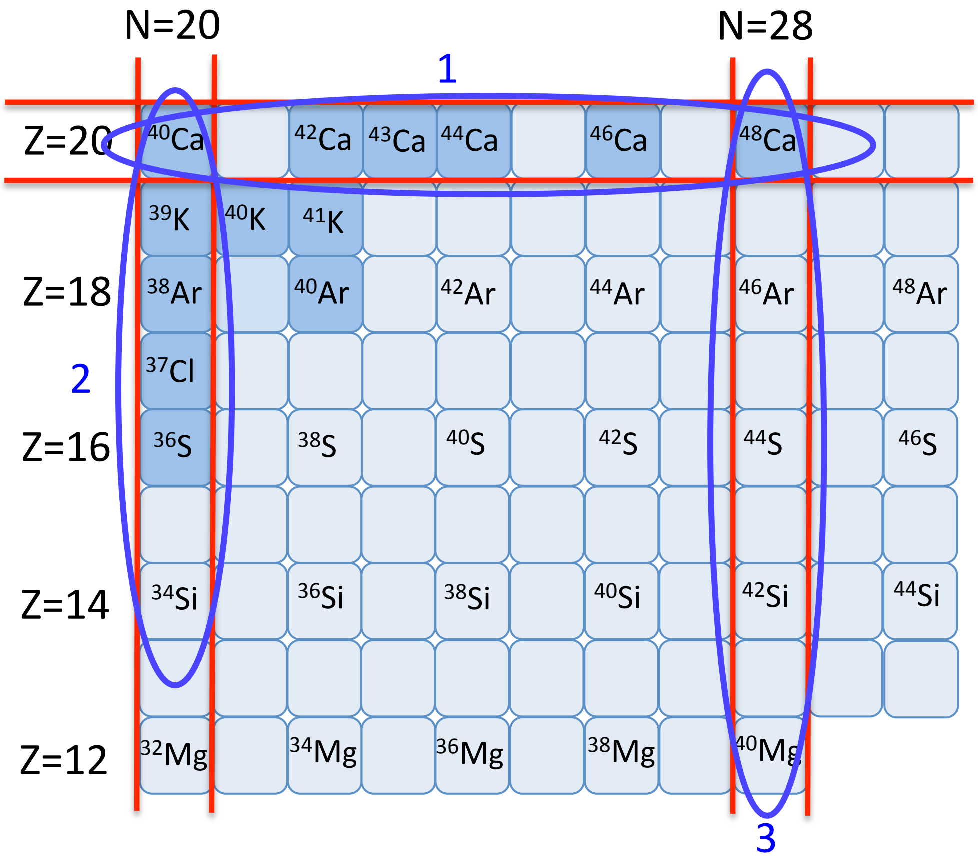
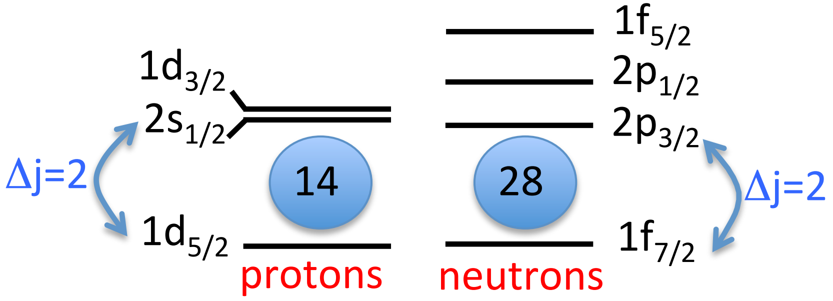
Recent opportunities in transfer reactions

O. Sorlin (GANIL)





Modifications of shell gaps & SO splittings

Moving away from stability explore various facets of nuclear force

Explore effects of three body forces, Tensor and two-body spin orbit

The ^{34}Si bubble nucleus
Link to physics of SHE ?

Use of transfer reactions
Analysis/Interpretation/consequences

sdpf-U interaction
F. Nowaki and A. Poves PRC (2009)
NA Smirnova et al. PLB (2009)

Olivier Sorlin

Cet article est une ébauche concernant un footballeur français.

Vous pouvez partager vos connaissances en l'améliorant (**comment ?**) selon les recommandations des projets correspondants.

Olivier Sorlin, né le 9 avril 1979 à Saint-Étienne, est un footballeur français qui évolue au poste de milieu de terrain à l'Évian Thonon Gaillard Football Club.

Sommaire [masquer]

Biographie [modifier]

Formé à ASOA Valence mais révélé à Montpellier, il arrive au Stade rennais FC pendant le mercato d'hiver de la saison 2000-2001. Un passage éclair à l'AS Monaco en 2005 il retourne à Rennes ou il a été un grand artisan des qualifications européennes de la saison 2004-2005 et 2006-2007. En janvier 2009 il part en Grèce rejoindre le PAOK Salonique. En 2010, Sorlin quitte le PAOK et retourne en France pour le club de Ligue 2 Évian TGFC.

En début de carrière, en mars 1997, il a effectué un essai à l'Olympique lyonnais en compagnie de Sidney Govou. Mais seul Govou sera conservé.

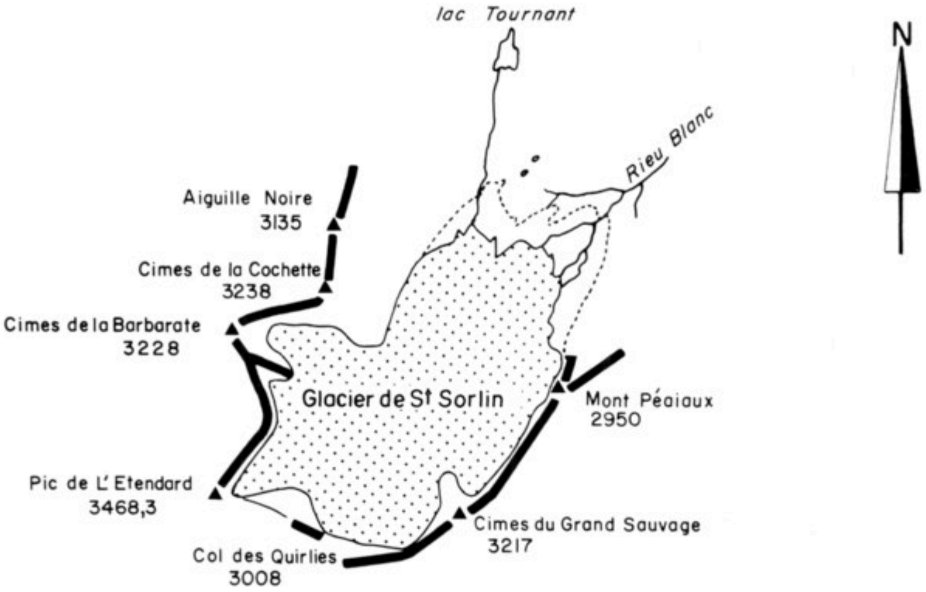
Olivier Sorlin

Sorlin avec Évian Thonon Gaillard en 2012.

Situation actuelle

Club actuel	Évian Thonon Gaillard

Glacier de Saint Sorlin



How the ^{48}Ca nucleus is produced in the universe ?
Neutron capture beta-decay process
The role of the N=28 shell closure
Beta-decay studies suggested the vanishing of N=28.

PhD IPN Orsay 1991
Stay in Orsay up to 2004
At GANIL since then

No sabbatical year so far….

Further studies established the progressive erosion of N=28
From the doubly magic ^{48}Ca, vibrational ^{46}Ar, shape coexistence in ^{44}S and deformation in ^{42}Si
Use of various experimental techniques at GANIL (beta-decay, isomer decay, transfer, in-beam)

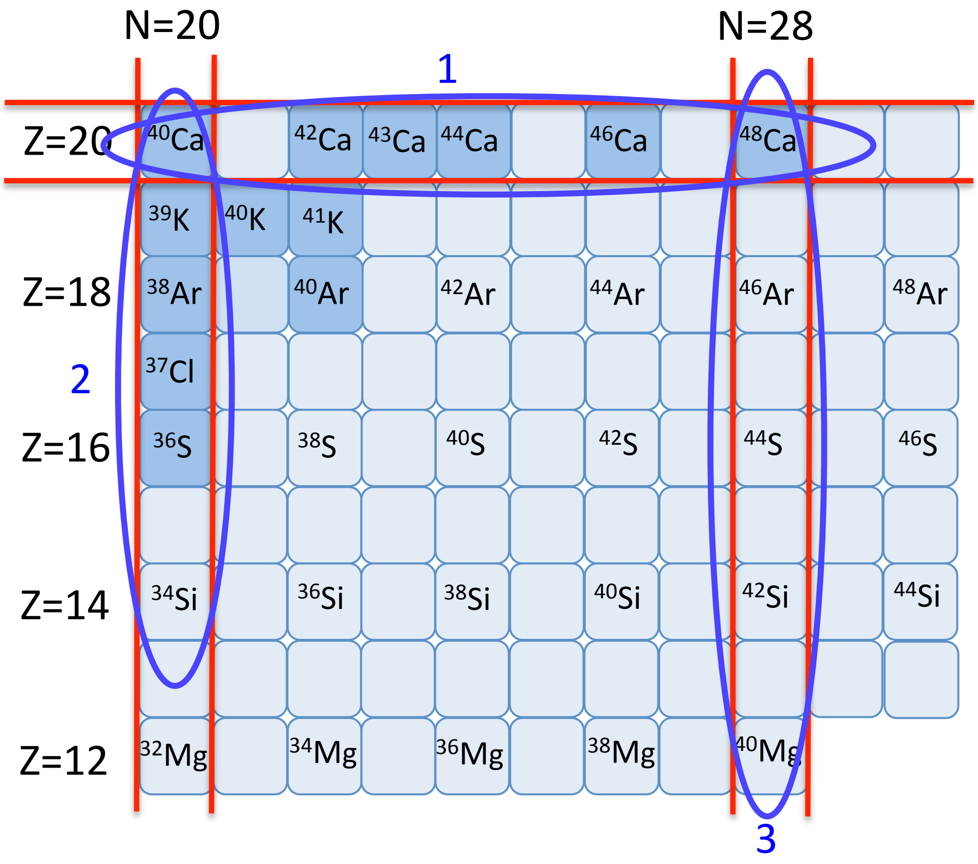
Study of other shell closures N=14,16 and N=40 …

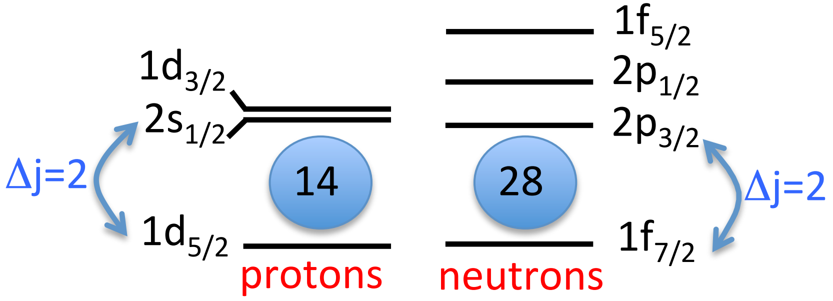
Towards a global understanding of which parts of nuclear force led to significant shell modifications (tensor, spin orbit)

Better understand the astrophysical r process
-> production of ½ heavy elements

'May the force be with you'
Obi-Wan Kenobi 'Star Wars'

Recent opportunities in transfer reactions
O. Sorlin (GANIL)





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Setting the scene…

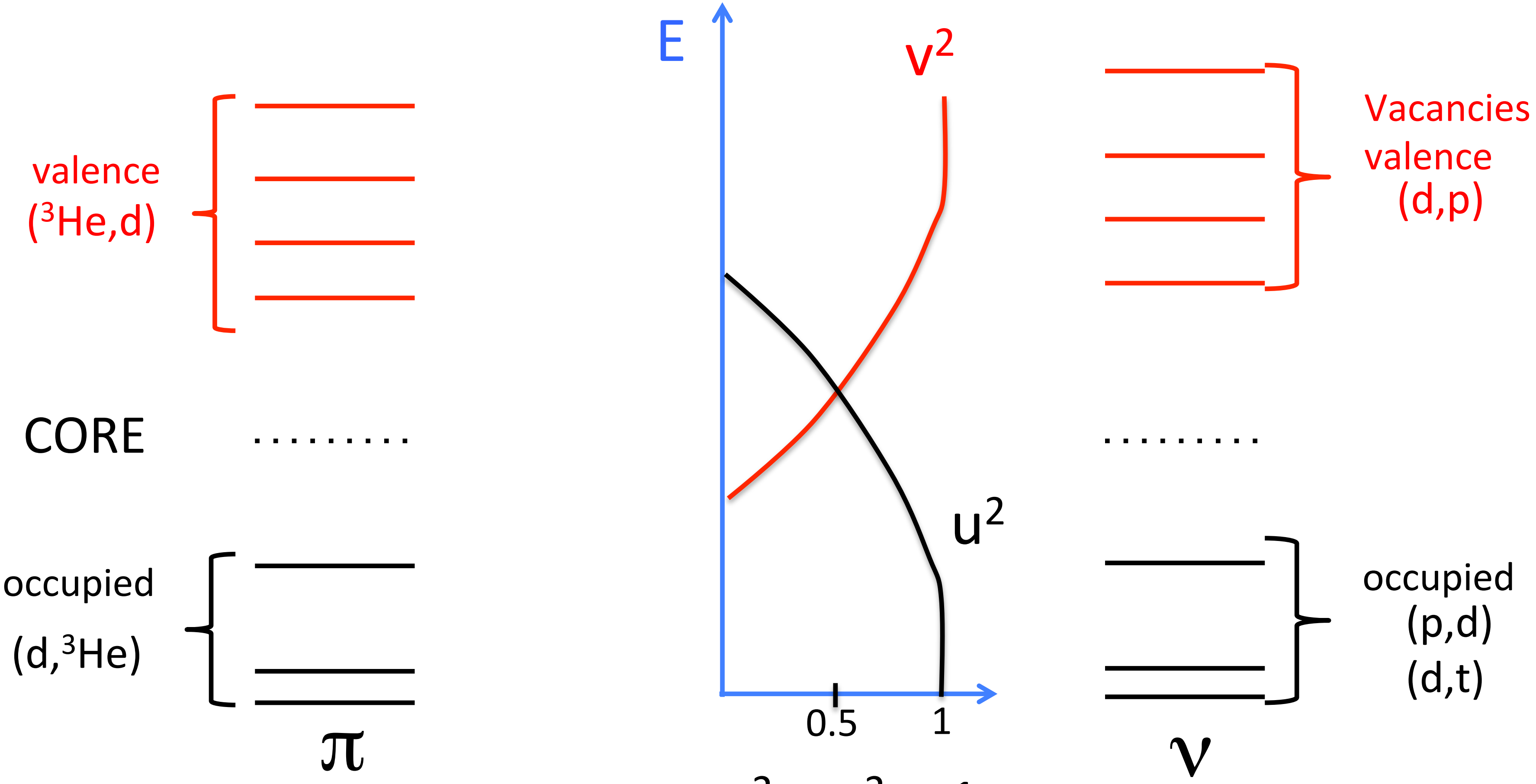
Basic features of transfer reactions

Which transfer reaction, for what ?

Choose the appropriate probe to determine occupancies / vacancies of orbits

Locate the energy levels carrying the largest SF -> study evolution of shell gaps

Learn about the role of correlations ➔ dilution of the Fermi surface ?



valence
(^{3}He,d)

CORE

occupied
(d,^{3}He)

π

Vacancies
valence
(d,p)

occupied
(p,d)
(d,t)

ν

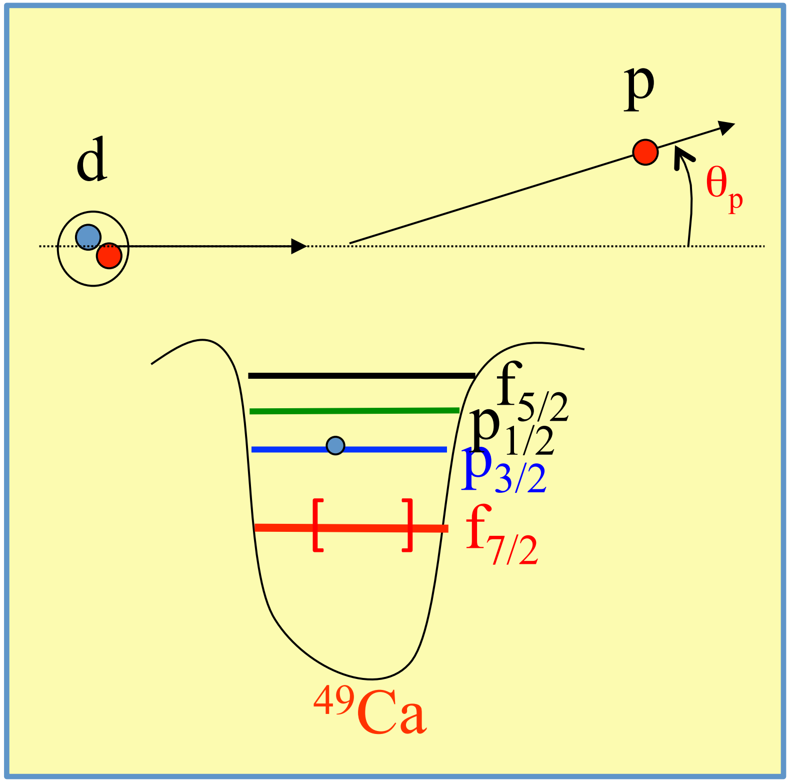
$$u^2 + v^2 = 1$$

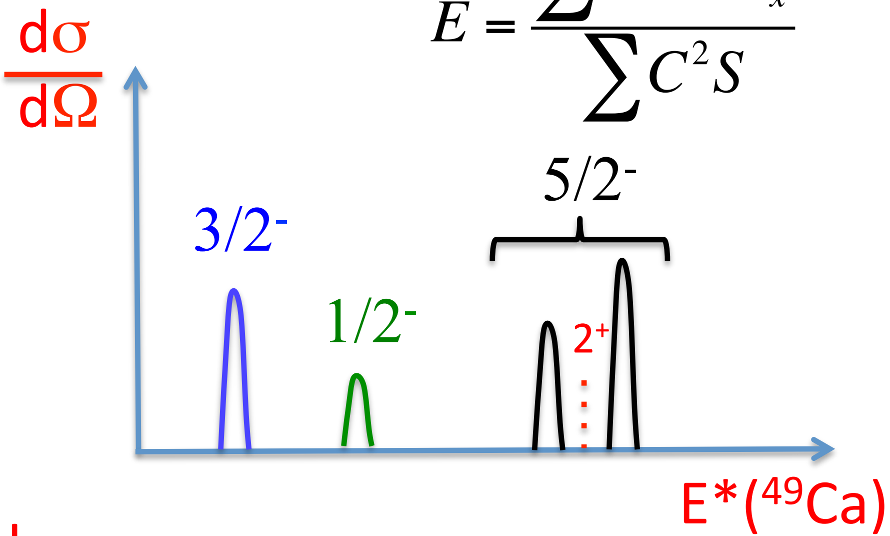
$$\sum (2j+1) C^2 S^+ + \sum C^2 S^- = 2j+1$$

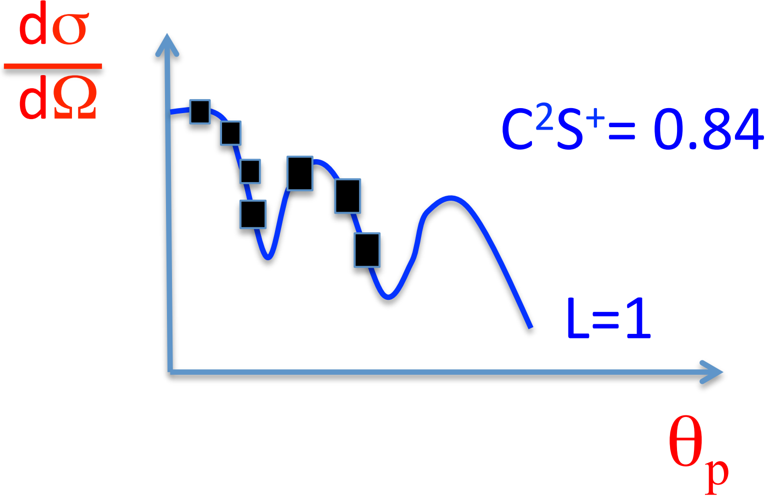
Basics features of a transfer reaction

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

^{48}Ca(d,p)^{49}Ca







Quantified energies -> shell structure

Cross section scales with vacancy (2J+1) C^2S^+ of the states ->ADWA calculations

Angular distribution typical of the transfered angular momentum L

Polarized beam/target to obtain info on J values.

