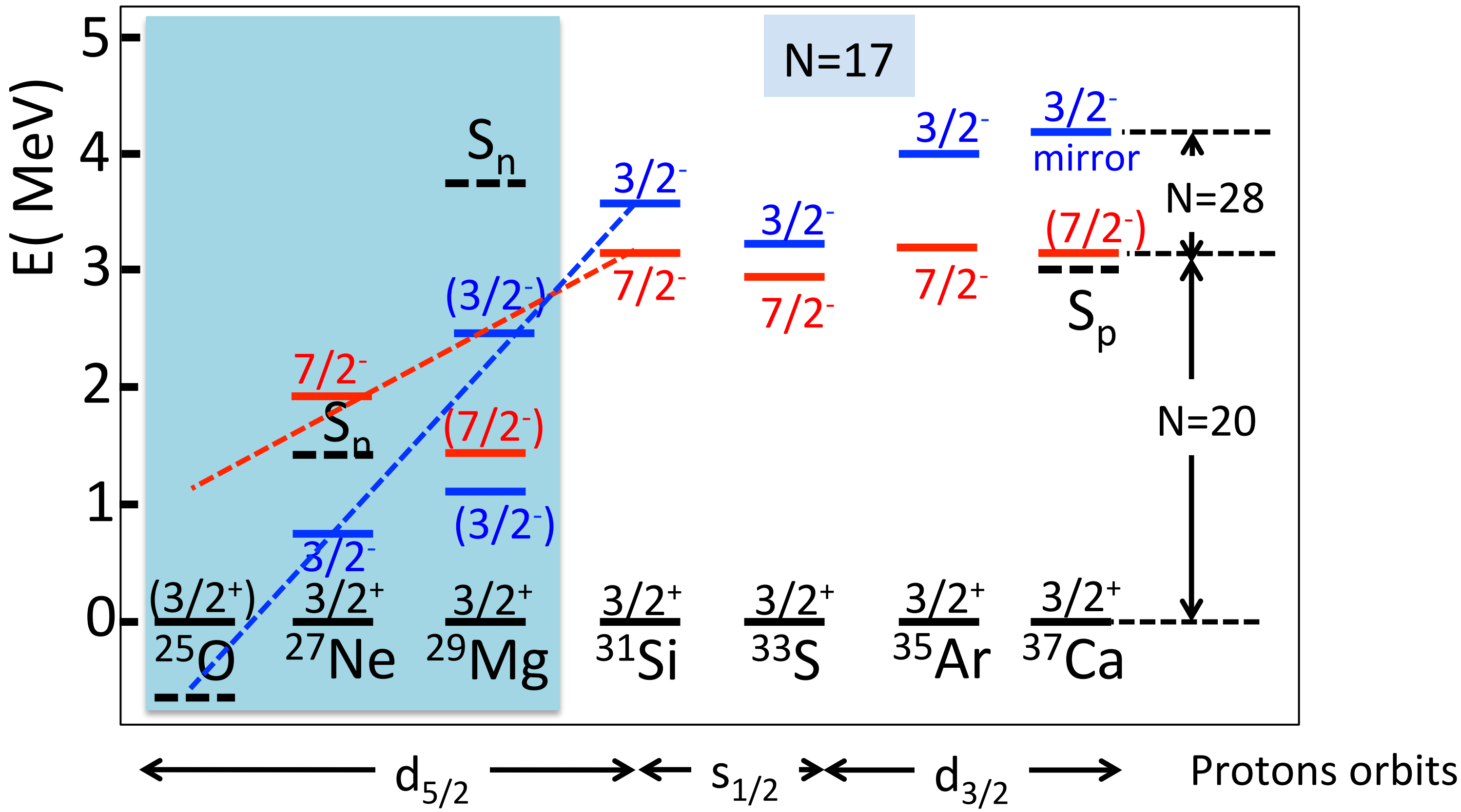






Refs : C.R. Hofmann et al. PRL 100 (2008), ibid PLB 672 (2009)

Shell evolution viewed from the N=17 systematics



Large N=20 gap between Z=14 and Z=20 -> collapses below Z=14 (Si)

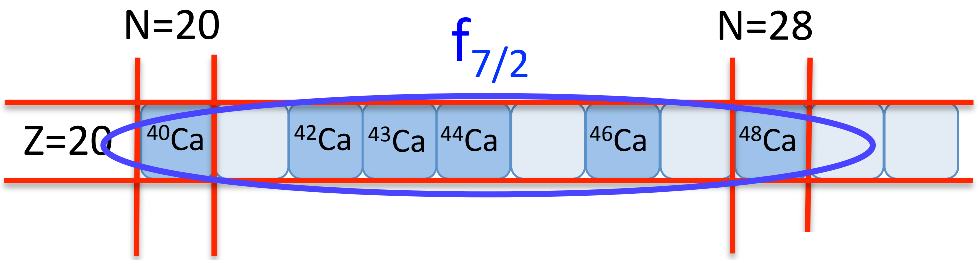
Swaping between the $f_{7/2}$ and $p_{3/2}$ orbits (N=28) below Z=14

-> role of specific proton-neutron forces (tensor and two-body SO)