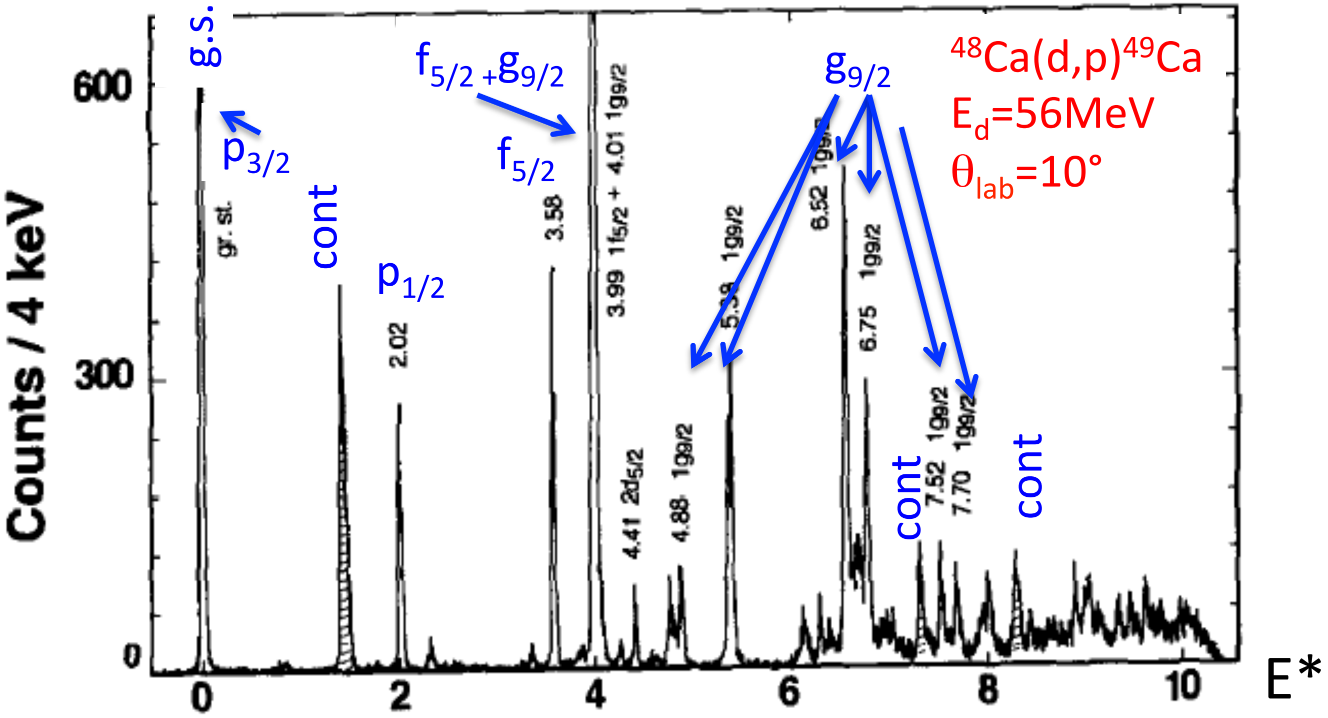
Use appropriate momentum matching

Valence neutron orbits in ^{48}Ca

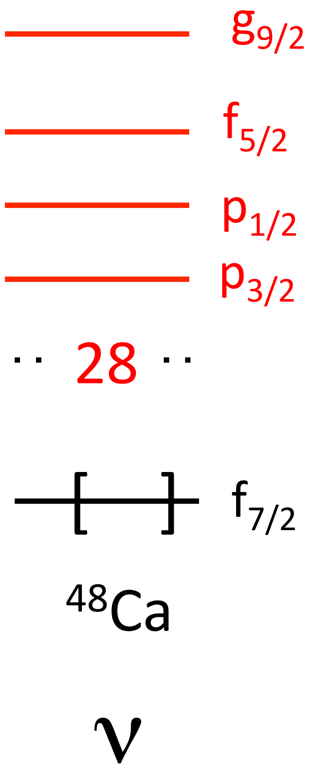
In a (d,p) reaction, we probe the vacancies of the states.

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.

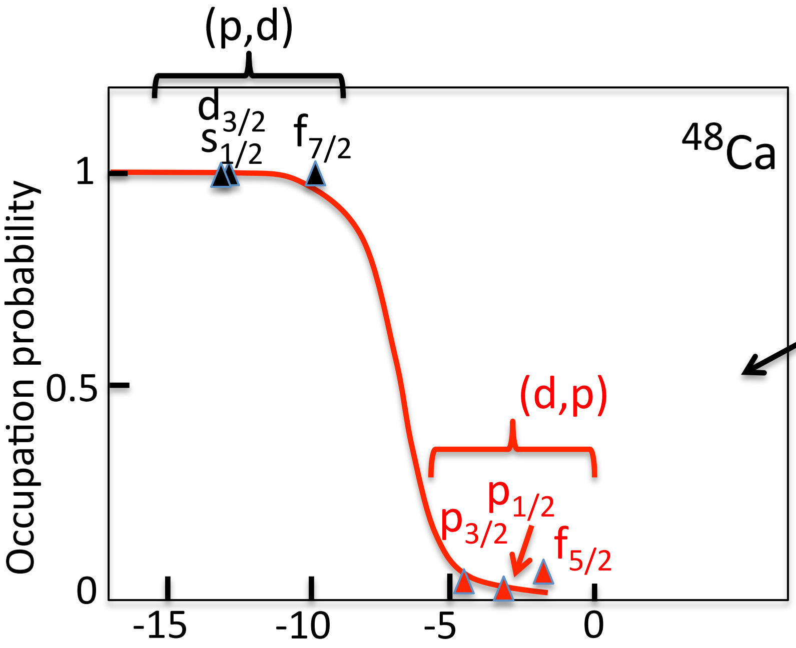


$$\bar{E} = \frac{\sum C^2 S \cdot E_x}{\sum C^2 S}$$



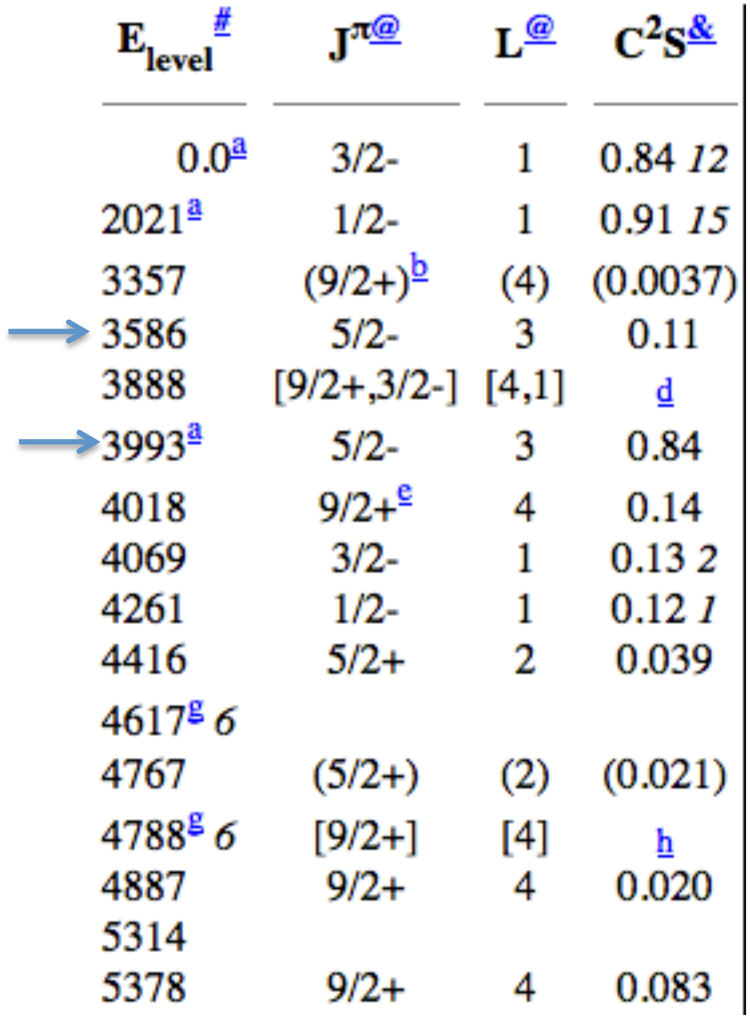
	Vacancy	occupancy	$\bar{E}$(MeV)
$f_{7/2}$	0	1	-5.1
$p_{3/2}$	0.97	0.03	g.s.
$p_{1/2}$	1.03	0	2.28
$f_{5/2}$	0.95	0.05	3.945

The ‘Fermi surface’ of ^{48}Ca derived from transfer reactions



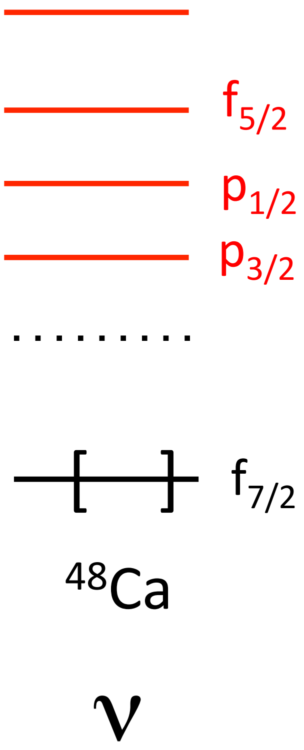
Sharp Fermi surface
^{48}Ca is a good core nucleus
with few correlations

^{48}Ca(d,p)^{49}Ca



E_{level}[#]	J^{π}[@]	L[@]	C^2S[&]
0.0[a]	3/2-	1	0.84 *12*
2021[a]	1/2-	1	0.91 *15*
3357	(9/2+)[b]	(4)	(0.0037)
3586	5/2-	3	0.11
3888	[9/2+,3/2-]	[4,1]	d
3993[a]	5/2-	3	0.84
4018	9/2+[c]	4	0.14
4069	3/2-	1	0.13 *2*
4261	1/2-	1	0.12 *1*
4416	5/2+	2	0.039
4617[g] *6*			
4767	(5/2+)	(2)	(0.021)
4788[g] *6*	[9/2+]	[4]	h
4887	9/2+	4	0.020
5314			
5378	9/2+	4	0.083

From ENSDF evaluation

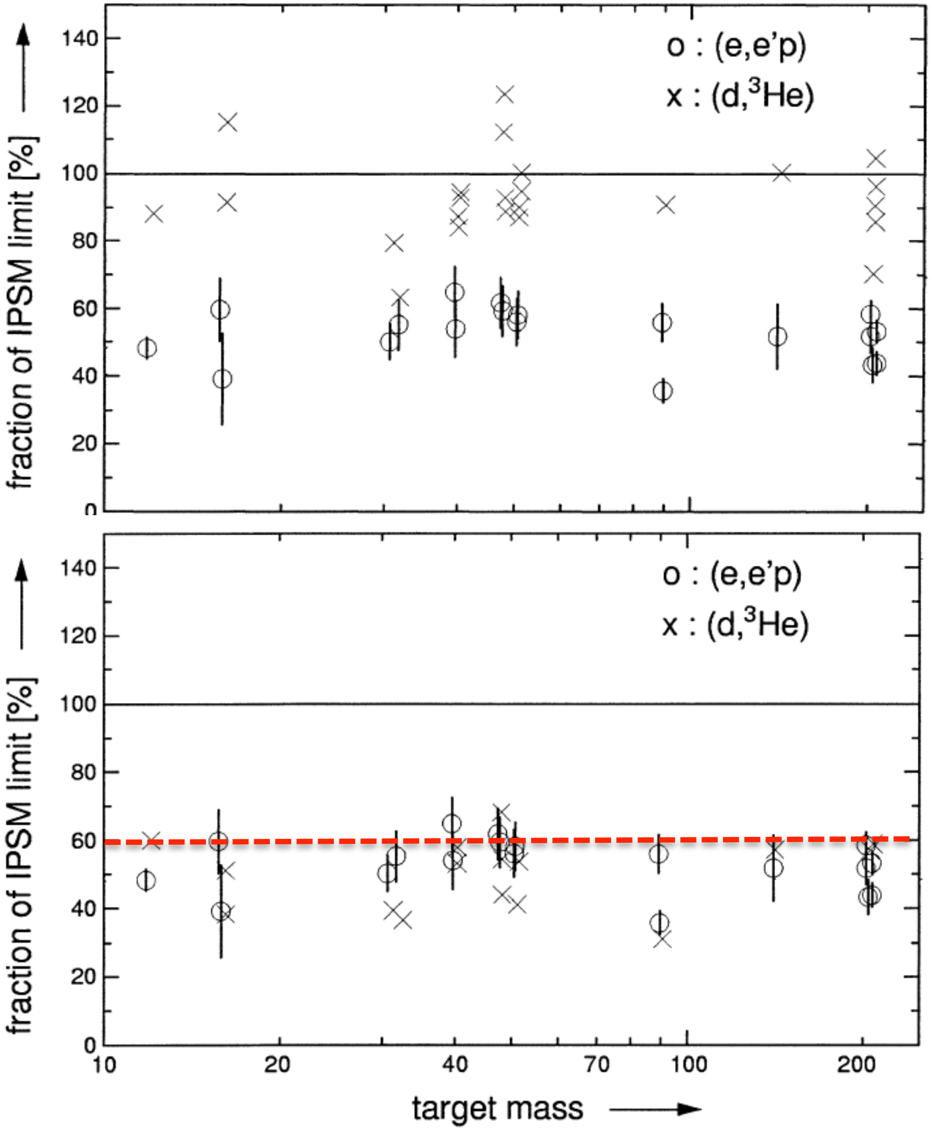


- Optical Models lead to about 20% uncertainty
- Quenching of the C^2S due to short and long range correlations in the nucleus

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

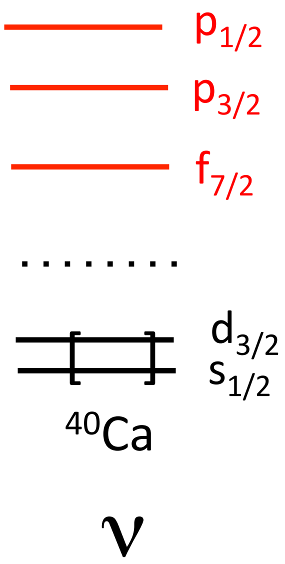
^{40}Ca(d,p)^{41}Ca

E_{level}[#]	J^{π}[@]	L[@]	$(2j+1)C^2S$
0.0	7/2-	3	6.82
1942.7 *3*	3/2-	1	2.14
2009.8 *8*	3/2+	2	0.26[a]
2462.6 *3*	3/2-	1	0.67
2574.2 *10*	5/2-	3	0.03
2606.5 *11*		(2)	(0.03)
2670.5 *11*	1/2+	0	0.03[a]
2884.2 *8*	9/2+	4	0.12
2959.8 *7*		(3)	(0.06)
3050.4 *23*			
3131?[c] *5*			
3200.4 *5*	9/2+	4	0.21

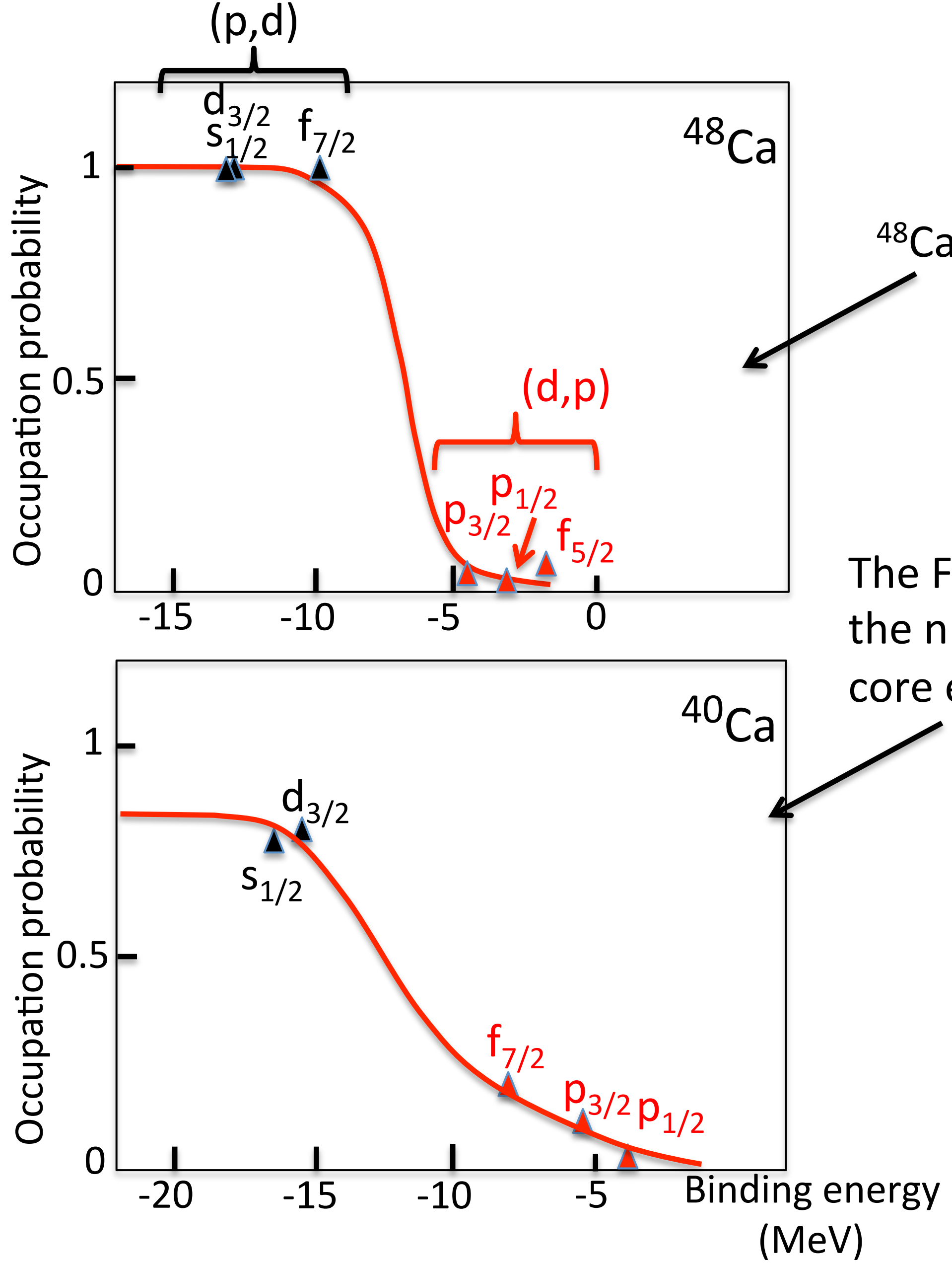
....

→ Not fully occupied !

from ENSDF evaluation



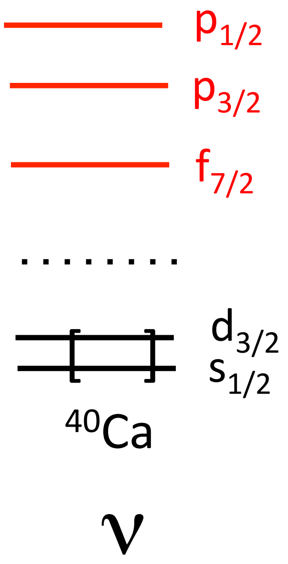
The ‘Fermi surfaces’ of ^{40,48}Ca derived from transfer reactions



^{48}Ca is a good core nucleus

The size of the N=28 gap is Significantly increased

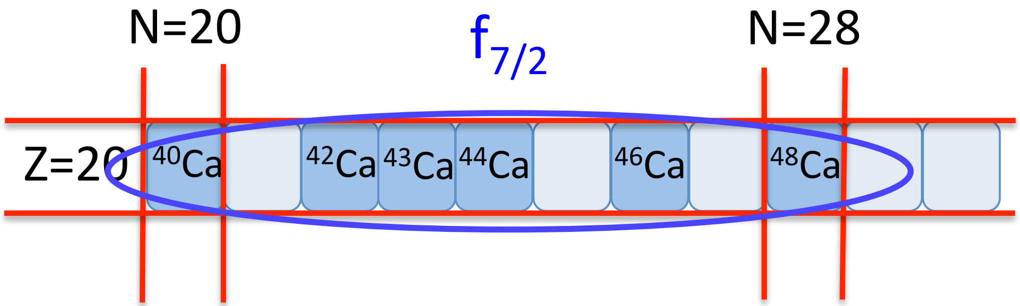
The Fermi surface of ^{40}Ca is soft, the nucleus contains significant core excitations



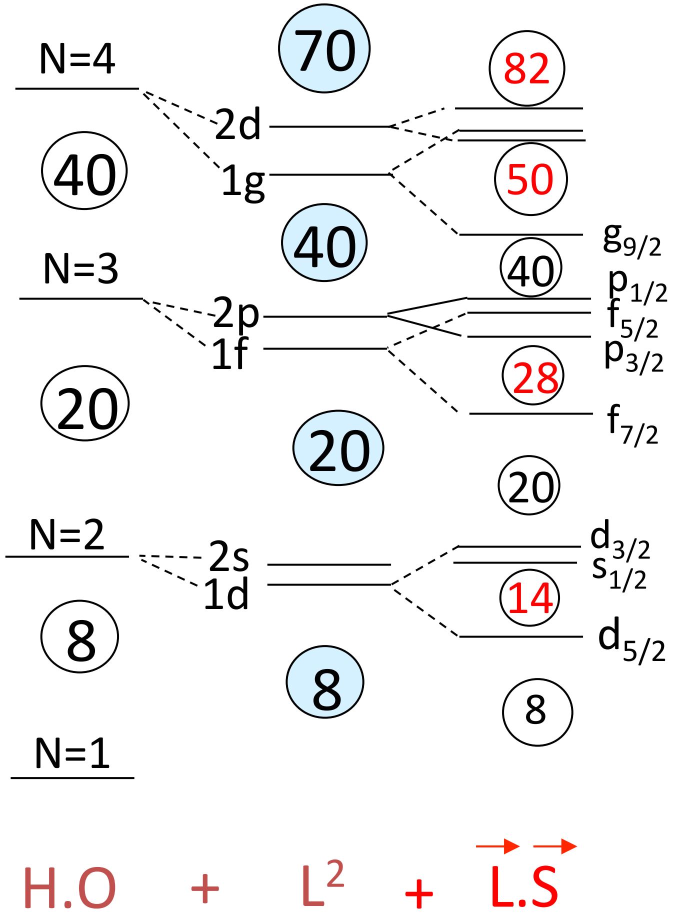
Hole strength (p,d): Martin et al. NPA 185(1972)465