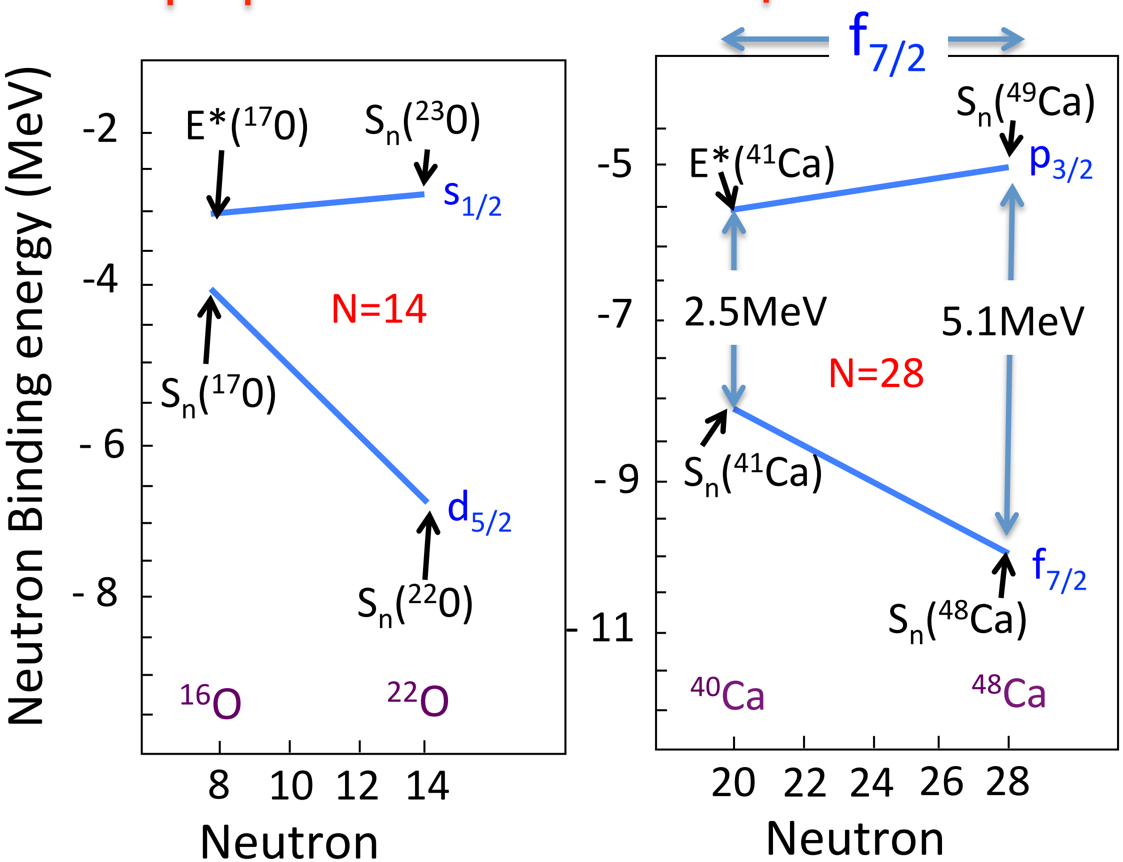
-> expected in other regions of the chart of nuclides

-> Study of ^{28}Mg(d,p) ^{29}Mg and ^{36}Ca(d,p) ^{37}Ca reactions

Increase of spin orbit (SO) shell gaps in the Ca and O chains



exp (d,p),(p,d)
from Uozumi et al. NPA 1994, PRC 1994



The N=28 gap is created to a large extent by nn interactions

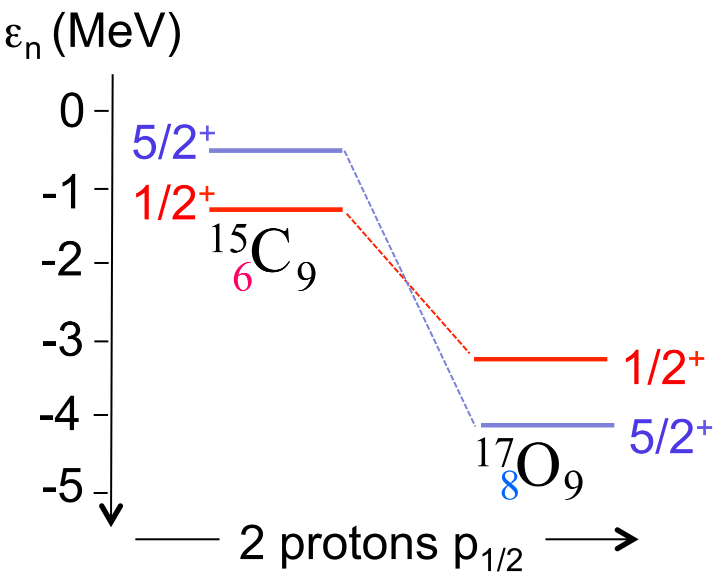
It increases by about 2.7 MeV

$$\delta\varepsilon(1f_{7/2}) \approx 7V^{nn}1f_{7/2}1f_{7/2}$$

$$\delta\varepsilon(1p_{3/2}) \approx 8V^{nn}1f_{7/2}2p_{3/2}$$

Striking analogy between the
N=14 and N=28 gaps in the O and Ca chains
Same increase of gap by 2.6 MeV !!