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

Evolution of the N=28 gap in the Ca isotopic chain



Mean-field approach

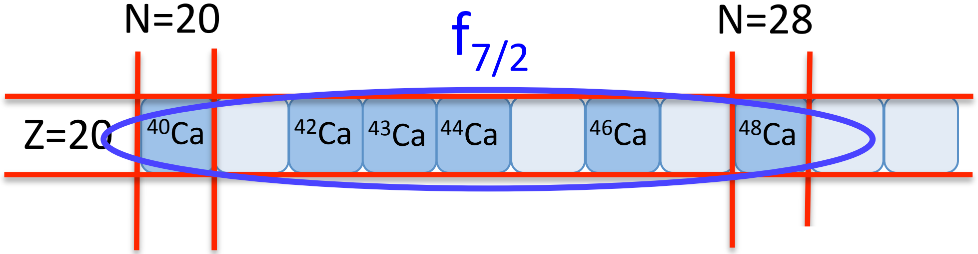


H.O + L^2 + $\vec{L}.\vec{S}$

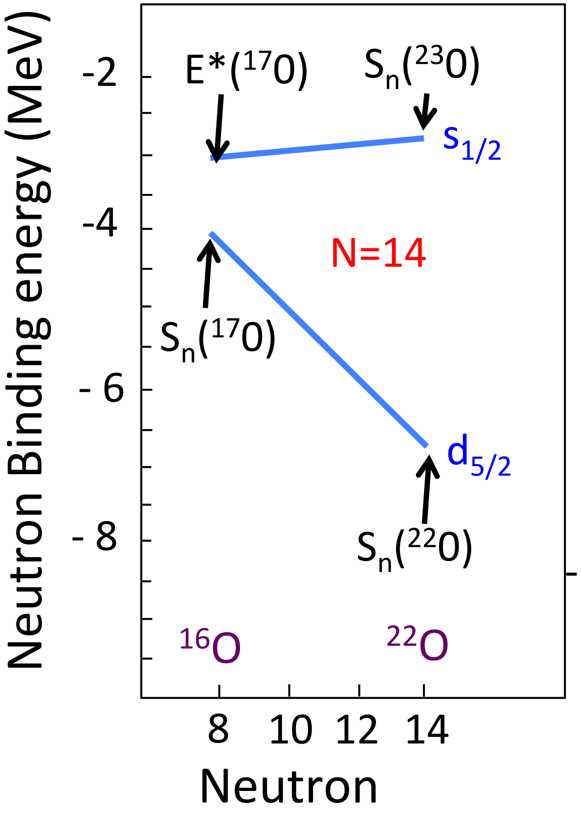
The N=28 comes from the one-body SO interaction

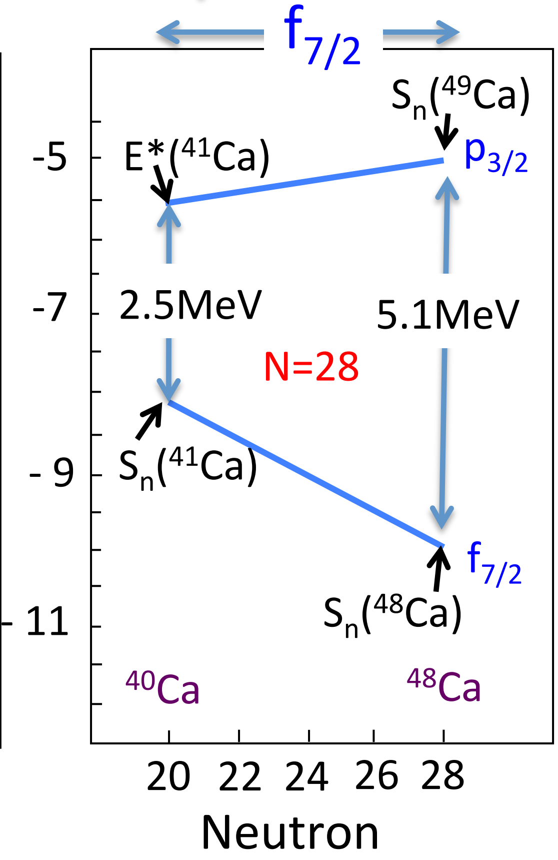
-> which forces are hidden behind this simplified view ?

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

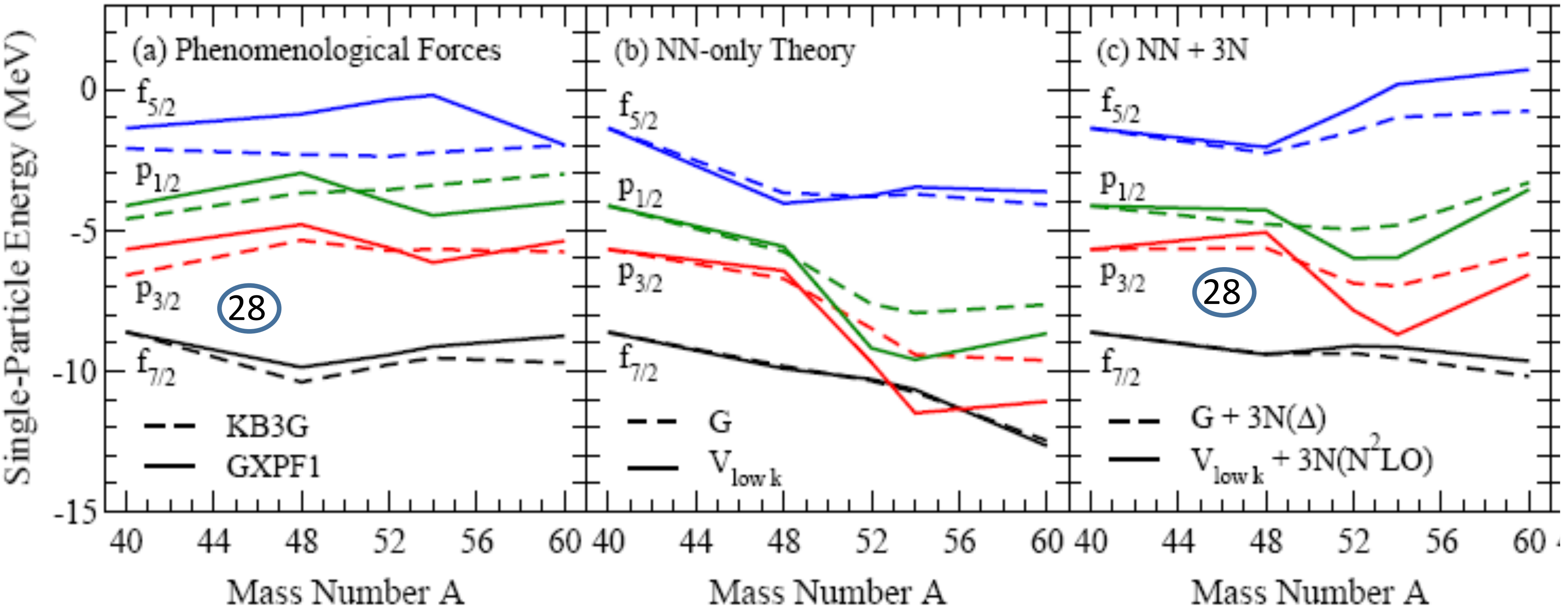
$$\delta\varepsilon(1f_{7/2}) \approx 7V^{nn}1f_{7/2}1f_{7/2}$$

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

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

The role of three body forces to create SO shell gaps

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



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

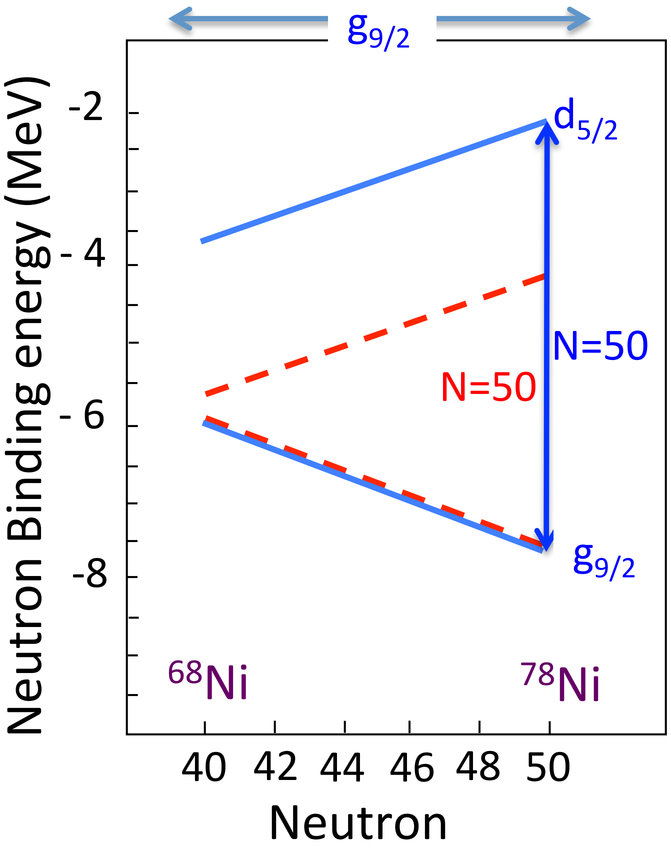
> Need three body forces

> Same holds true for the N=14 gap

> What about N=50 ?

Is the N=50 increasing by the same mechanism ?

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



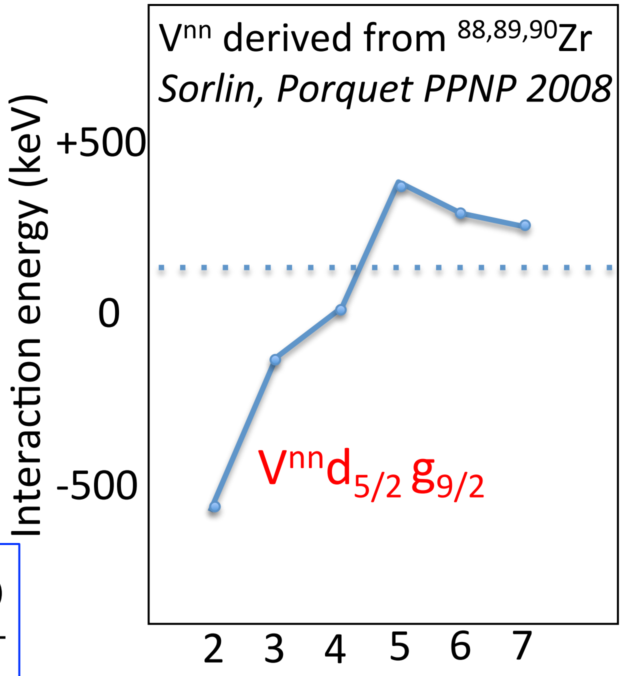
Monopole

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

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

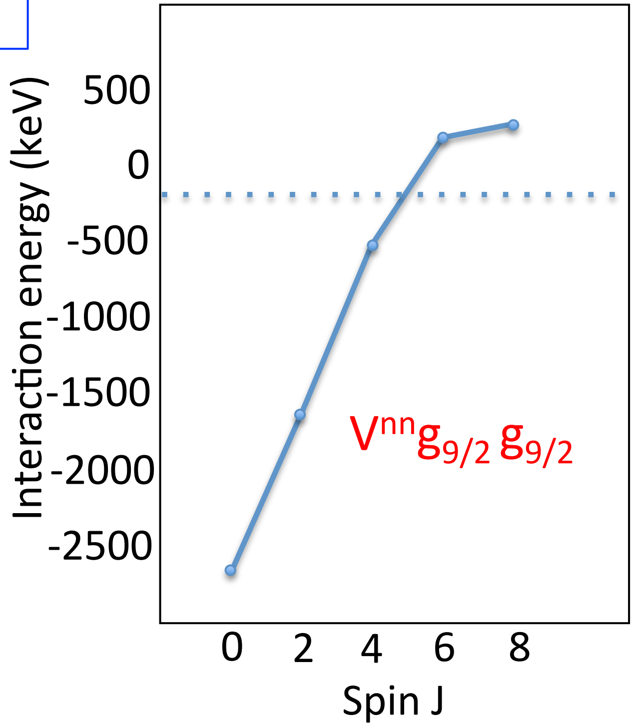
$$\delta\varepsilon(1d_{5/2}) \approx 10V^{nn}1g_{9/2}2d_{5/2}$$

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



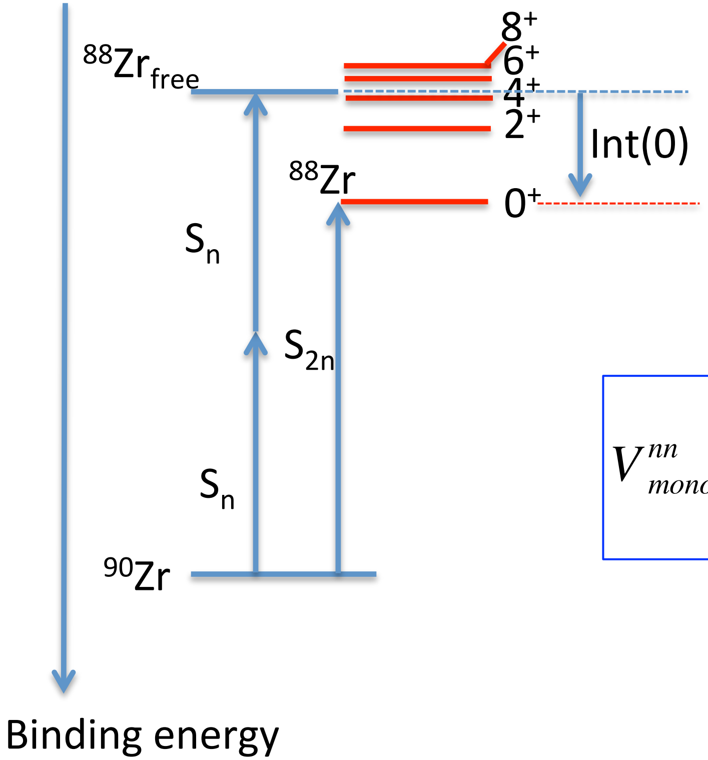
V^{nn} derived from ^{88,89,90}Zr

Sorlin, Porquet PPNP 2008

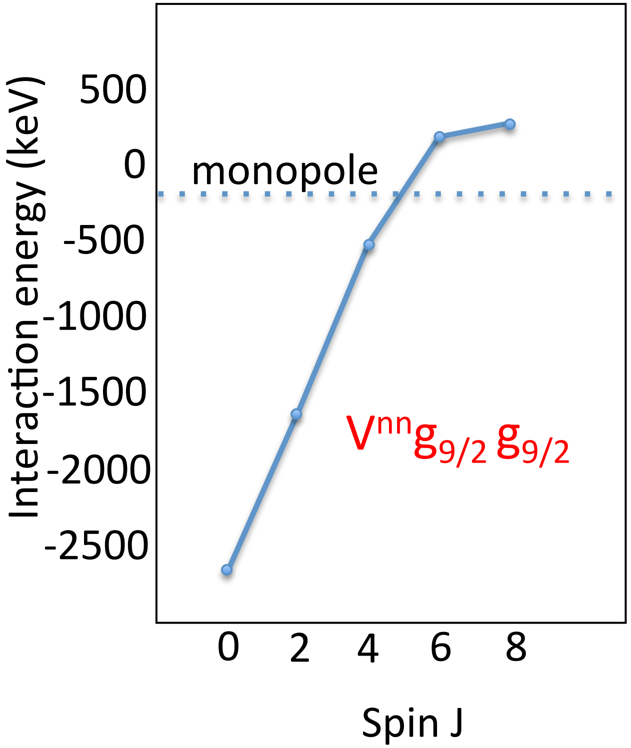


The same trend seems present in the Ni isotopic chain !

The size of the gap at N=40 constraints the one at N=50.



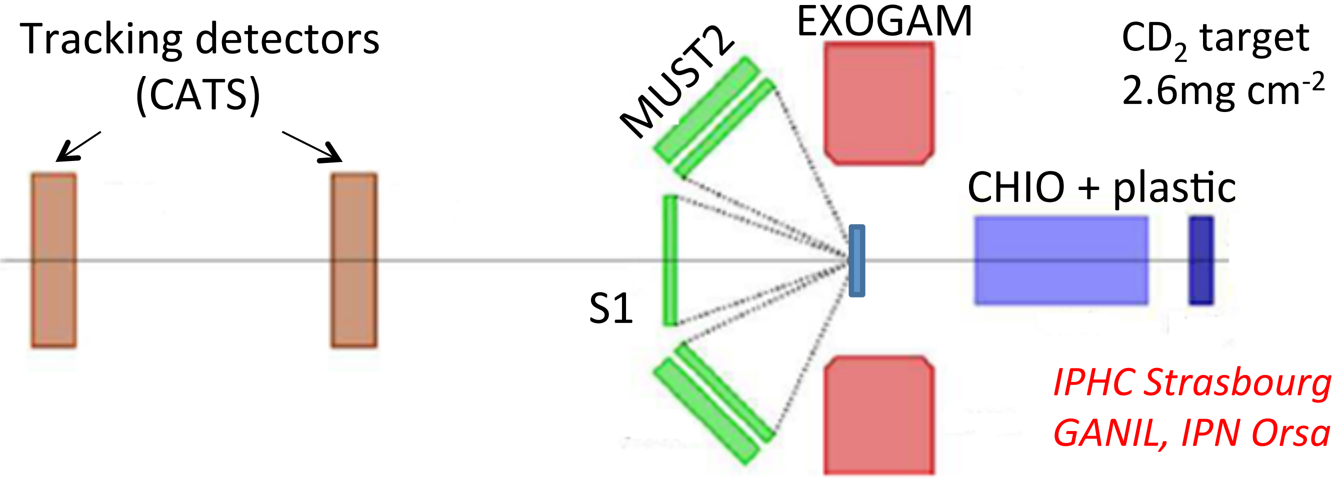
$$V^{nn}_{monopole} \approx \frac{\sum (2J+1)\,\mathrm{int}(J)}{\sum (2J+1)}$$



Monopole Very powerfull to predict structural evolution …

Too much monopole can get you dizzy !

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



^{68}Ni
10^5pps
20A.MeV
GANIL

Tracking detectors
(CATS)

MUST2

EXOGAM

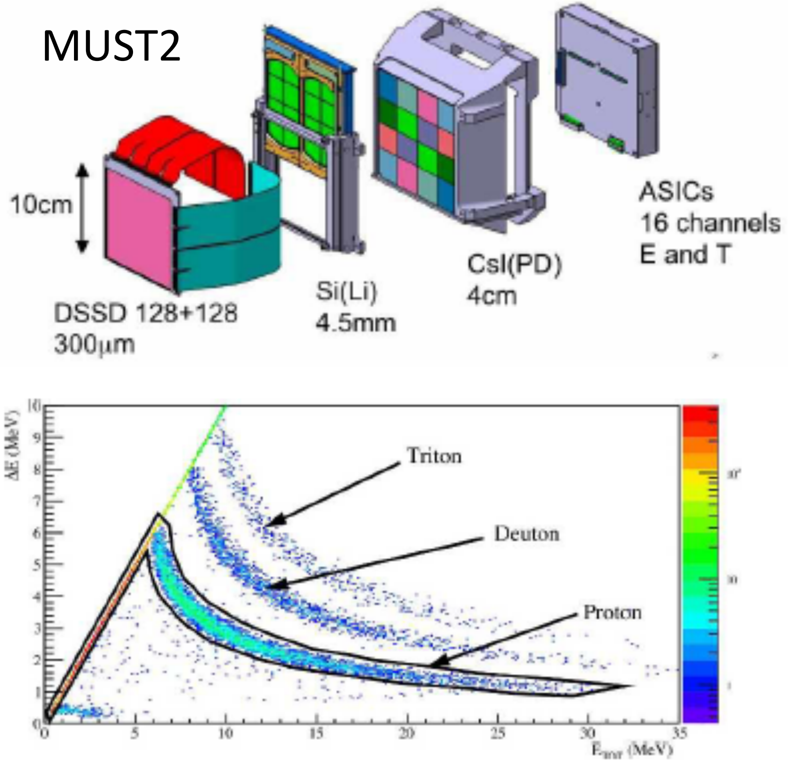
S1

CD_2 target
2.6mg cm^{-2}

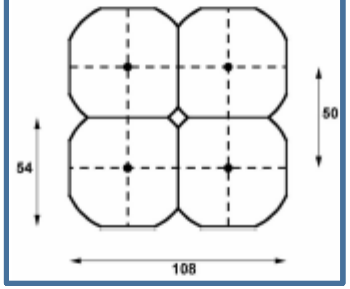
CHIO + plastic

IPHC Strasbourg
GANIL, IPN Orsay, CEA Saclay

MUST2

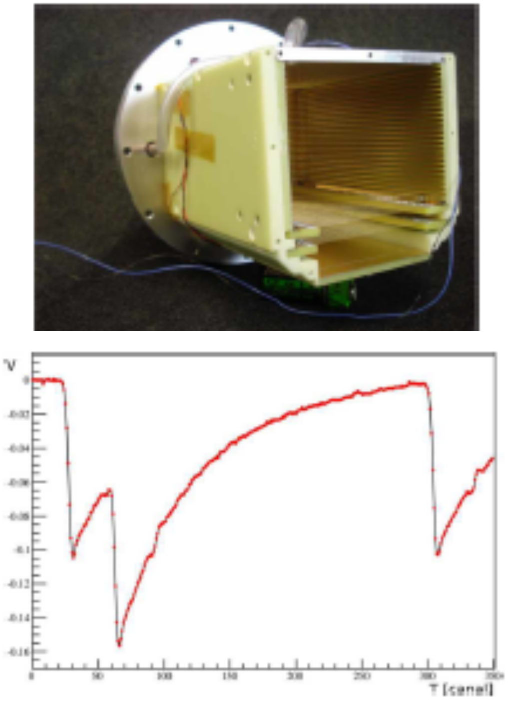


EXOGAM

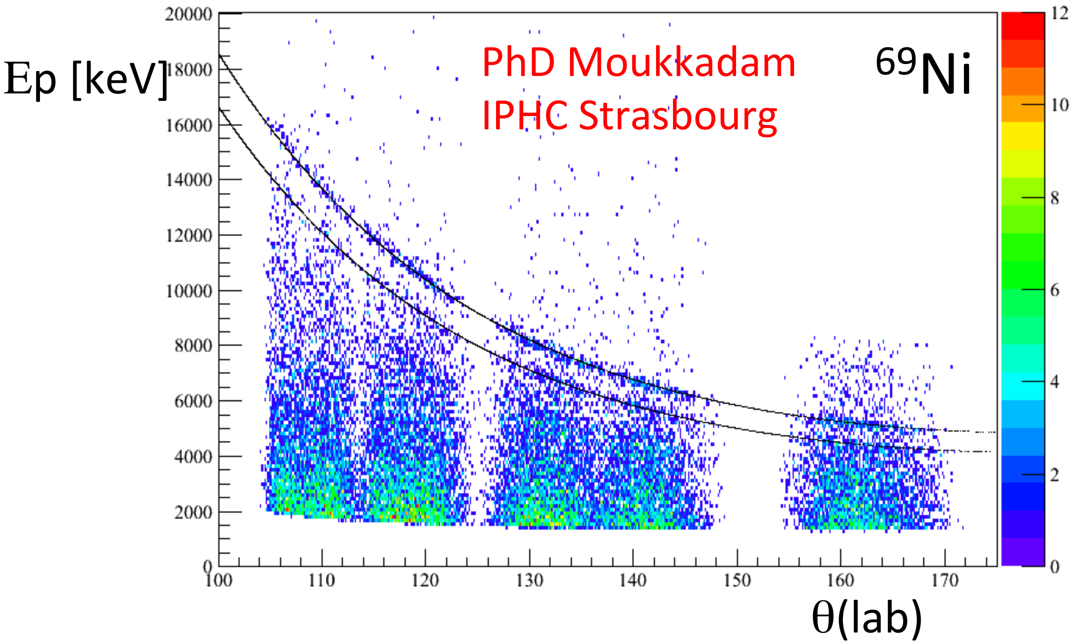


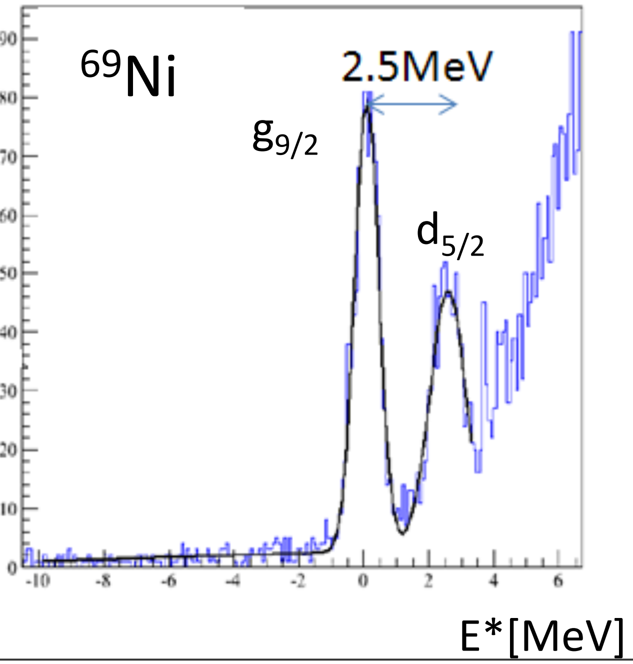
Annular detector (S1)