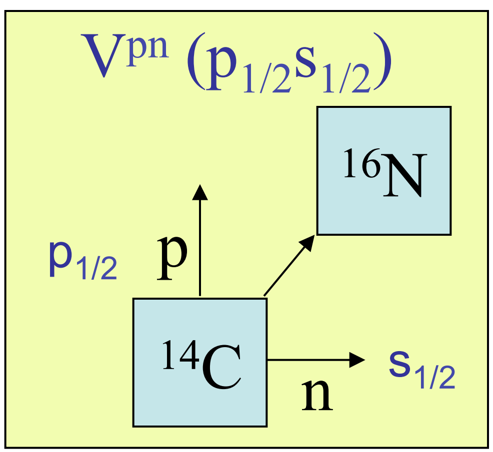
Derivation of nuclear forces using the two methods



$$|V^{pn}\ p_{1/2}\ d_{5/2}| \sim 2\ |V^{pn}\ p_{1/2}\ s_{1/2}|$$

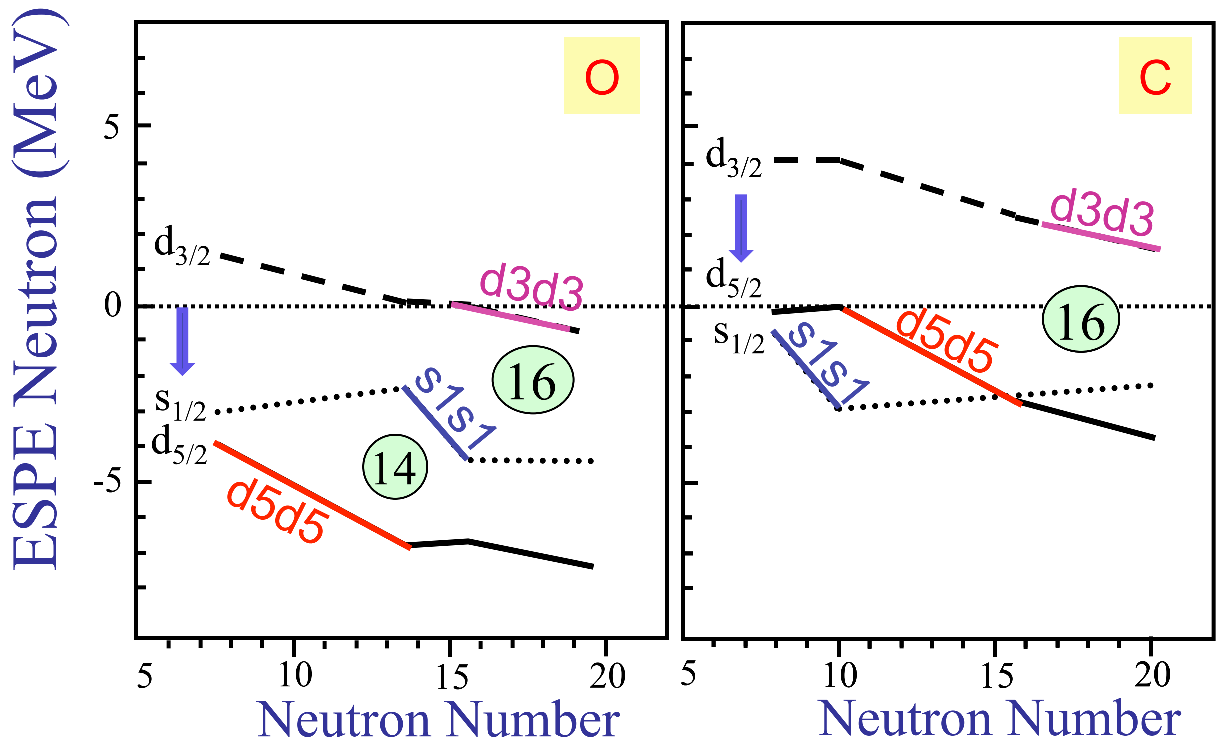
Attractive tensor — repulsive two body SO

$$2(V^{pn}\ p_{1/2}\ s_{1/2} - V^{pn}\ p_{1/2}\ d_{5/2}) = 1610\text{keV}$$



^{16}N
$V^{pn}(p_{1/2}\ s_{1/2}) = -0.943$ MeV
$V^{pn}(p_{1/2}\ d_{5/2}) = -1.83$ MeV

Evolution of neutron orbits in C and O isotopic chains



Swapping of levels at N=9

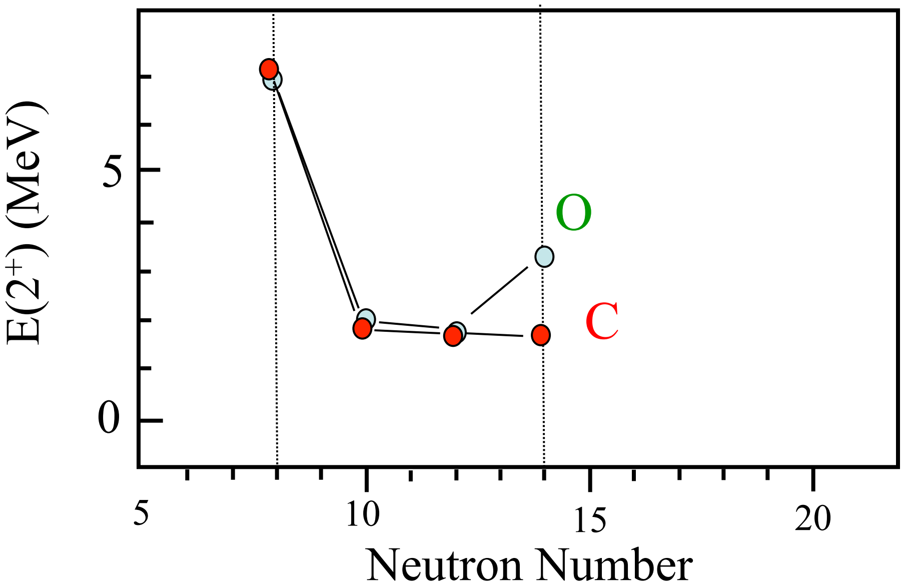
-Shell gap ceated at N=14 in O, not present in the C chain *Stanoiu et al. PRC 78, (2008)*

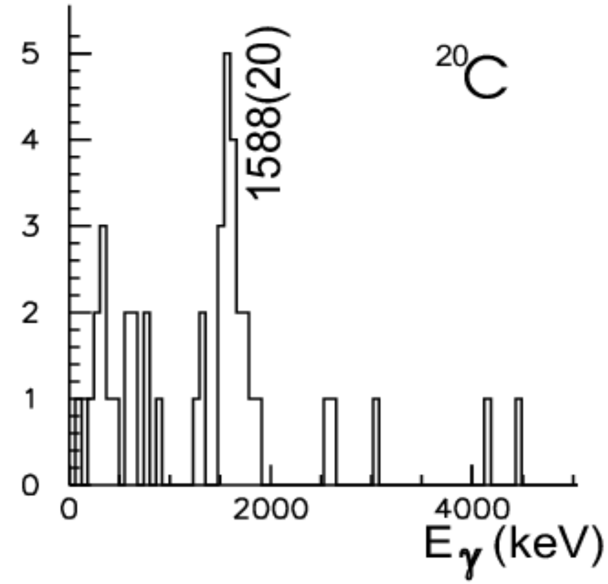
- Degeneracy of $s_{1/2}$ and $d_{5/2}$ orbits at N~14 in C

-$s_{1/2}$ states at low energy at N=9, N~14-16 in the C isotopes -> haloes ?

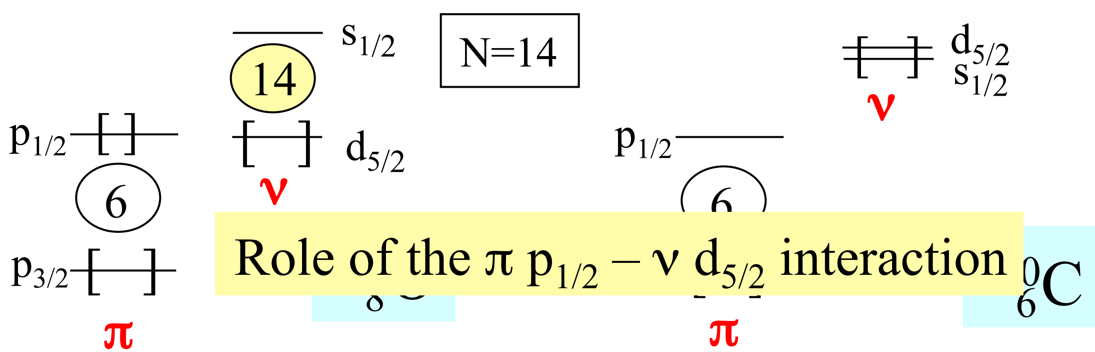
Binding energy (BE) of the O is about twice as large as that of the C isotones

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





Thirolf et al. PLB 485 (2000) M. Stanoiu et al. PRC 69 (2004) and PRC 78 (2008)



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

Rapid disappeareance of N=14 shell closure !!

Evolution of neutron orbits in the Ni isotopic chain

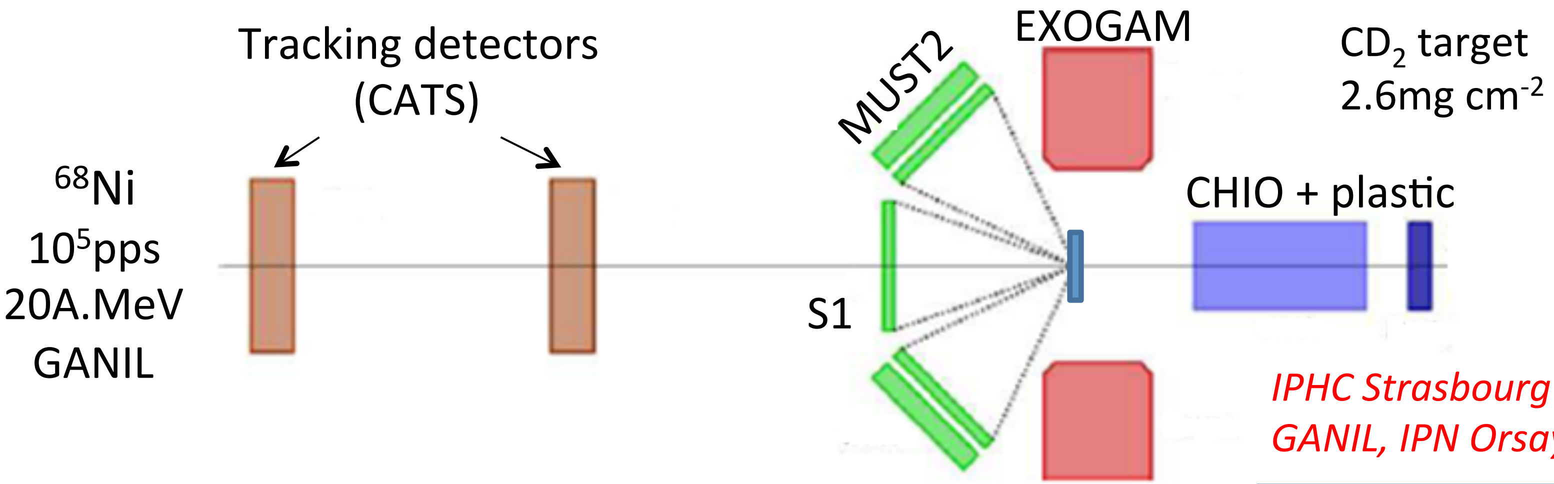
^{68}Ni(d,p) to probe the size of N=50 SO gap