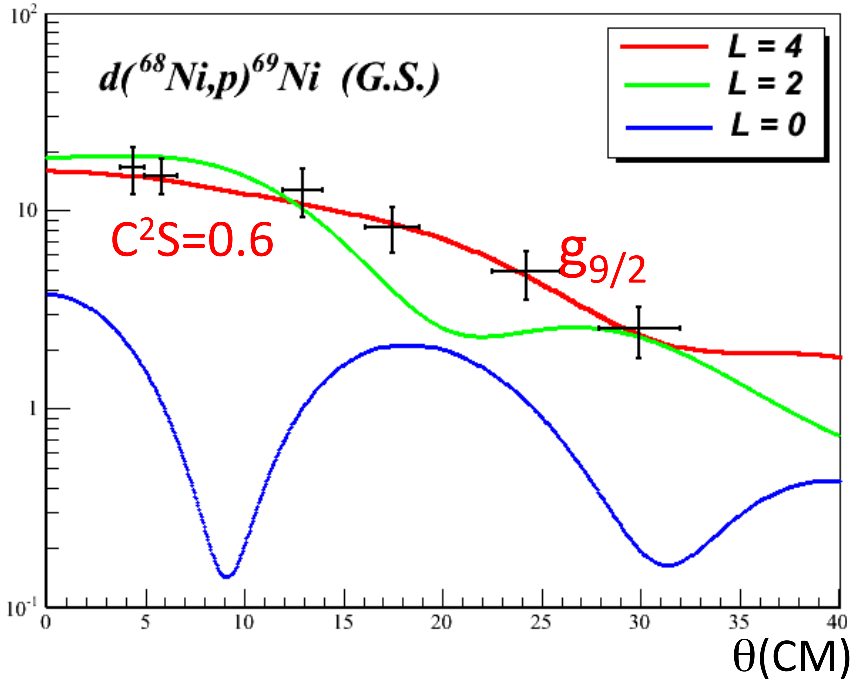
Ionization chamber (CHIO)

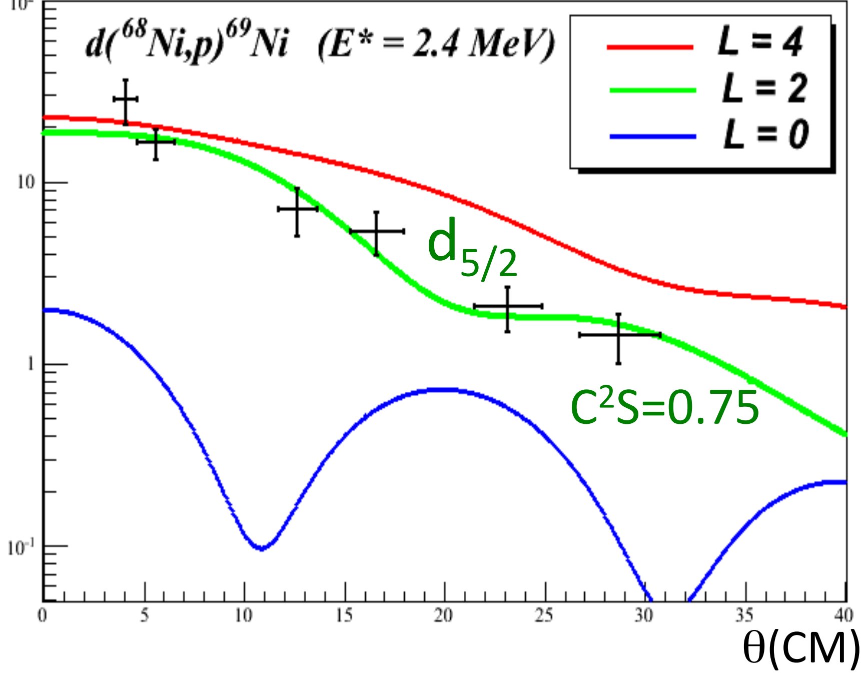


RESULTS FOR $^{68}Ni(d,p)^{69}Ni$

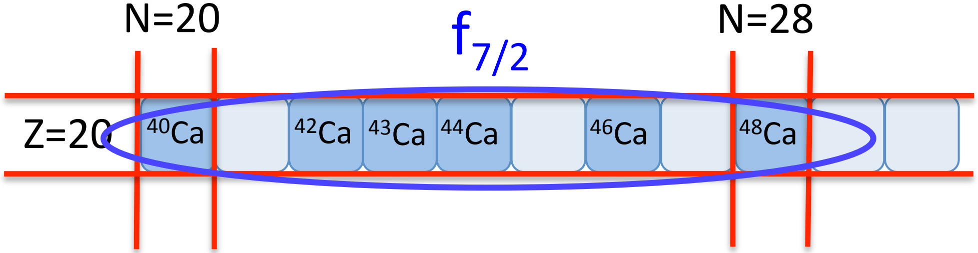

PhD Moukkadam
IPHC Strasbourg





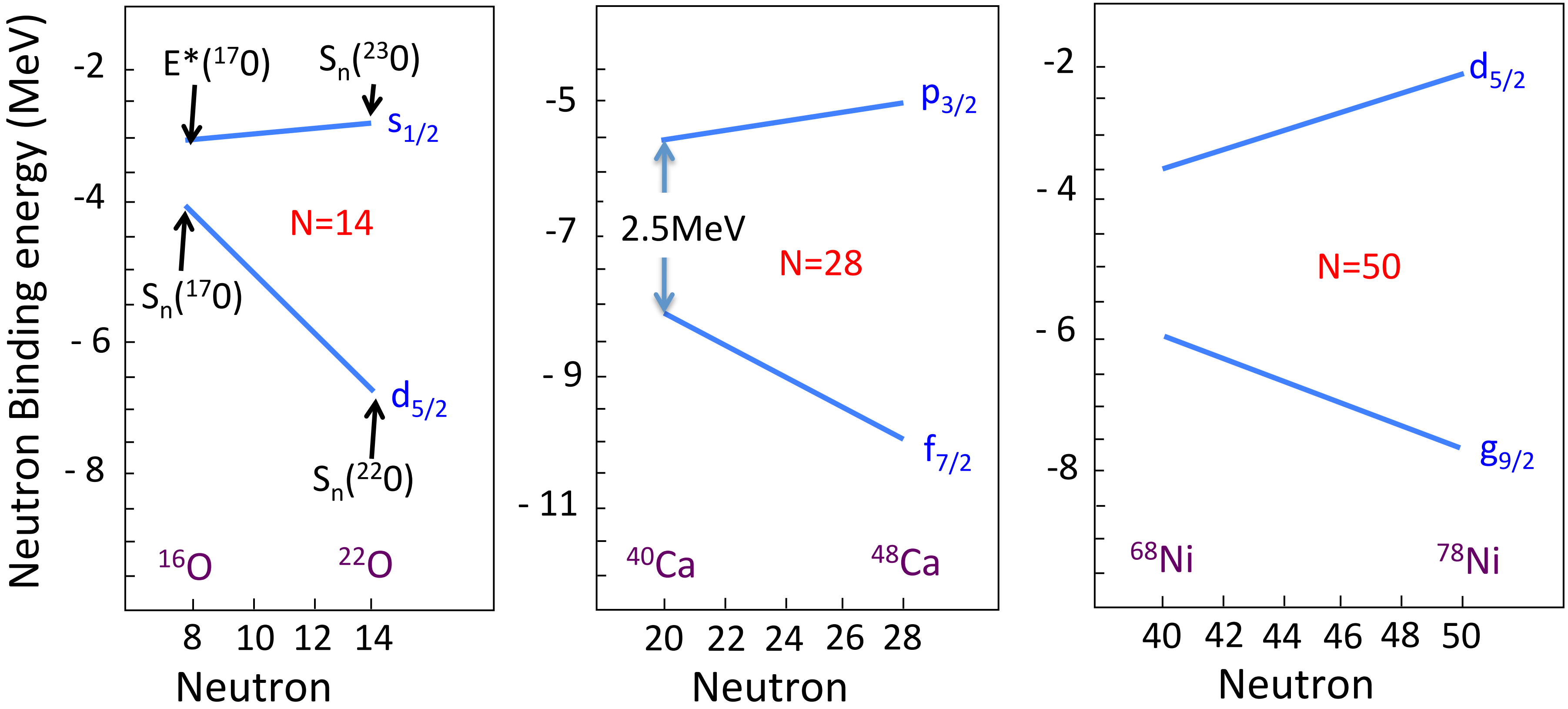


The role of three body n-n forces to create SO shell gaps



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

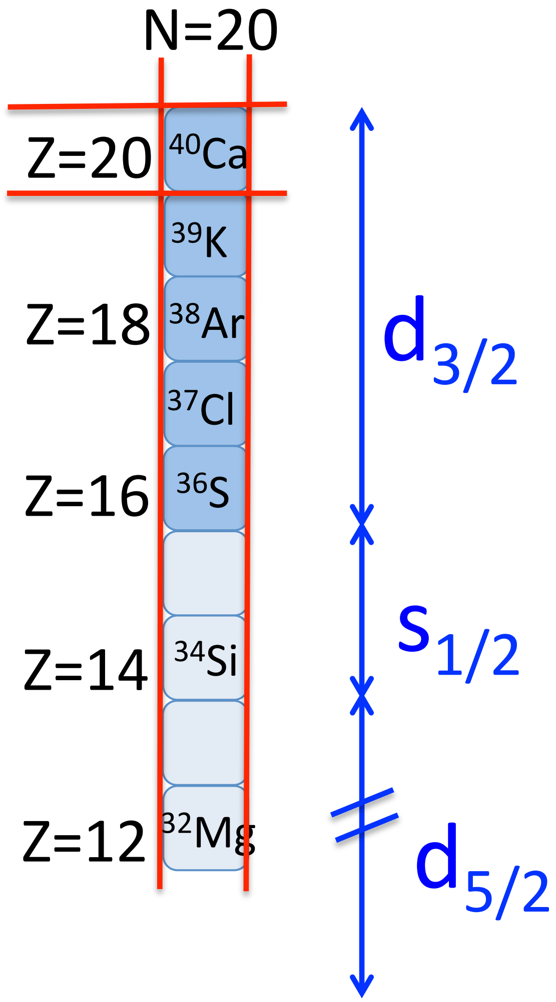


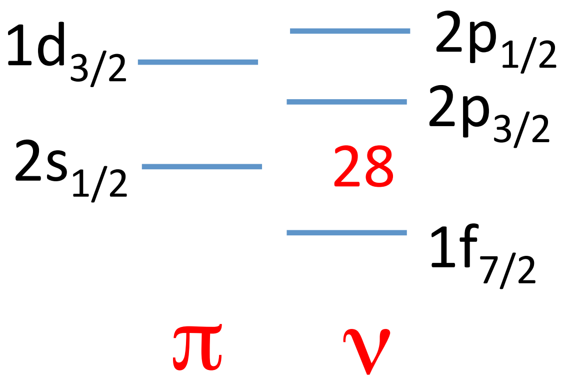
Increase of ALL SO shell gaps from n-n interactions by about 2.7 MeV !!!

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

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

Studying proton-neutron forces in the N=20 isotopic chain



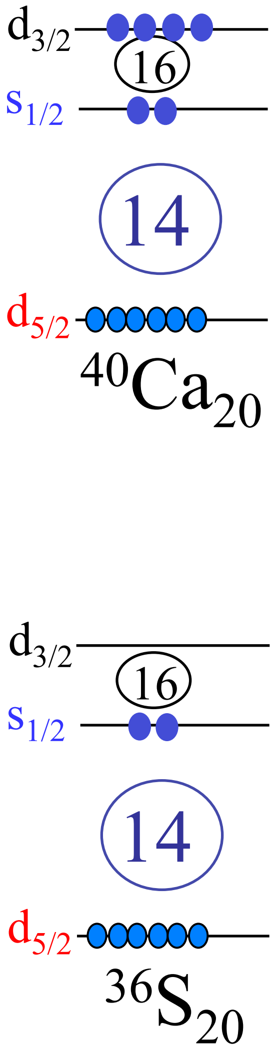


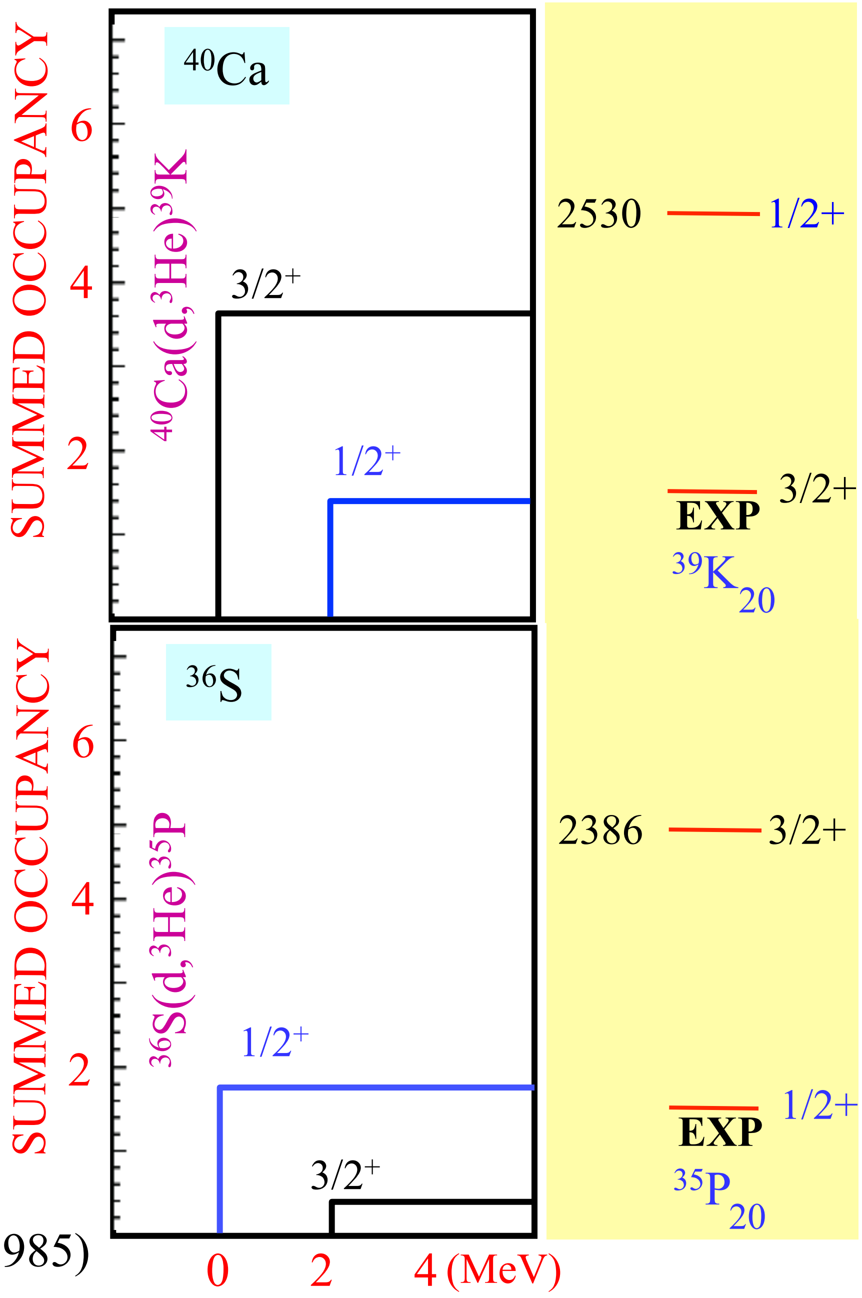
Which components of the 2 body proton-neutron interactions act on the N=28 shell gap ?

Which shell evolution for N=28 and p3-p1 SO splitting ?

Occupancies of proton orbits in ^{40}Ca and ^{36}S

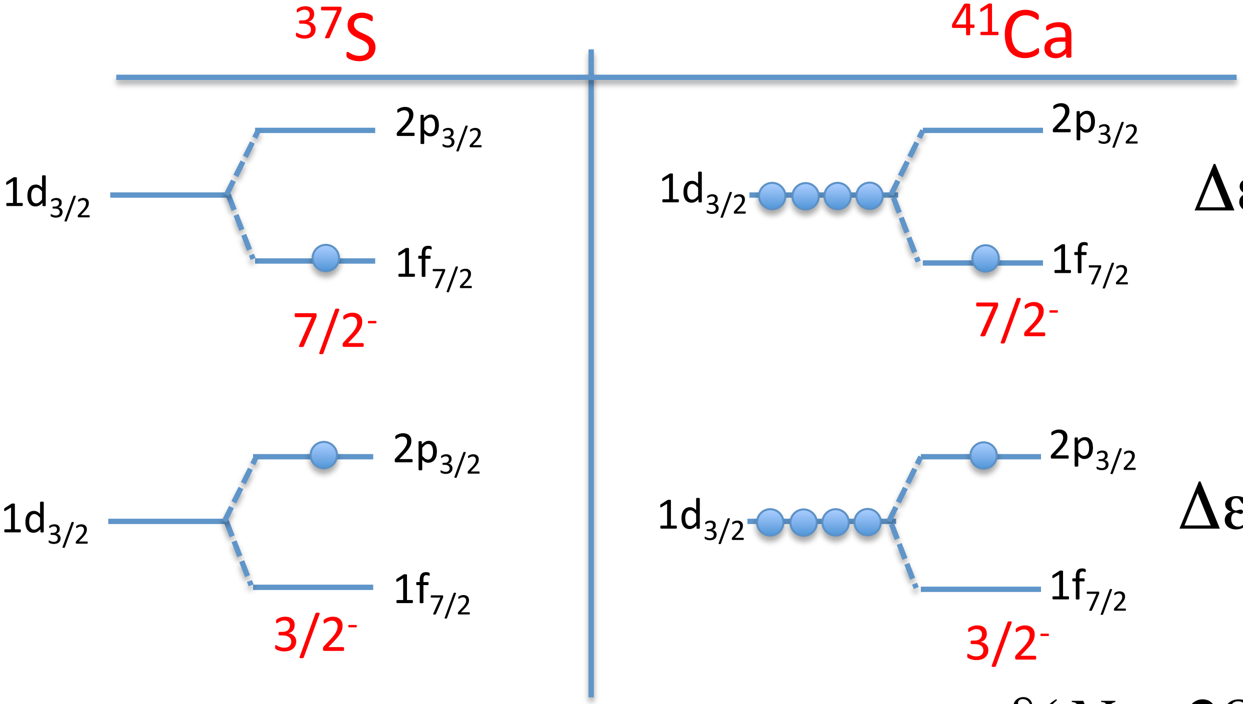
About 4 protons are removed from the $d_{3/2}$ orbit





Khan et al. PLB 156 (1985)

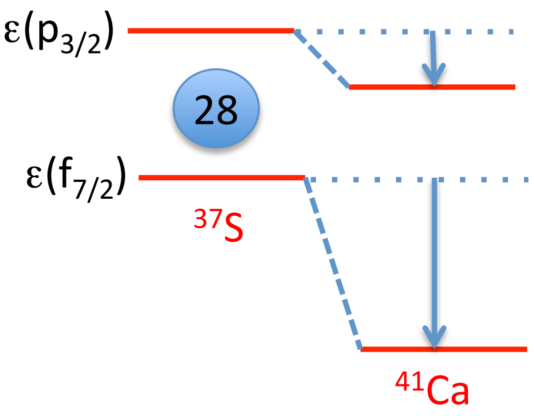
Evolution of the N=28 due to proton-neutron forces



$$\Delta\varepsilon(\frac{f7}{2}) \approx 4\,V_{1d_{\frac{3}{2}}\,1f_{\frac{7}{2}}}^{pn}$$

$$\Delta\varepsilon(p\,\frac{3}{2}) \approx 4\,V_{1d_{\frac{3}{2}}\,2p_{\frac{3}{2}}}^{pn}$$

$$\delta(N=28)=\Delta\varepsilon(p_{3/2})-\Delta\varepsilon(f_{7/2})$$



$$4\,V_{1d_{\frac{3}{2}}\,2p_{\frac{3}{2}}}^{pn}$$

Number of nodes differ -> weak central
Attractive tensor
Lp=2 sp ↓ Ln=1 sn↑ spin anti-aligned

$$4\,V_{1d_{\frac{3}{2}}\,1f_{\frac{7}{2}}}^{pn}$$

Large attractive central (same n value)
Attractive tensor
Lp=2 sp ↓ Ln=3 sn↑ spin anti-aligned

Otsuka et al 2010 Phys. Rev. Lett. 104 012501
Smirnova et al 2010 Phys. Lett. B 686 109

End of Lecture I

The roles of nuclear force

$V_{nucl} = V_{monopole} + V_{correlations}$; $V_{monopole} = V_{central} + V_{tensor} + V_{SO}$

Far from stability we access unexplored parts of the nuclear force:

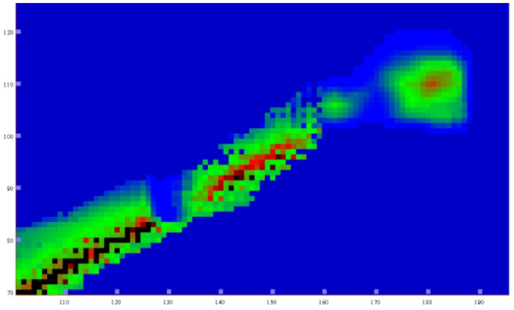
- -Nodes in wave function (radial overlap)
- -Spin orientations
- -ΔL angular momentum difference
- -Isospin dependence
- -Drip line effects

Derive in-medium from bare forces ?