Systematics of ESPE derived from recent values and from T=1 TBME derived from the Zr chains

Generalization of the role of T=1 forces in O, Ca and Ni

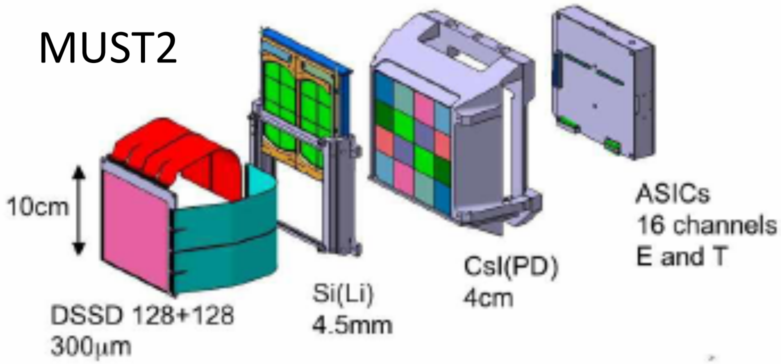
General rule of increase by about 3 MeV of SO gap

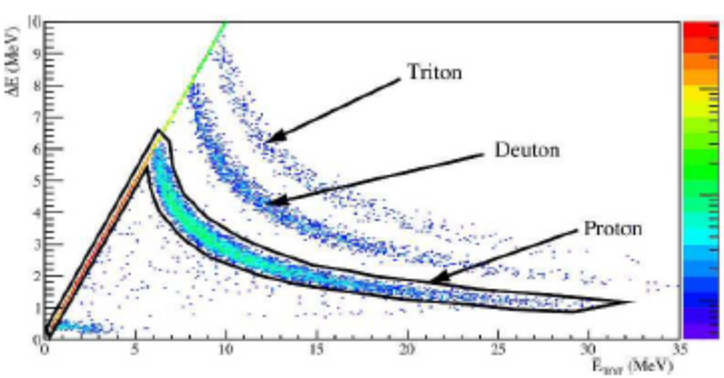
^{68}Ni(d,p) reaction in inverse kinematics



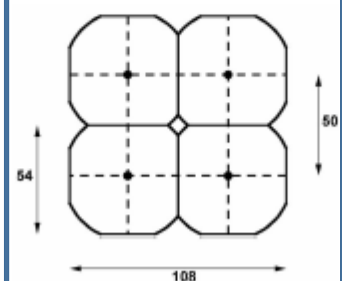
IPHC Strasbourg
GANIL, IPN Orsay, CEA Saclay

MUST2

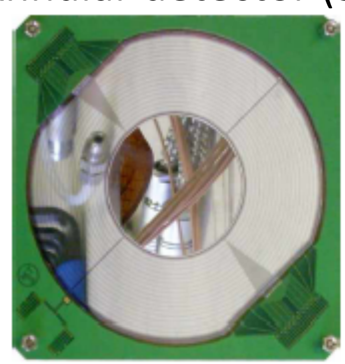




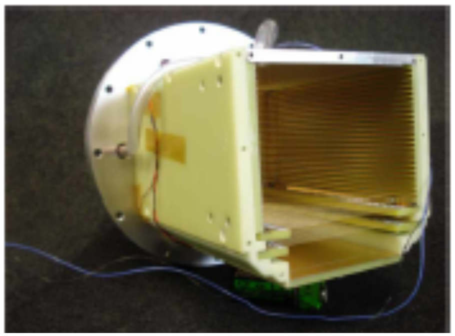
EXOGAM

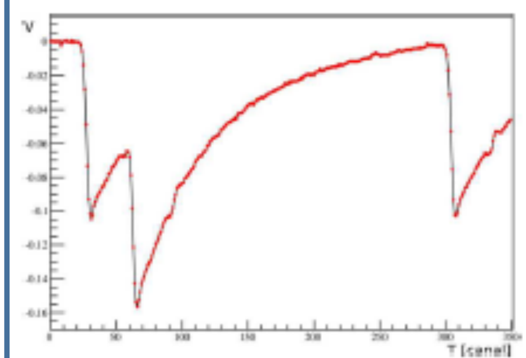


Annular detector (S1)

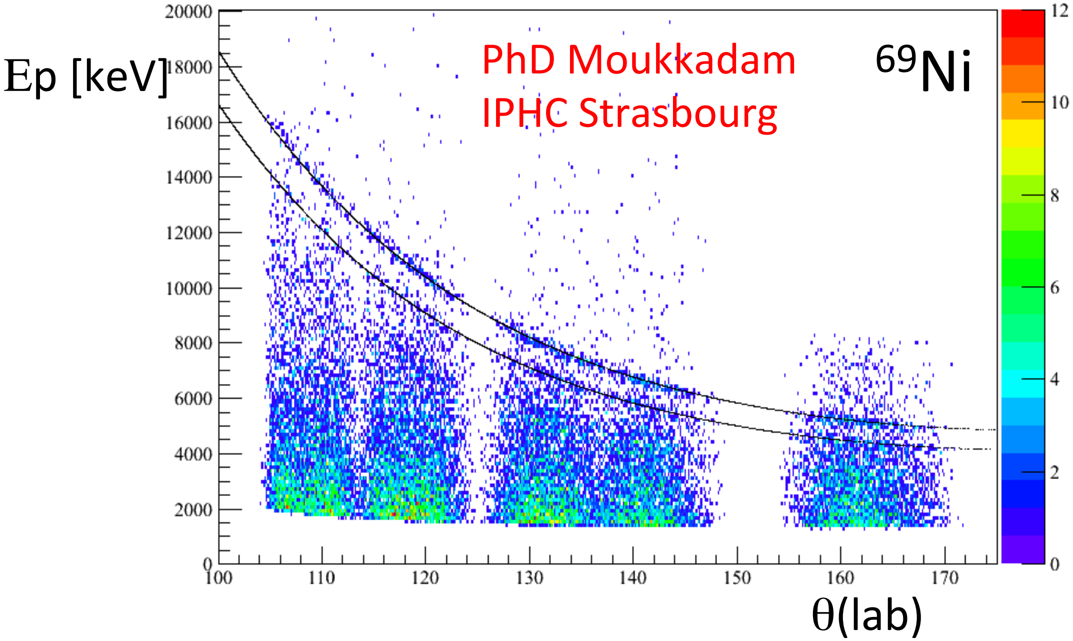


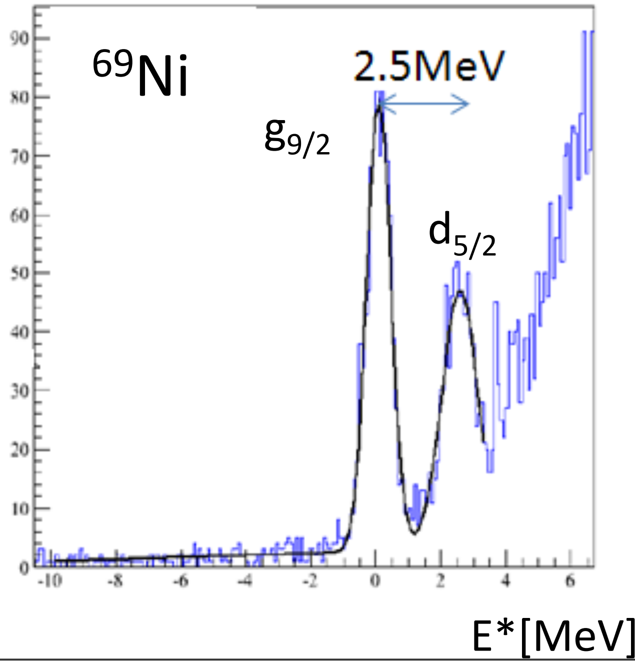
Ionization chamber (CHIO)