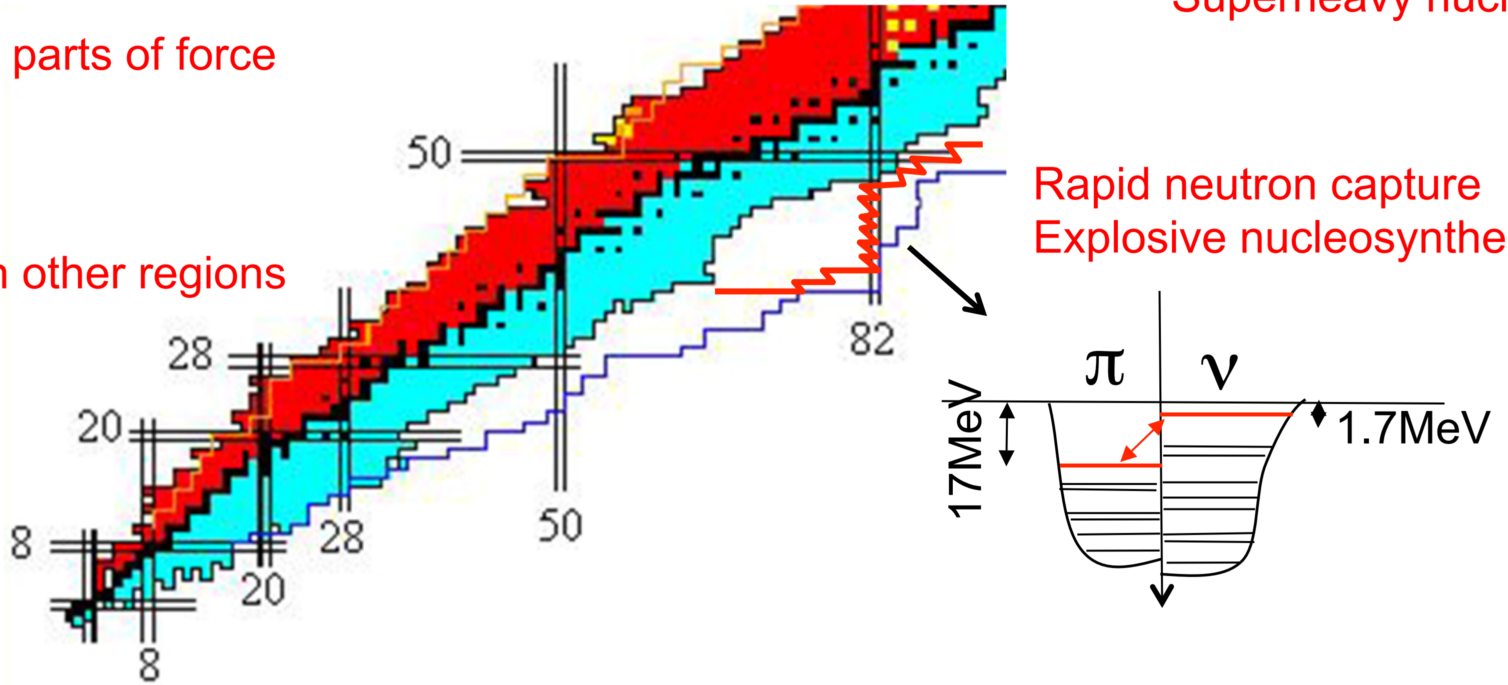
Study specific parts of force

to reach

Predictibility in other regions



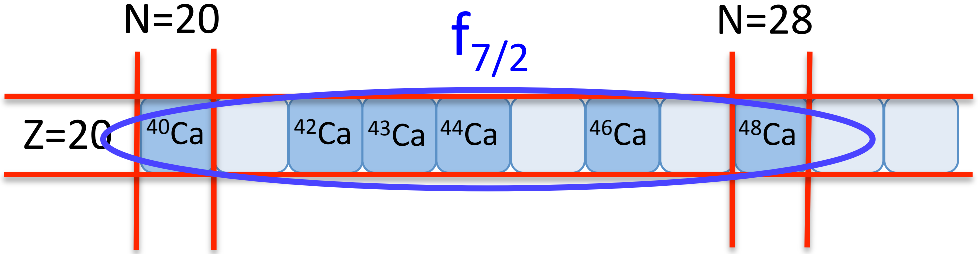
Superheavy nuclei



Rapid neutron capture
Explosive nucleosynthesis

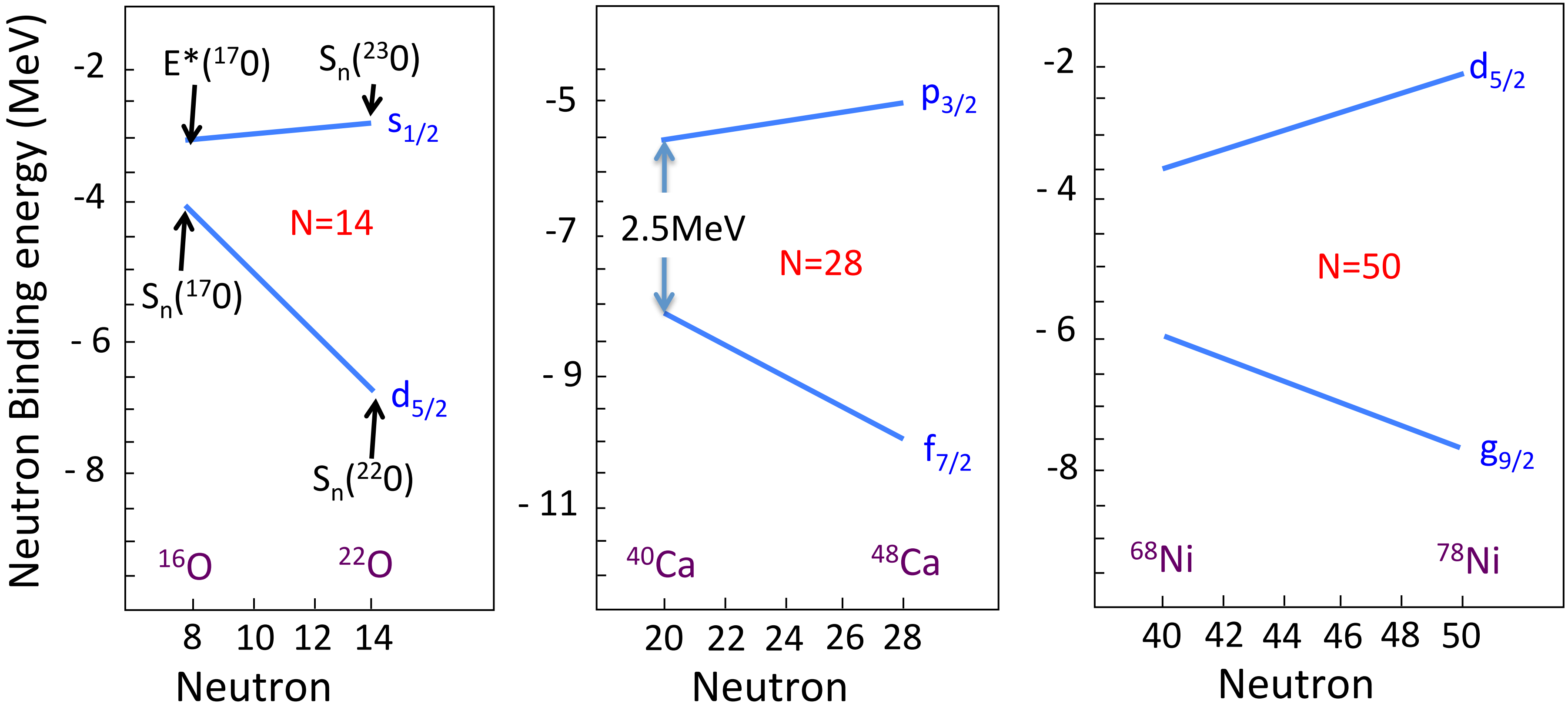
Summary of previous highlights

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

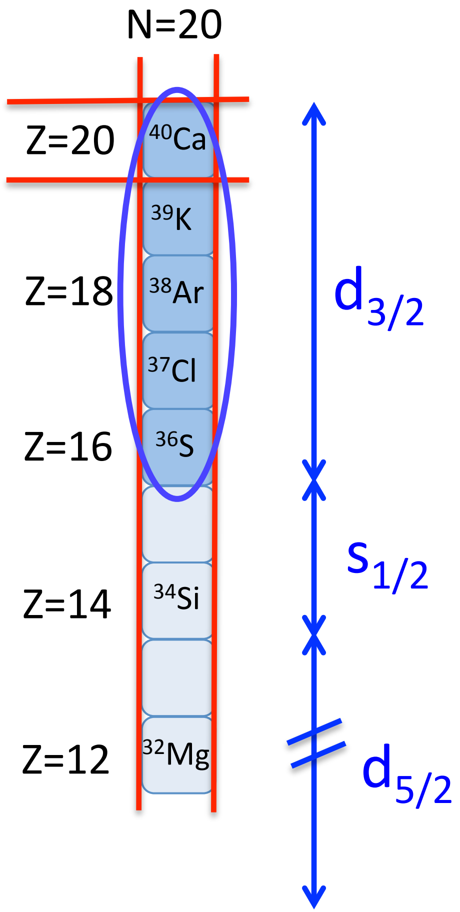


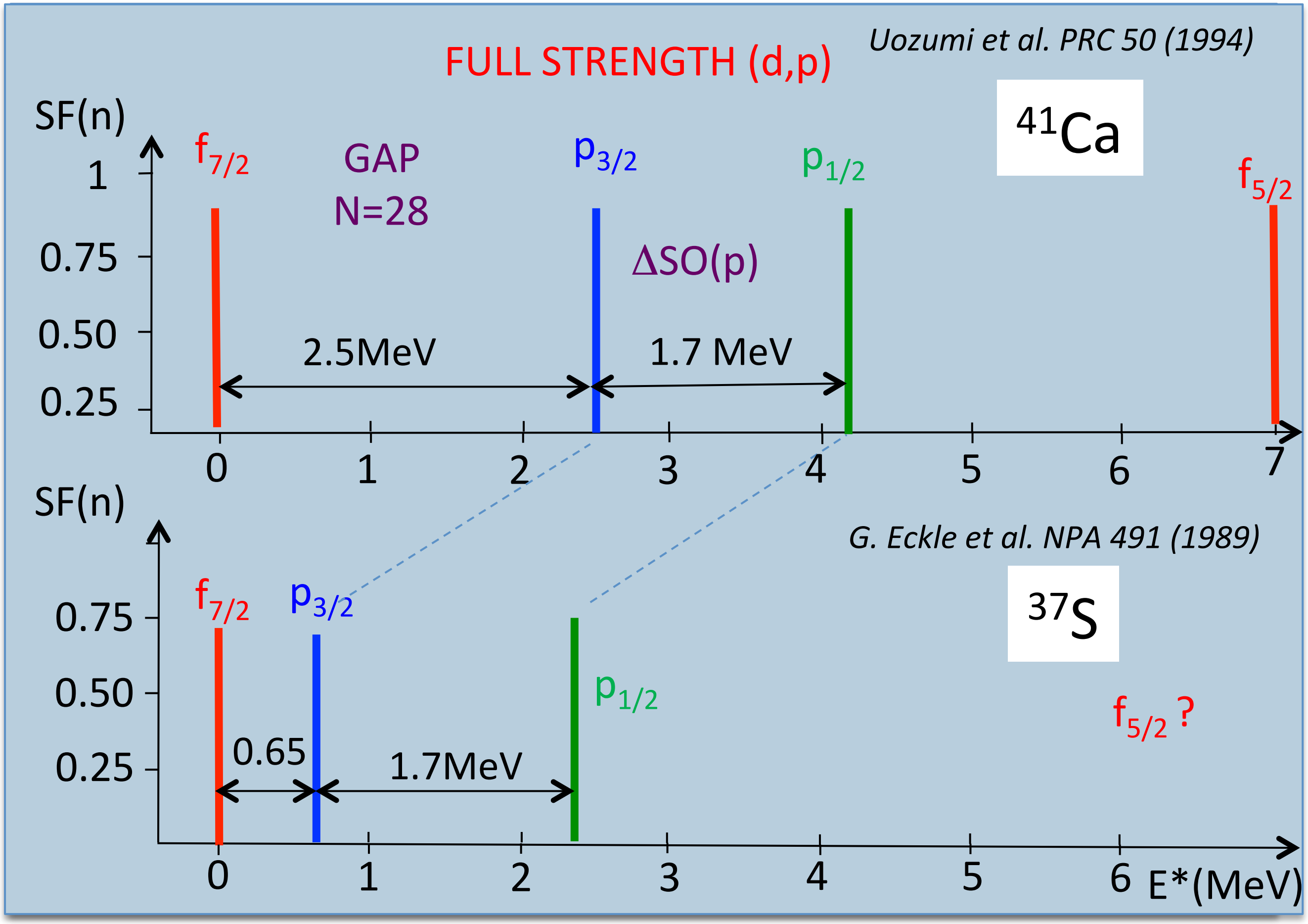
Increase of ALL SO shell gaps from n-n interactions by about 2.7 MeV !!!

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

Predictibility for other high j orbits -> h $_{11/2}$, i $_{13/2}$

Proton-neutron forces involving the $d_{3/2}$ proton orbit

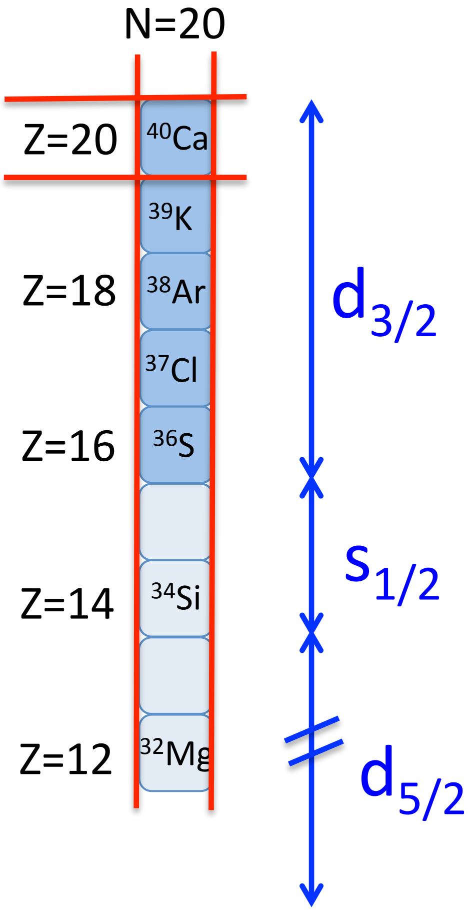


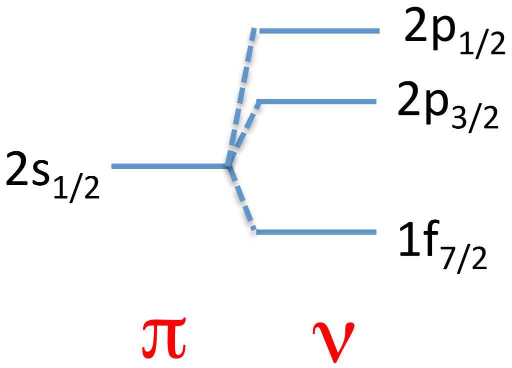


No change in p SO splitting

THE N=28 gap no longer exists in ^{37}S !!!

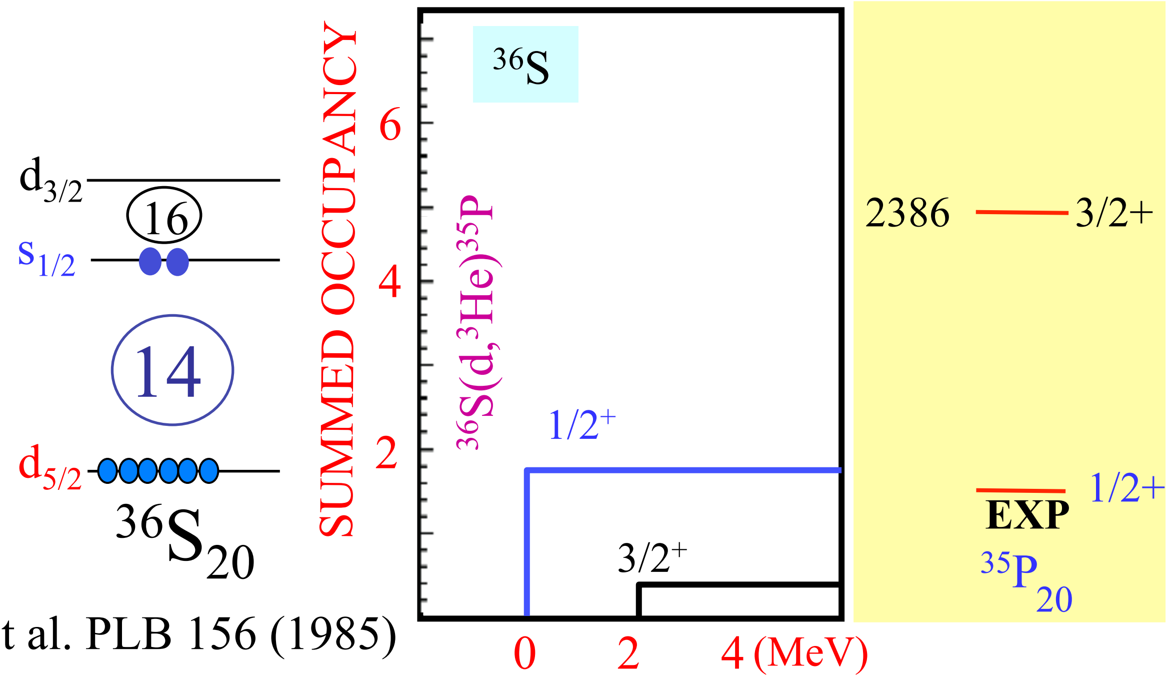
Which forces below ^{36}S ?