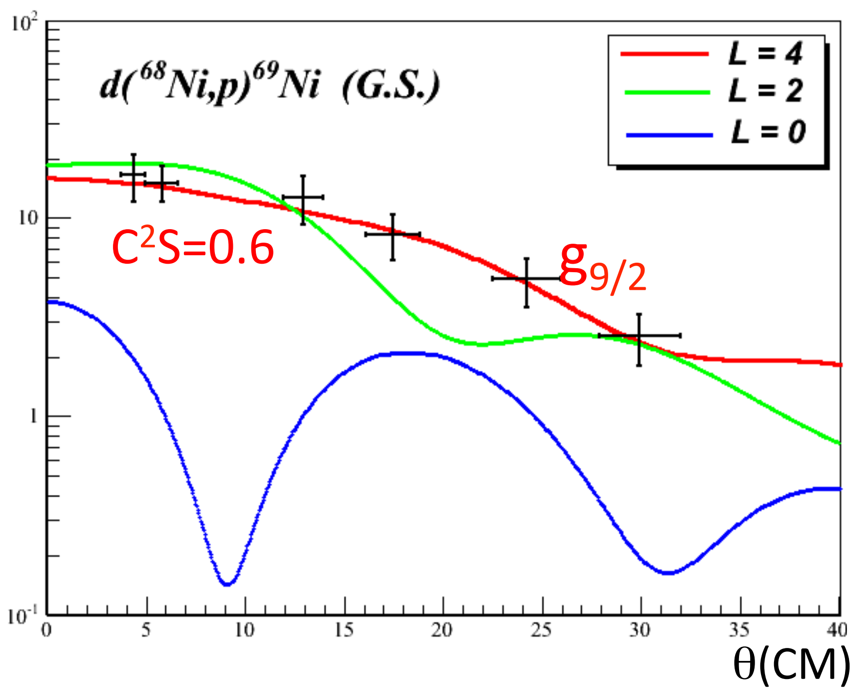


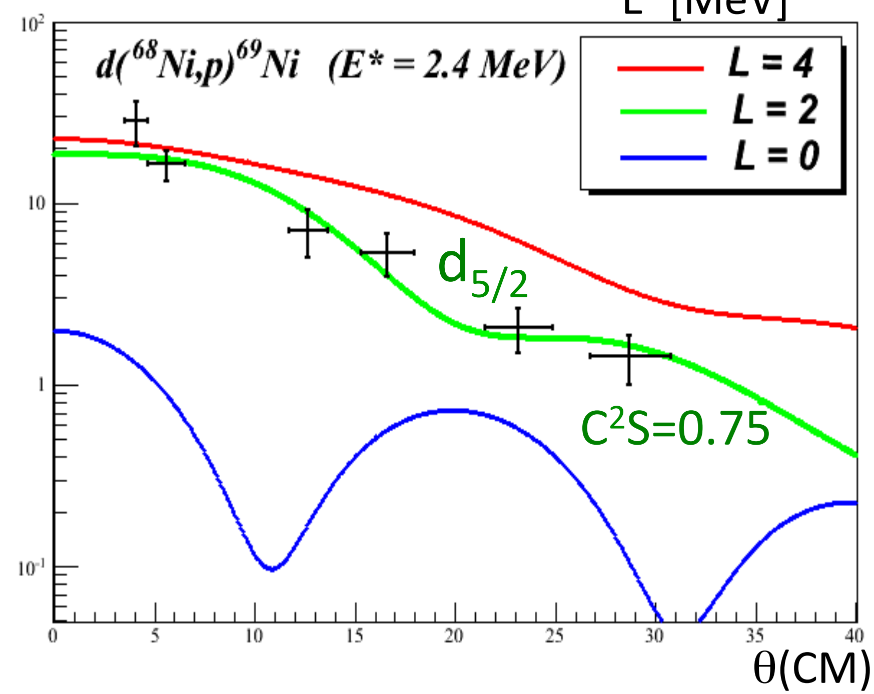


RESULTS FOR ^{68}Ni(d,p)^{69}Ni



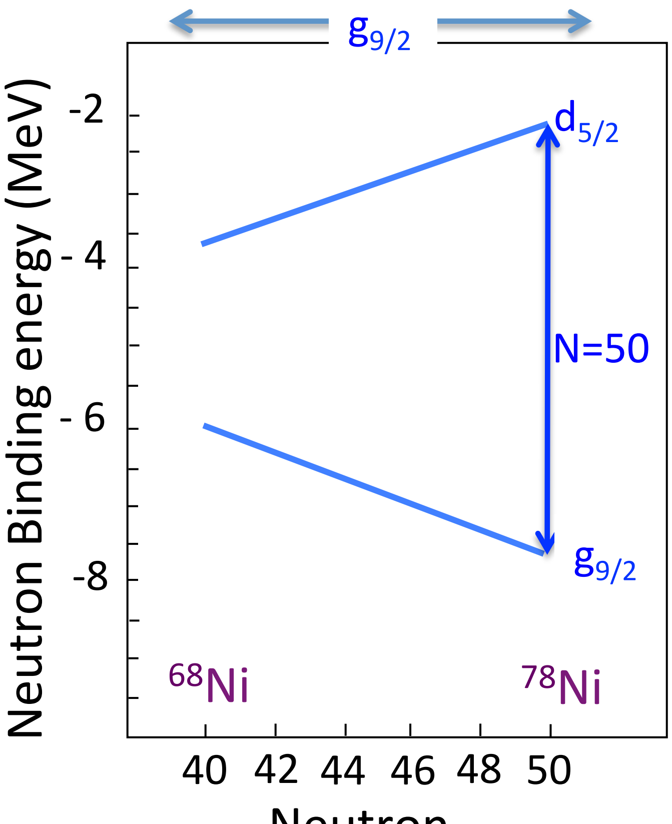






Is the N=50 increasing by the same mechanism ?

See also K. Sieja et al. PRC 85 051301 (2012)



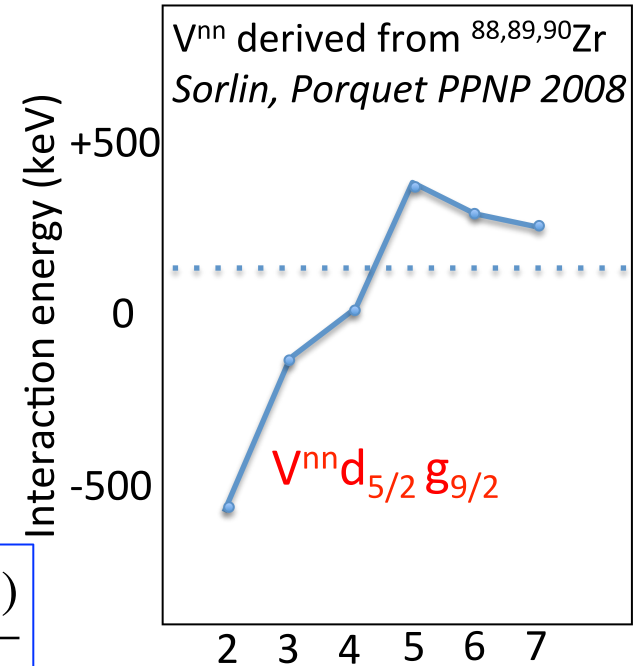
$$\delta\varepsilon(1g_{9/2}) \approx 9V^{nn}1g_{9/2}1g_{9/2}$$

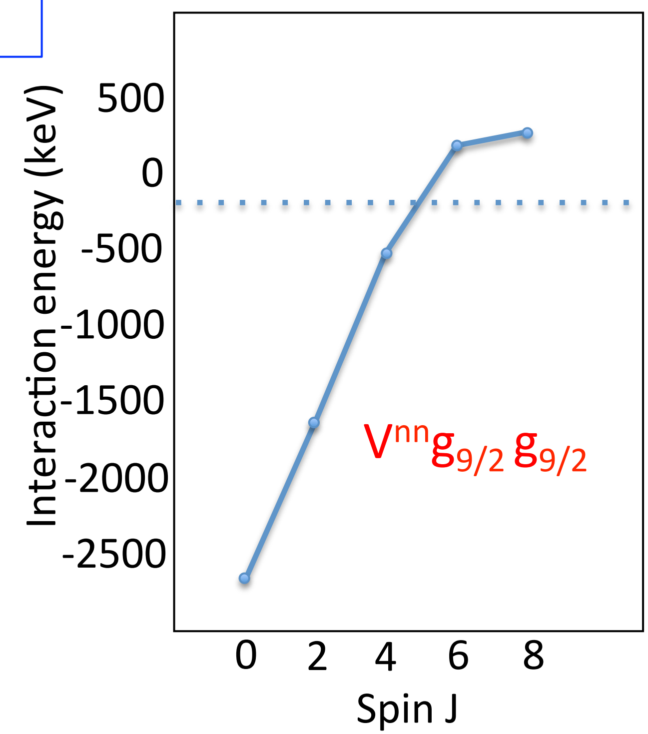
$$\delta\varepsilon(1d_{5/2}) \approx 10V^{nn}1g_{9/2}2d_{5/2}$$

Monopole

$$V^{nn}_{monopole} \approx \frac{\sum(2J+1)\,\mathrm{int}(J)}{\sum(2J+1)}$$

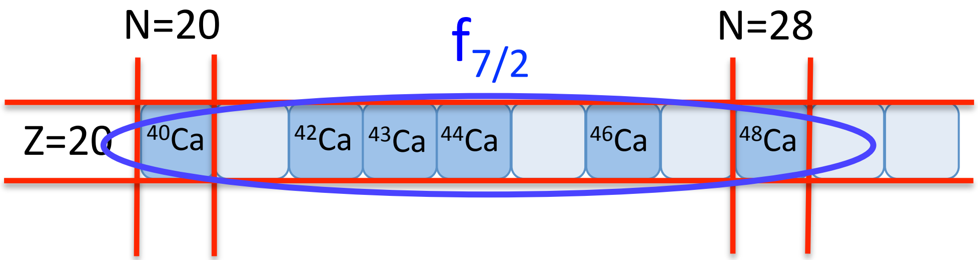
$$\delta(N=50) \approx 3MeV$$





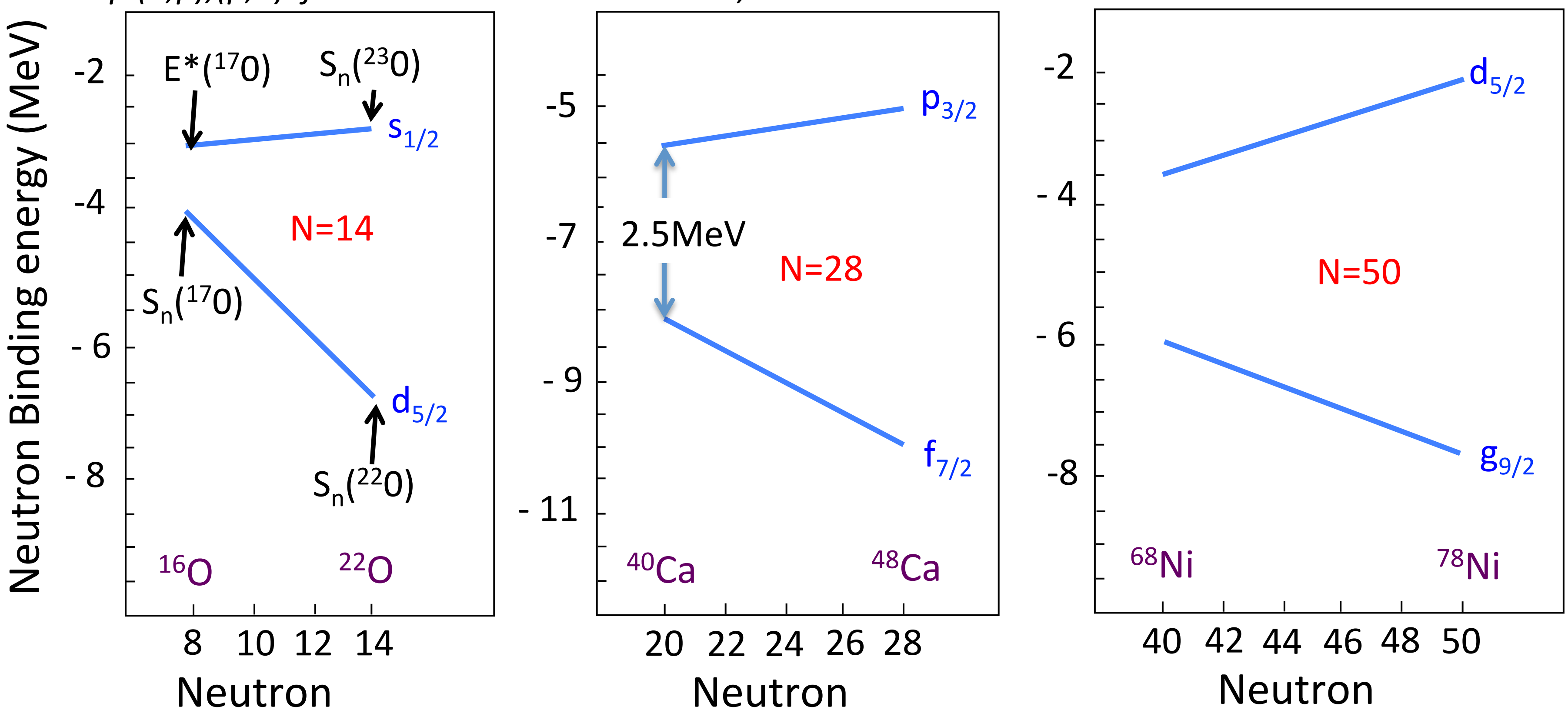
The same trend seems present in the Ni isotopic chain !
The size of the gap at N=40 constraints the one at N=50.

The role of three body n-n forces to create SO shell gaps



Theory: *J.D. Holt et al. JPG 39 (2012)*
G. Hagen et al. PRL 109 (2012)
K. Sieja et al. PRC 85 051301 (2012)

exp (d,p),(p,d) from Uozumi et al. NPA 1994, PRC 1994



Increase of ALL SO shell gaps from n-n interactions by about 2.7 MeV !!!

A relatively large N=50 gap is expected in ^{78}Ni.

Predictibility for other high j orbits -> $h_{11/2}$, $i_{13/2}$