Lecture 2

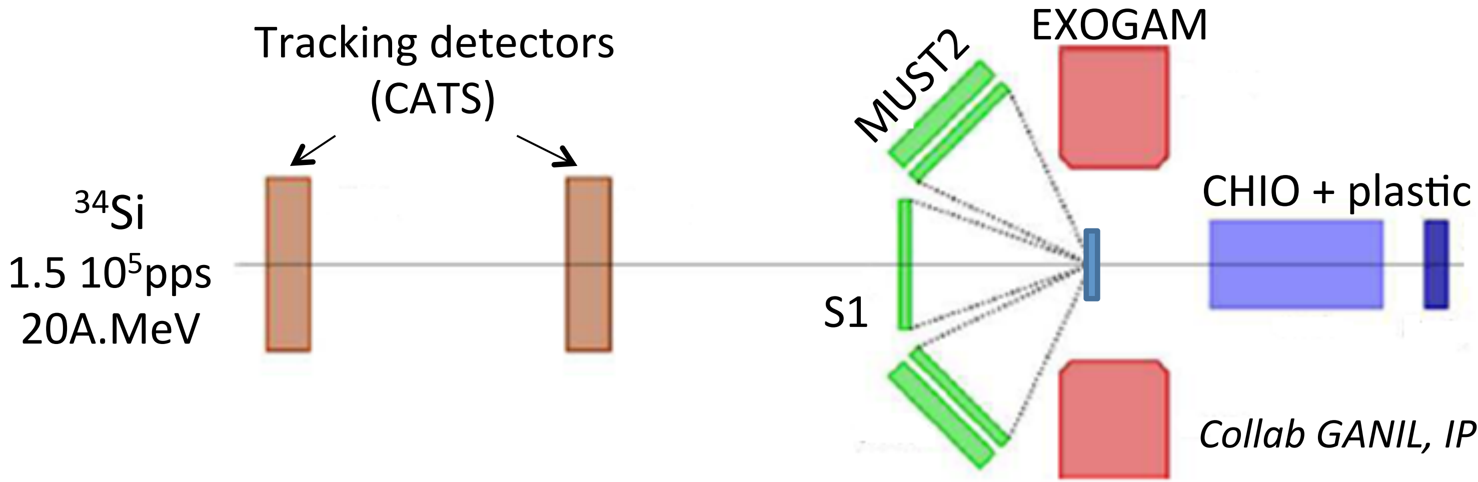
Occupancies of proton orbits ^{36}S



Khan et al. PLB 156 (1985)

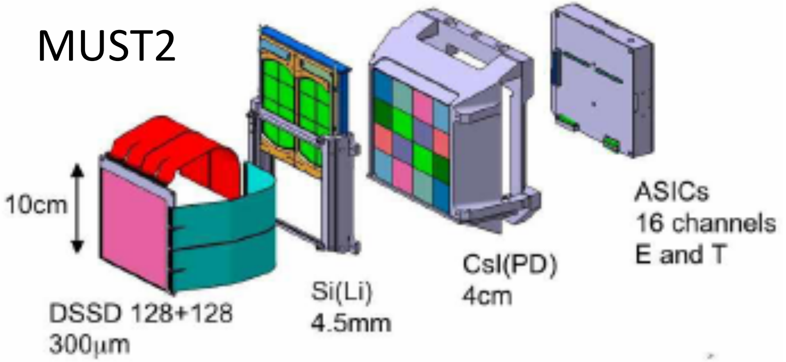
Very likely that the $s_{1/2}$ orbit is empty in ^{34}Si.
Should be proved -> PHD A. Mutschler (IPN/GANIL)

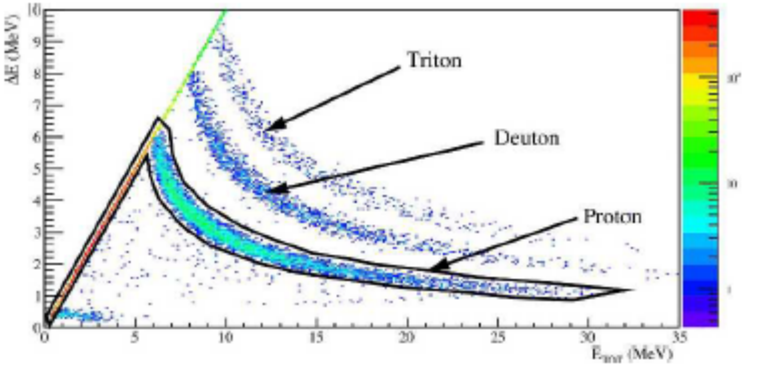
EXPERIMENTAL SETUP



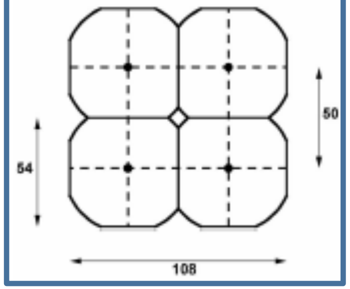
Collab GANIL, IPN Orsay, CEA Saclay

MUST2



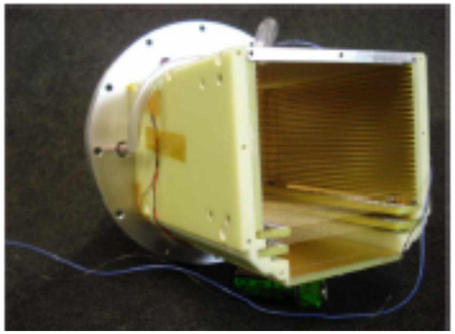


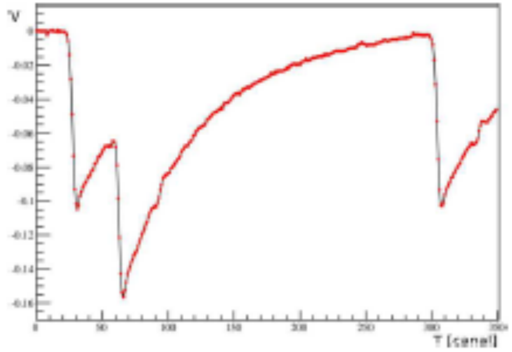
EXOGAM



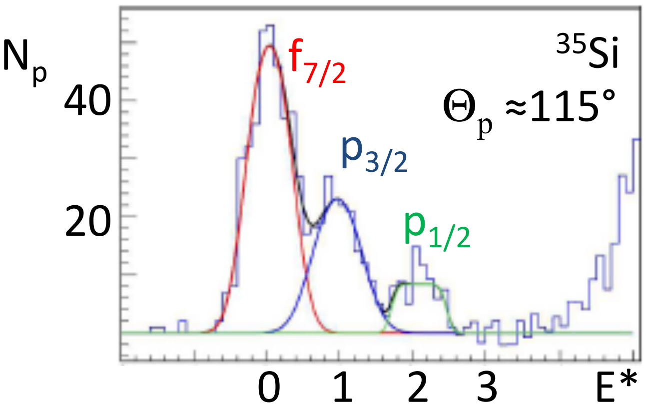
Annular detector (S1)

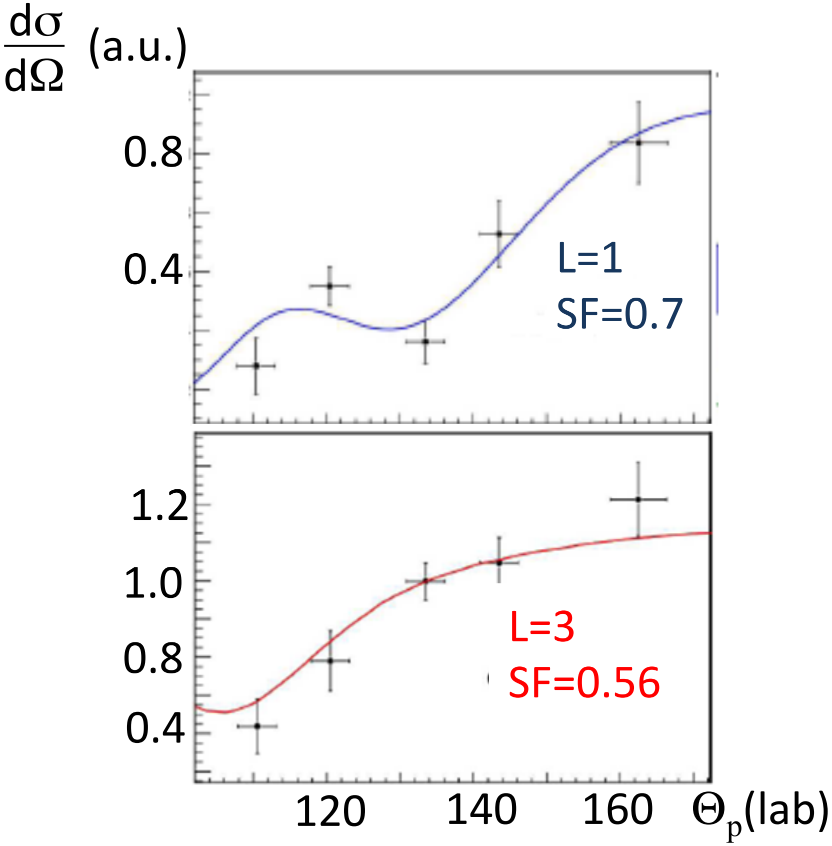
Ionization chamber (CHIO)

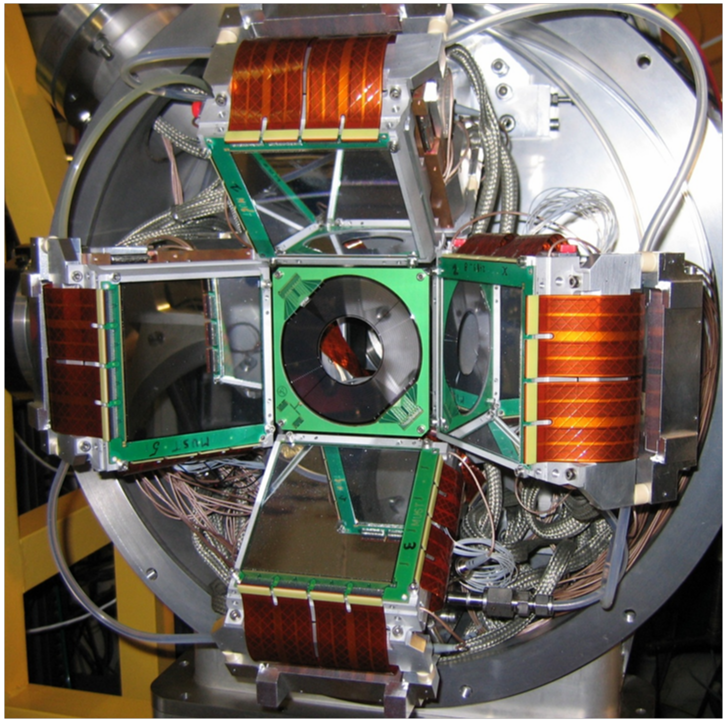




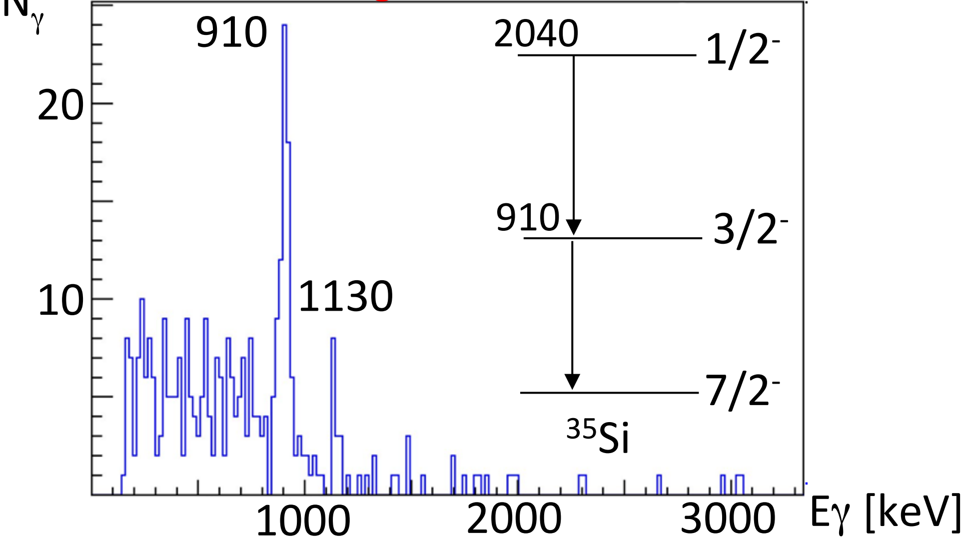
EXPERIMENTAL RESULTS $^{34}Si(d,p)^{35}Si$



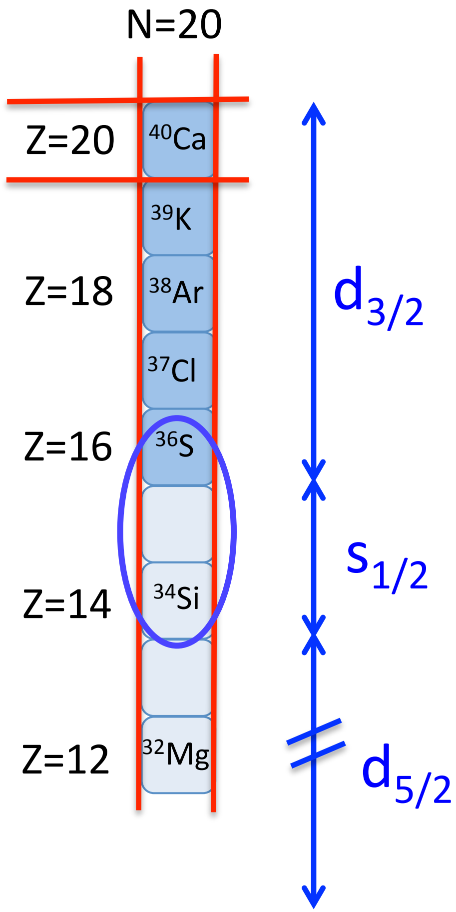


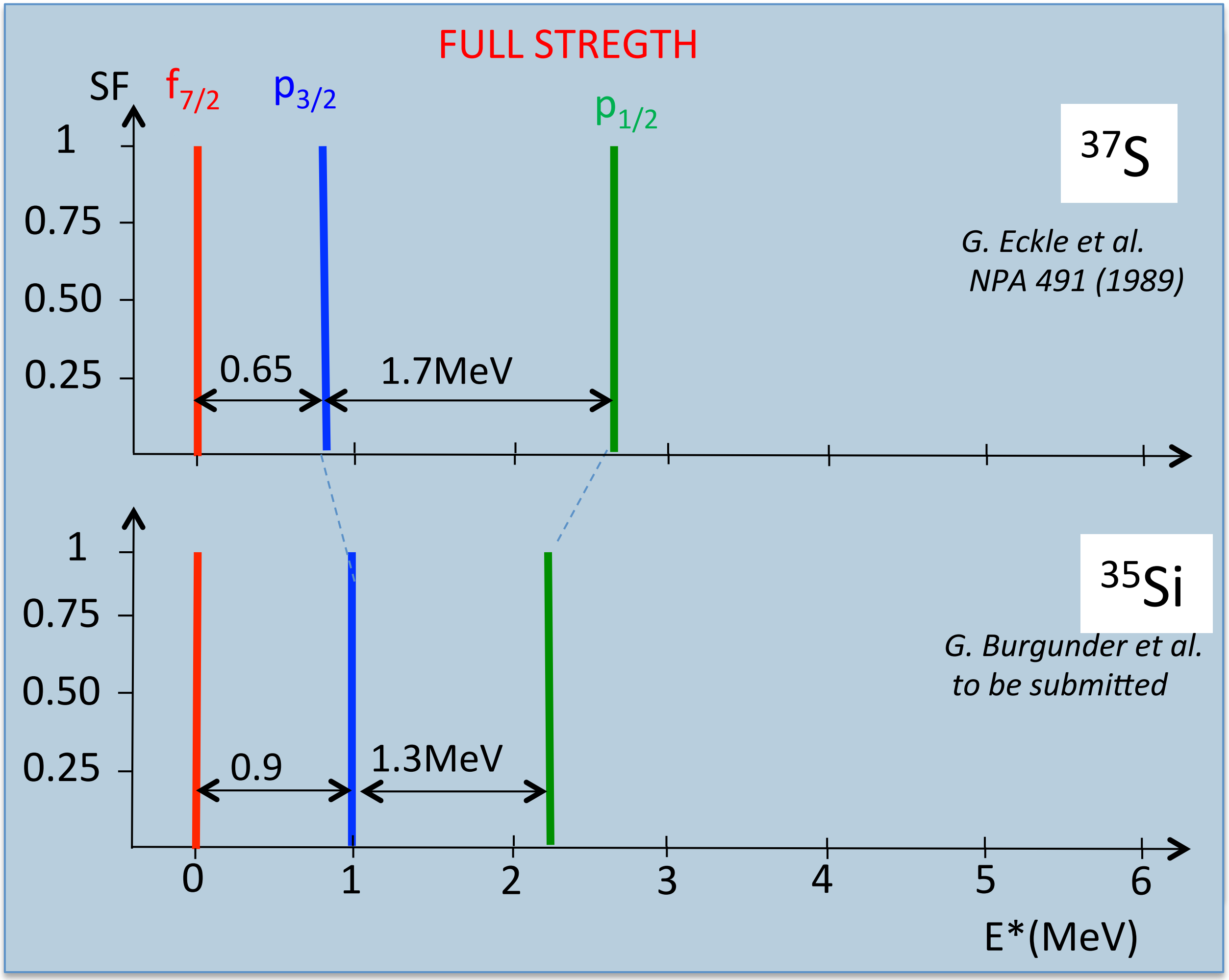


G. Burgunder PHd GANIL.



Proton-neutron forces involving the $s_{1/2}$ proton orbit





$$\delta(N=28) \approx 1.45 \left(V 2s_{\frac{1}{2}} 2p_{\frac{3}{2}}{}^{pn} - V 2s_{\frac{1}{2}} 1f_{\frac{7}{2}}{}^{pn} \right)$$

N=28 gap changed by about 300keV

$$\delta(SO\ p) \approx 1.45 \left(V 2s_{\frac{1}{2}} 2p_{\frac{1}{2}}{}^{pn} - V 2s_{\frac{1}{2}} 2p_{\frac{3}{2}}{}^{pn} \right) \approx +400keV$$

Correlations play a sizeable role here

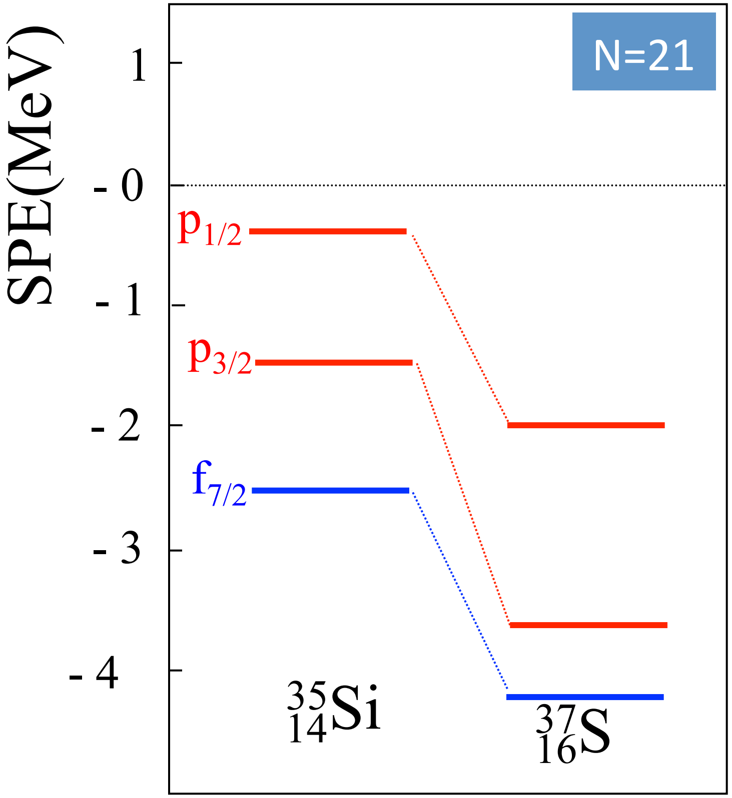
Large change in p SO splitting

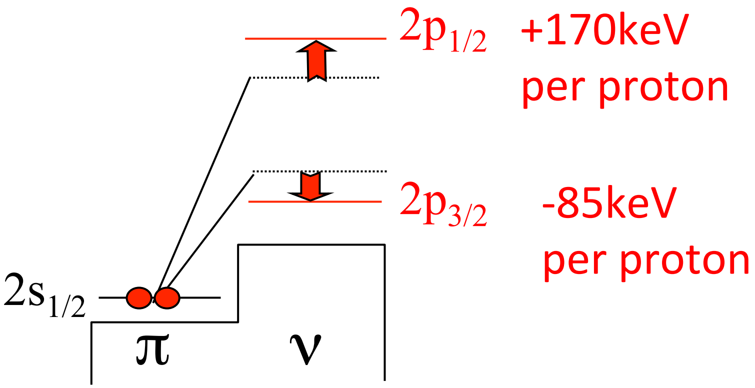
Two-body SO interaction

See Nowacki, Otsuka, Smirnova

Evolution of SPE from two-body SO interaction

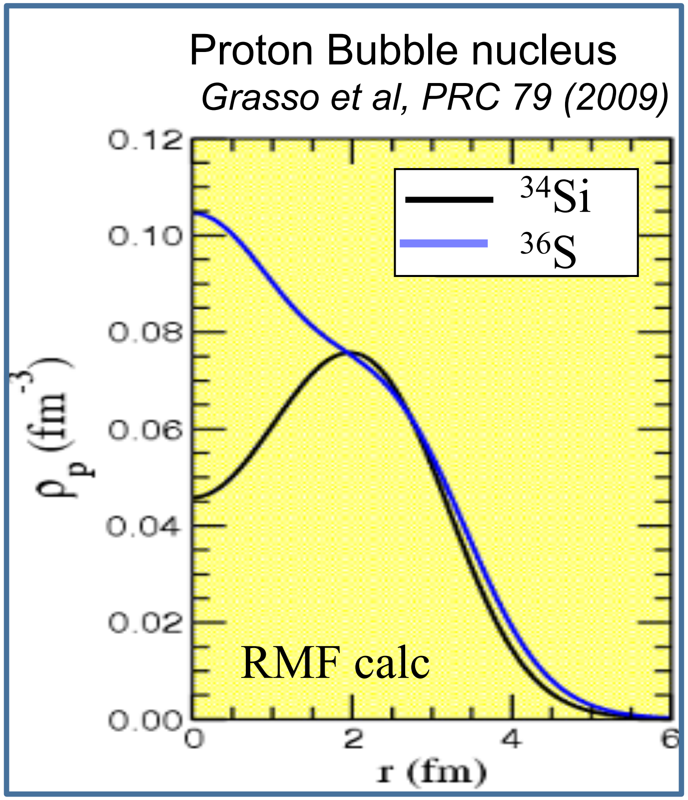
Reduction of $\nu p_{1/2}$-$p_{3/2}$ splitting between
^{37}S and ^{35}Si and after removal of ≈2 protons* from $\pi ds_{1/2}$
*1.45 according to shell model (F. Nowacki)-> to be confirmed experimentally





Increase of the SO splitting due to the two- body SO interaction

Bubble nucleus and the spin orbit interaction in mean field (MF) theories



Central proton density depletion in ^{34}Si as the $s_{1/2}$ is no longer filled

Same global picture in shell model and Mean field calculations

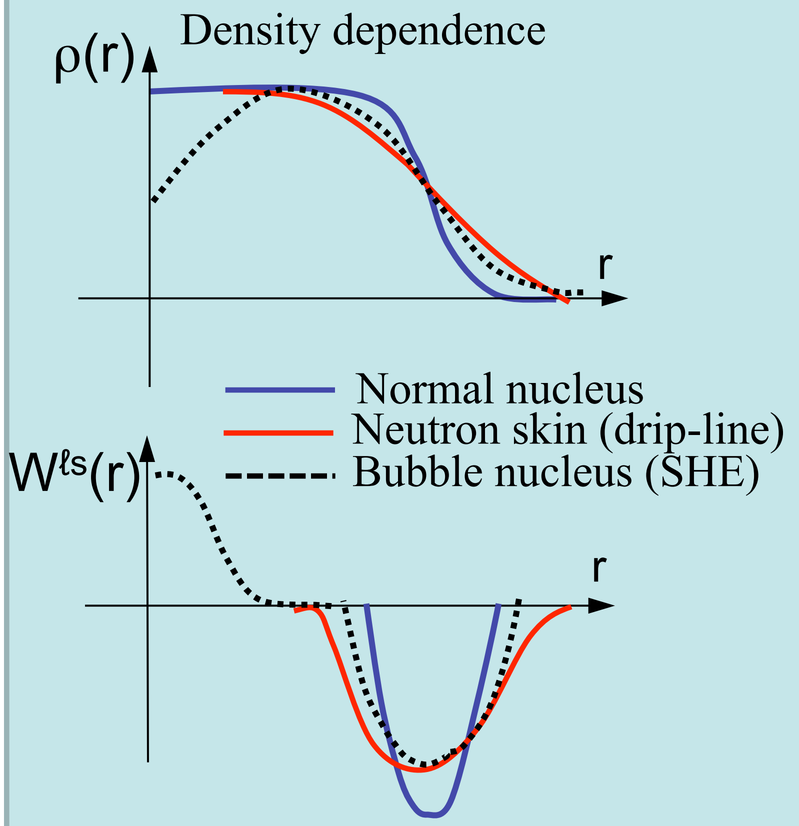
Correlations reduce the amplitude of the bubble

Spin orbit interaction depends on the Derivative of the density MF models

How can we probe its reliability ?

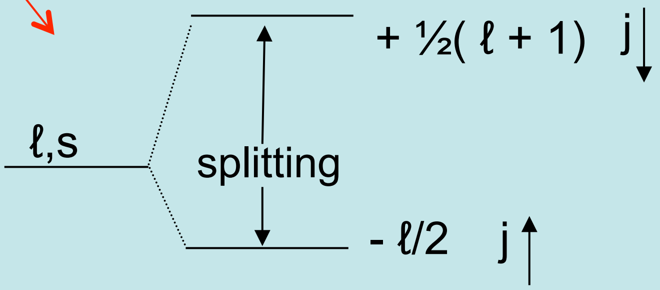
The spin orbit (SO) interaction in Mean Field models

$$W_\tau^{\ell s}(r) = -\left[W_1 \frac{\partial\rho_\tau(r)}{\partial r} + W_2 \frac{\partial \rho_{\tau'\neq\tau}(r)}{\partial r}\right]\vec{\ell}\cdot\vec{s}$$



- SO force 'revealed' in atomic nuclei as nuclei have finite size

-Its density dependence should play a role in extreme systems, not studied so far



Asymmetric splitting of j orbits

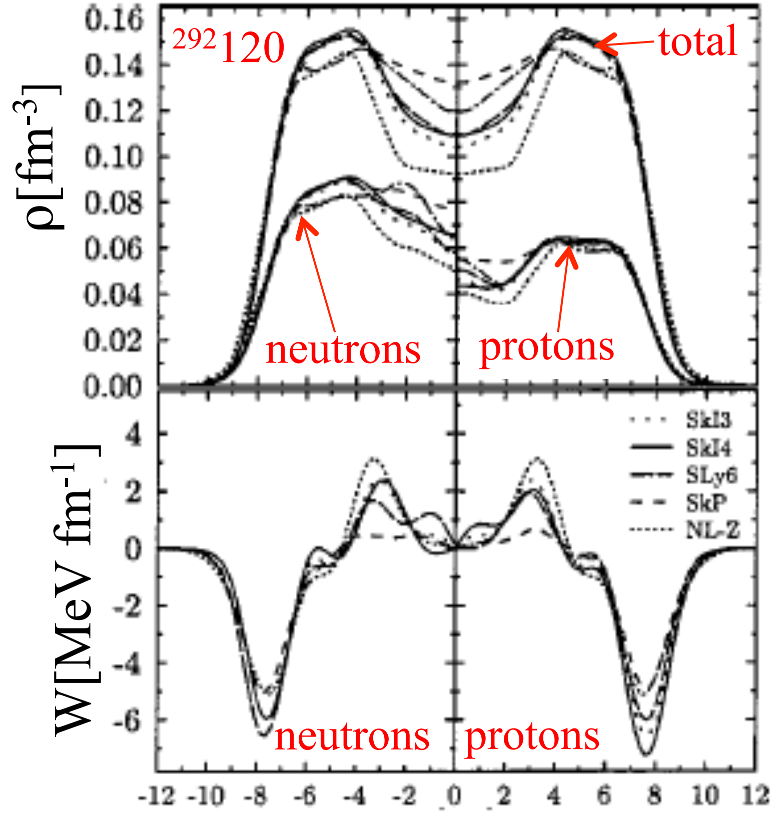
Isospin dependence

$$W_1 / W_2 \approx 2 \quad (MF)$$

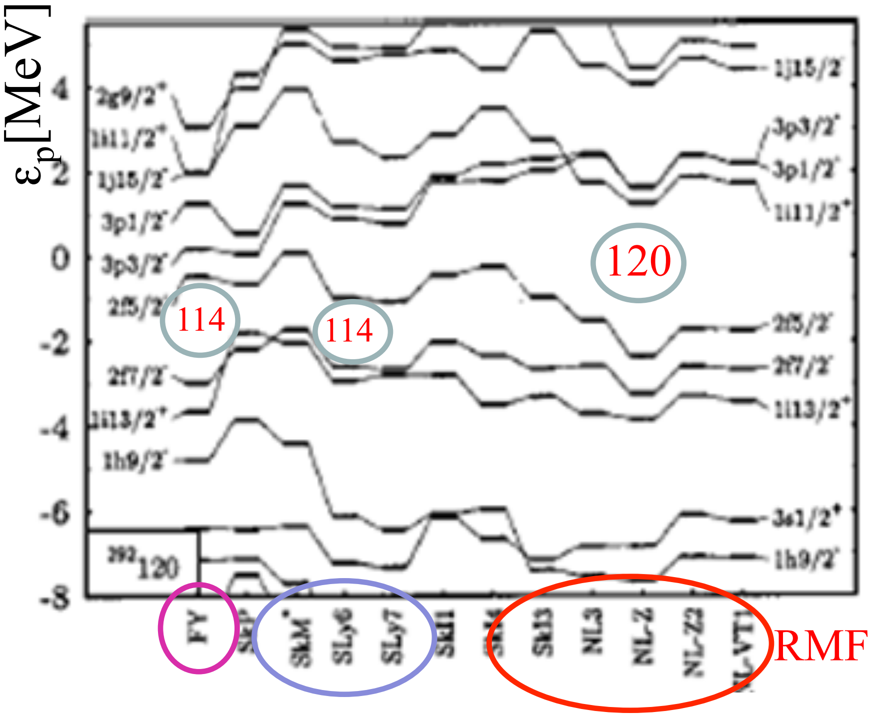
$$W_1 / W_2 \approx 1 \quad (RMF)$$

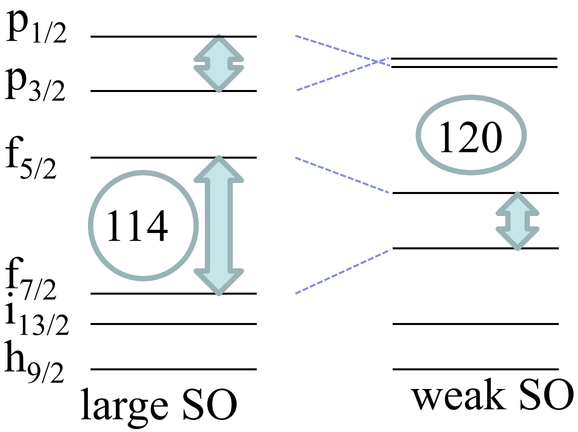
No isospin dependence in RMF

Spin orbit interaction and superheavy elements



M. Bender et al. PRC 60 (1999)034304



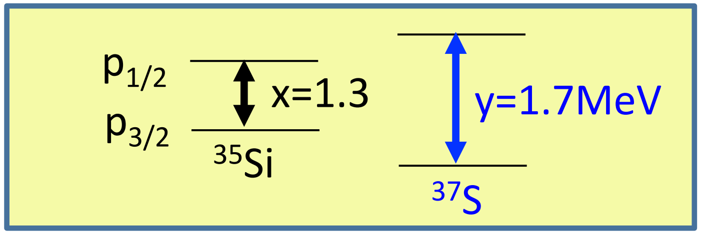


Size of gaps depends on strength of the SO force

Isospin dependence change their strength…

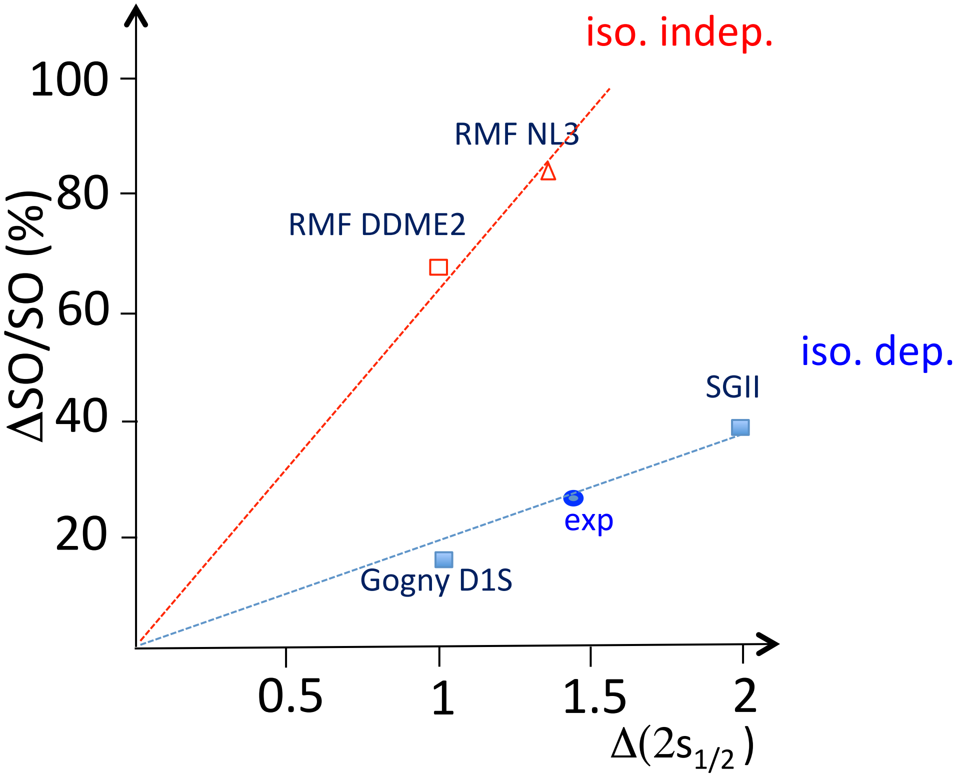
Modification of the SO splitting in a bubble nucleus

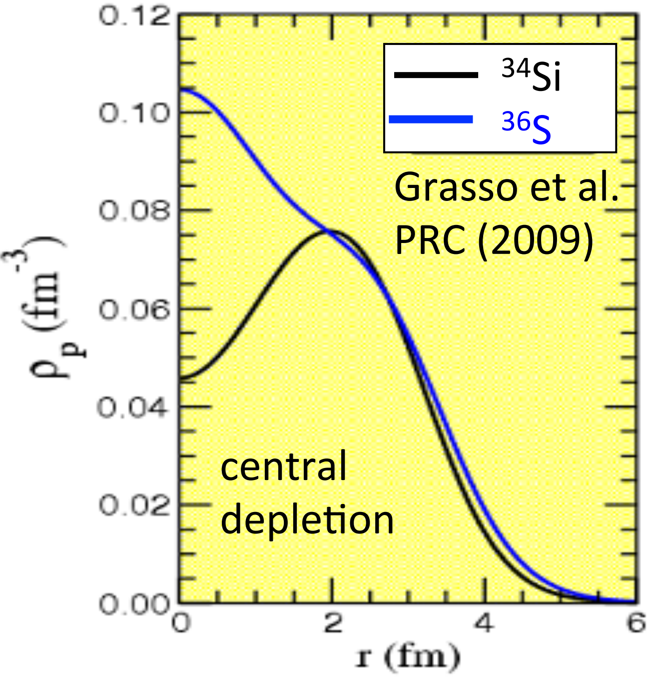
Change of ν($p_{1/2}$-$p_{3/2}$) splitting



$$\Delta_n SO/SO\ (\%) = \frac{\text{Diff}}{\text{Mean}} = \frac{0.4}{1.5} = 26\%$$

for $\Delta s_{1/2}$ = 1.45 (to be confirmed experimentally)





$$W_\tau^{\ell s}(r) = -\left[W_1 \frac{\partial \rho_\tau(r)}{\partial r} + W_2 \frac{\partial \rho_{\tau' \neq \tau}(r)}{\partial r}\right] \vec{\ell} \cdot \vec{s}$$

$W_1 / W_2 \approx 2 \quad (MF)$ isospin dependence

$W_1 / W_2 \approx 1 \quad (RMF)$ Isospin independence

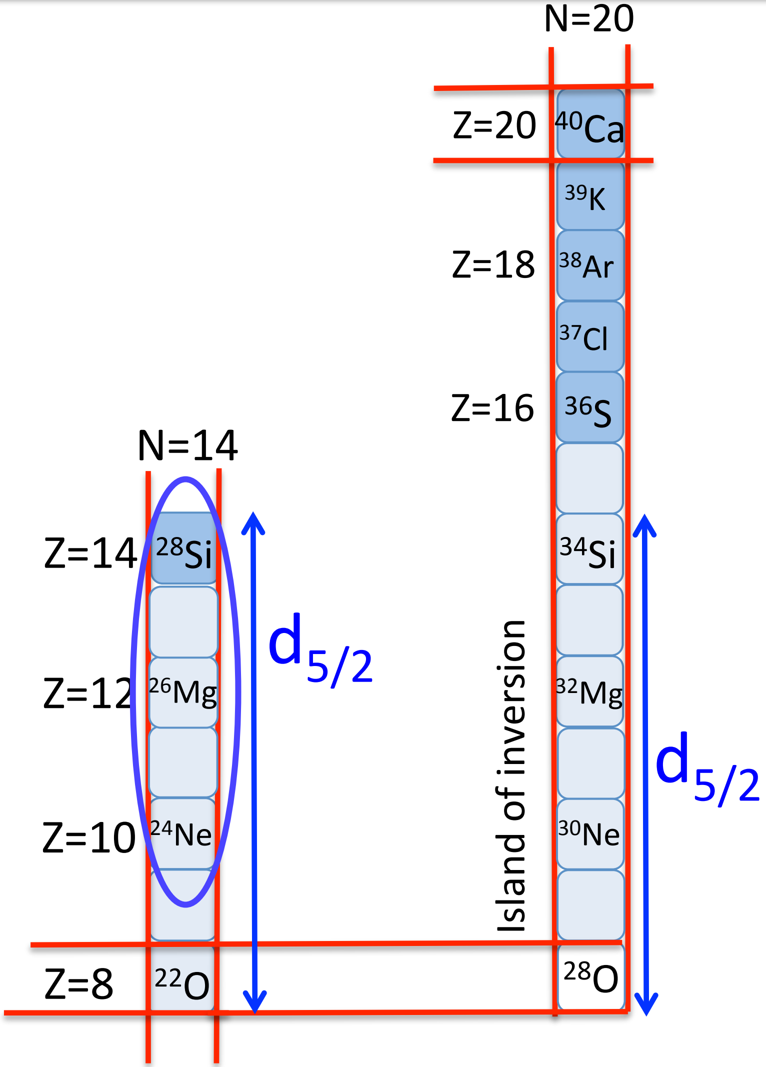
Exp. favors density AND isospin dependence of SO interaction

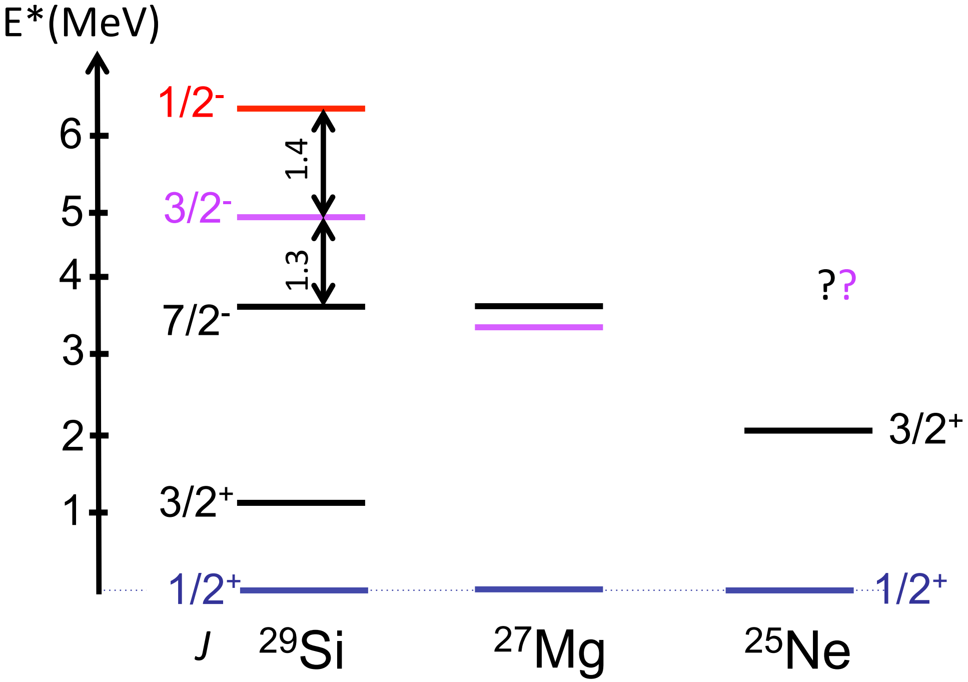
Anticipate consequences for drip line and SHE nuclei …

Neutron proton forces below ^{34}Si –

How to learn on the physics of the island of inversion ?

Proton-neutron forces involving the $d_{5/2}$ proton orbit

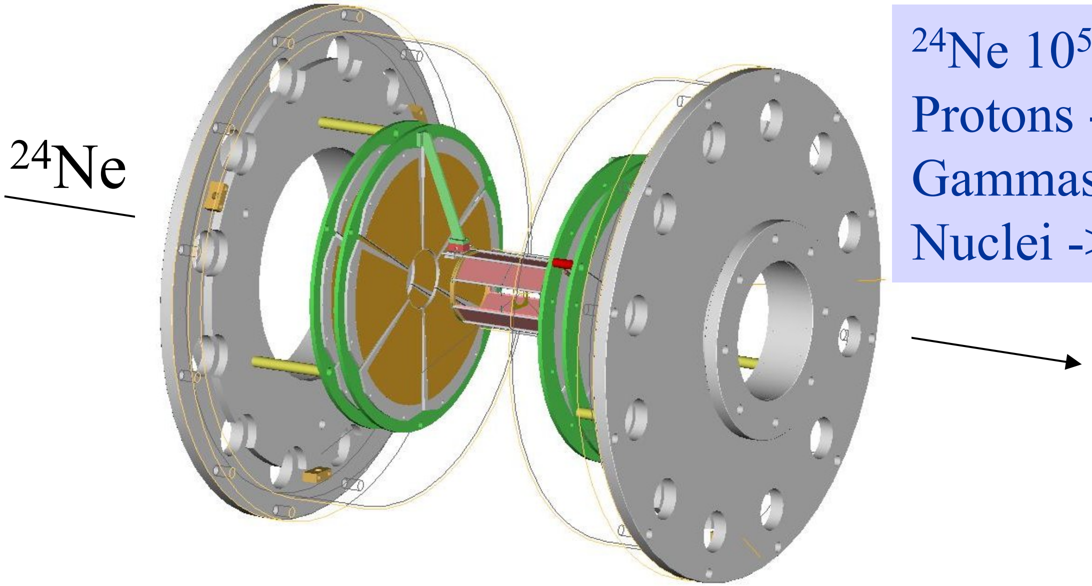




Is the N=28 gap further decreasing when removing protons in the $d_{5/2}$ orbit ?

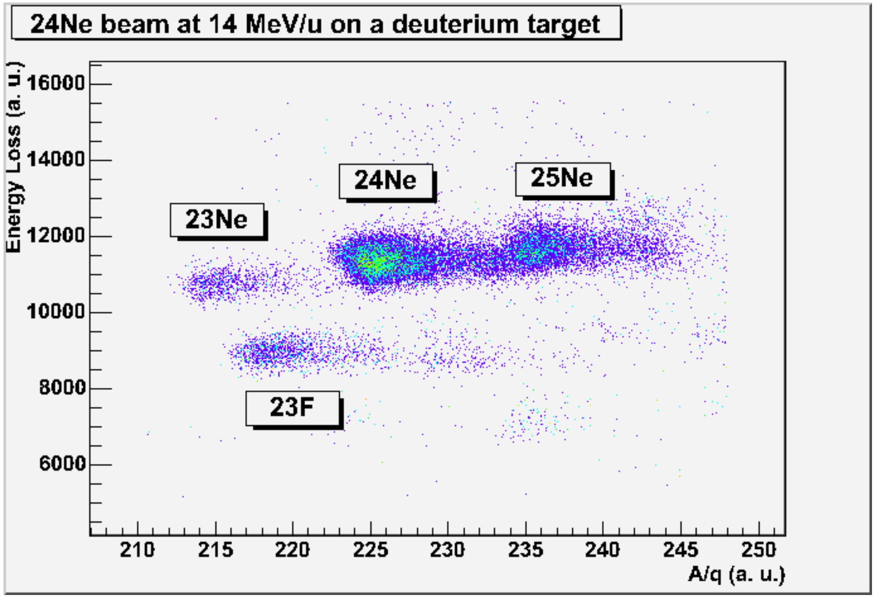
Study of the ^{25}Ne via ^{24}Ne(d,p)^{25}Ne

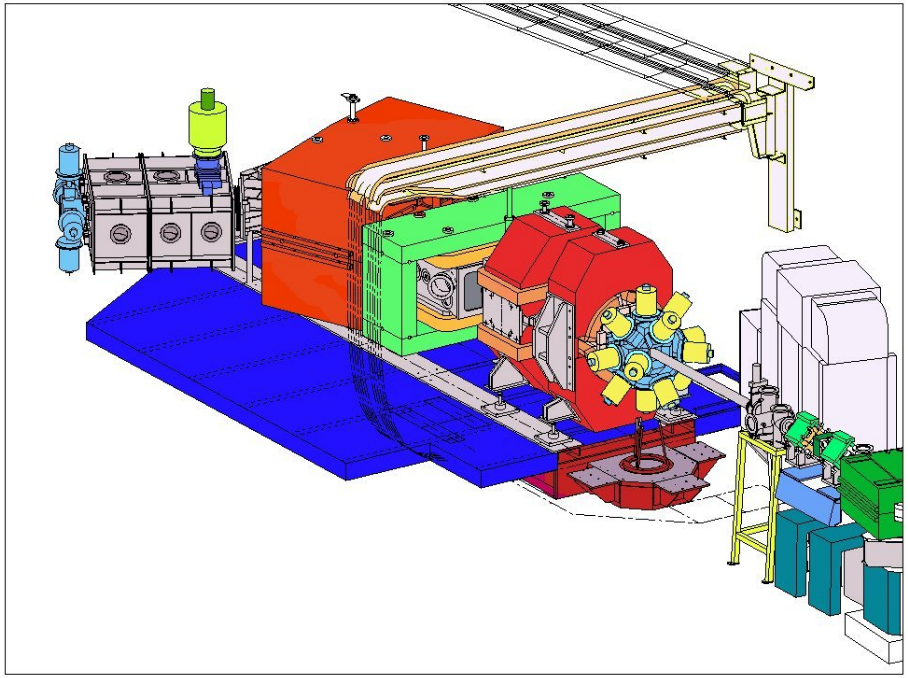
Location of fp states using ^{24}Ne(d,p)^{25}Ne



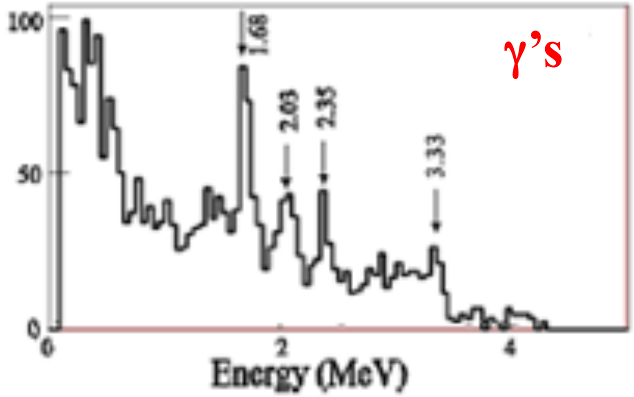
^{24}Ne 10^5pps SPIRAL
Protons -> TIARA
Gammas -> 4 Exogam
Nuclei -> Vamos

VAMOS Projectile-Like ID

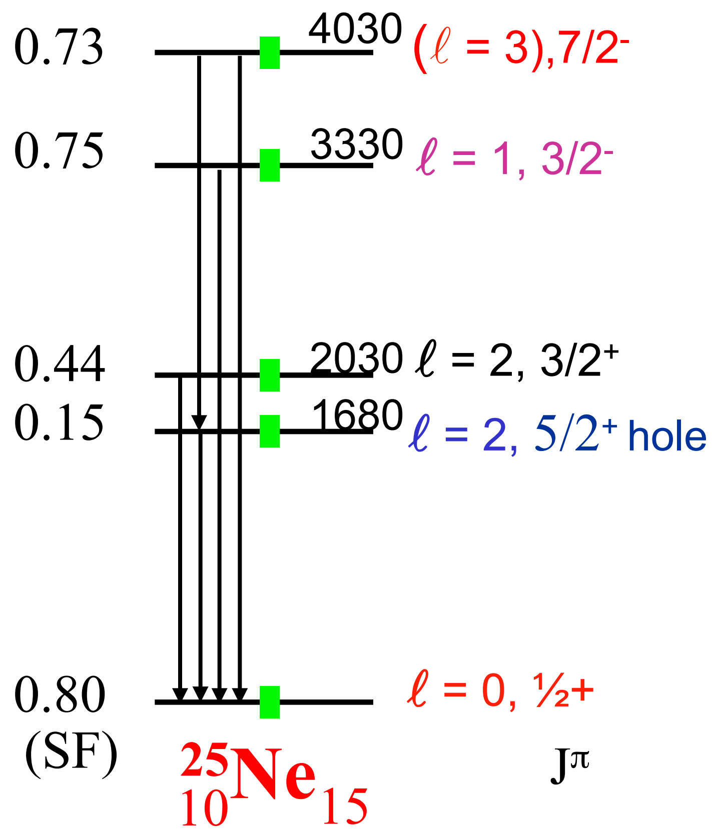




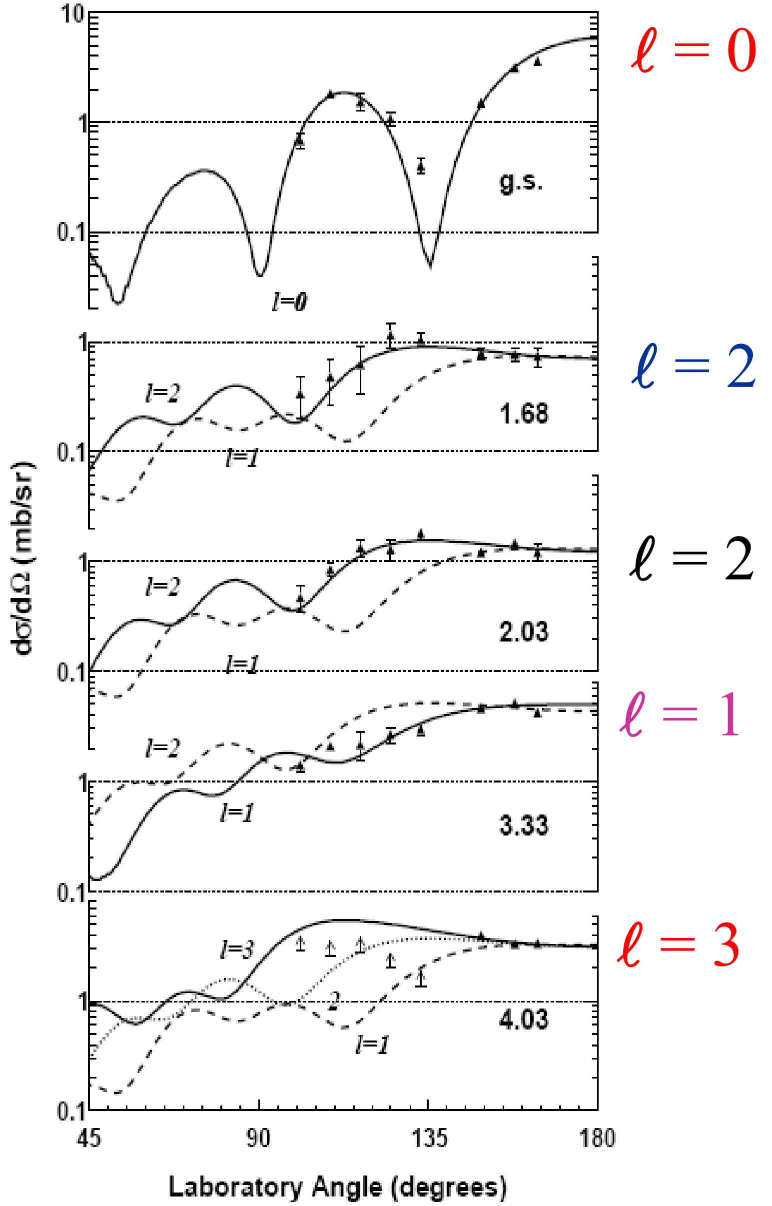
Location of fp states using ^{24}Ne(d,p)^{25}Ne



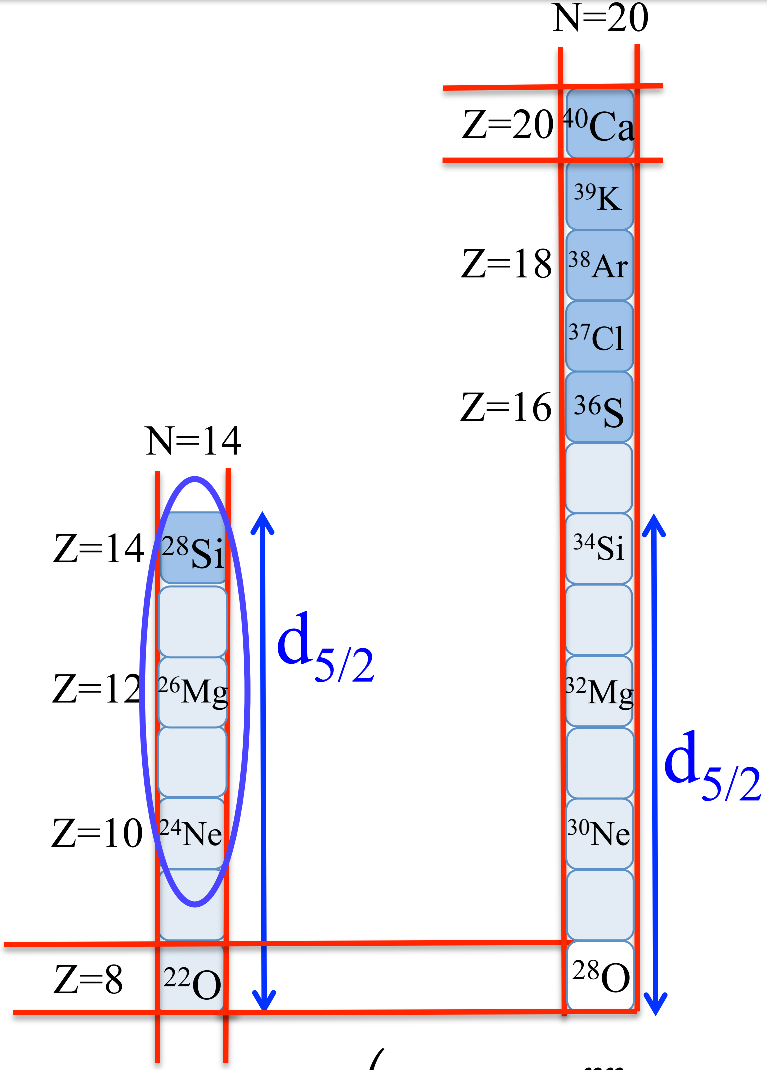
fp states
reversed

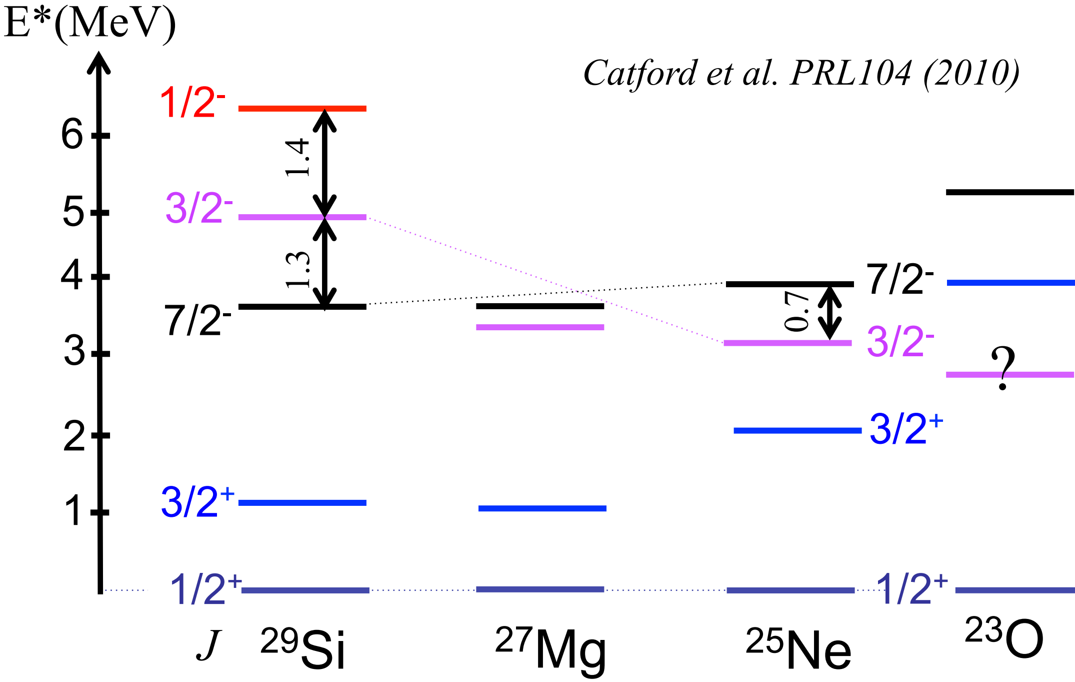


W. Catford et al., PRL 104 (2010)



Proton-neutron forces involving the $d_{5/2}$ proton orbit





Catford et al. PRL104 (2010)

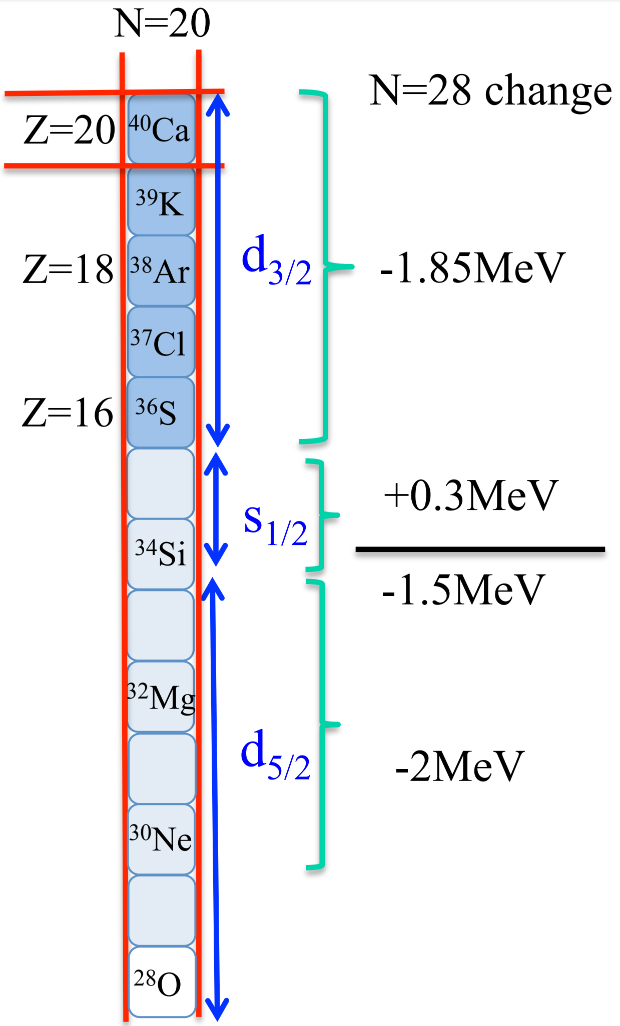
Lowering of $p_{3/2}$ also proven in ^{27}Ne
Brown et al. PRC 85 (2012) R
Obertelli. et al. PLB (2006)
Terry et al. PLB (2006)

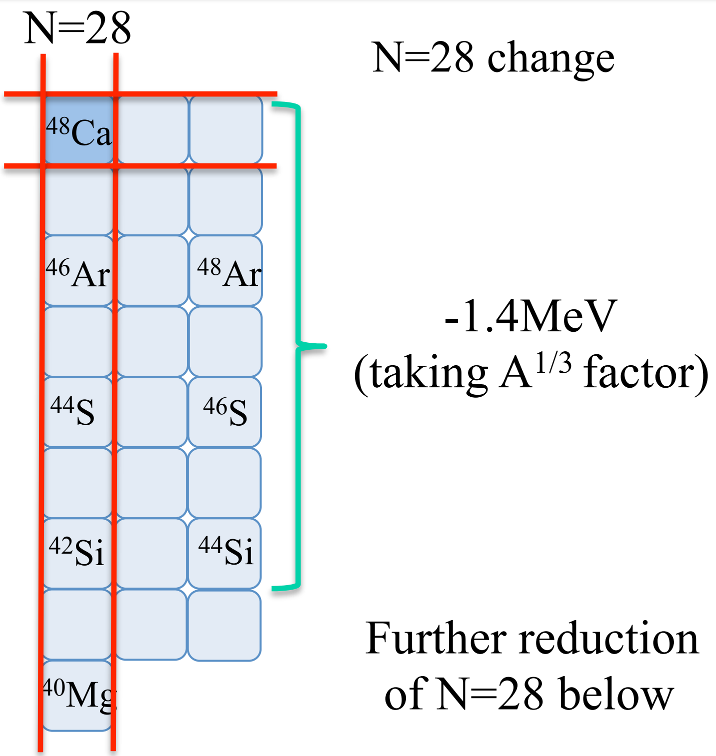
$$\delta(N=28) \approx 4\left(V1d_{\frac{5}{2}}2p_{\frac{3}{2}}{}^{pn} - V1d_{\frac{5}{2}}1f_{\frac{7}{2}}{}^{pn}\right) \approx 2MeV$$

The N=28 gap decreases further by 2MeV ⟶ swapping between the $f_{7/2}$ and $p_{3/2}$ orbits

The $p_{3/2}$ orbit should lie right above the $d_{3/2}$ in the Ne-O chains
See Nakamura et al. PRL 103 (2010), Wimmer et al. PRL105 (2010)

Proton-neutron forces applied to the N=28 shell closure

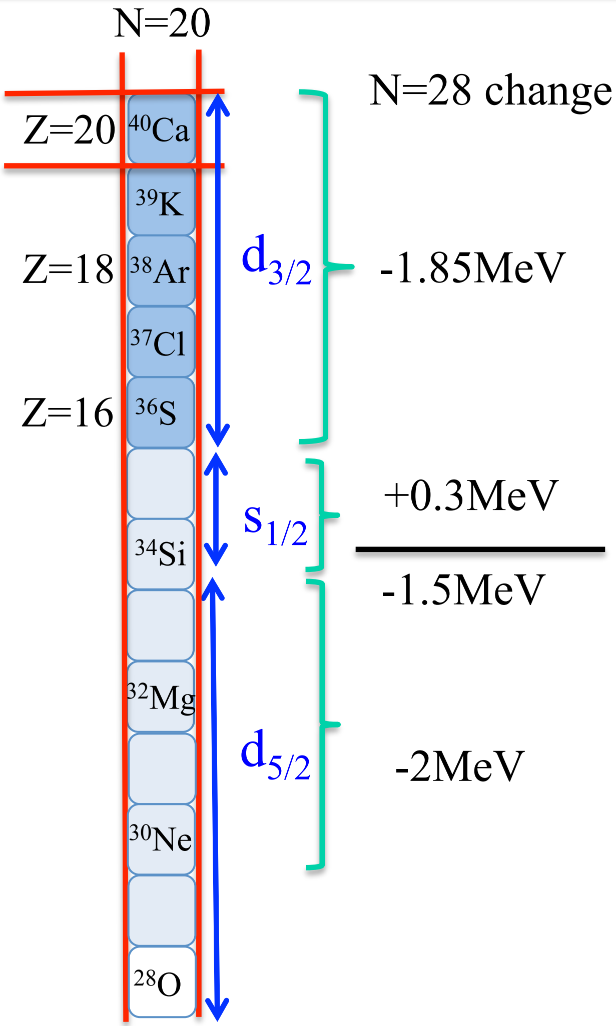




Applying the same forces, the N=28 shell gap should be reduced by about 1.4MeV in ^{42}Si and further reduced below

-> quadrupole correlations further increase the onset of deformation

Proton-neutron forces applied to the N=28 shell closure


N=20

N=28 change

Z=20 ^{40}Ca

^{39}K

Z=18 ^{38}Ar

^{37}Cl

Z=16 ^{36}S

^{34}Si

^{32}Mg

^{30}Ne

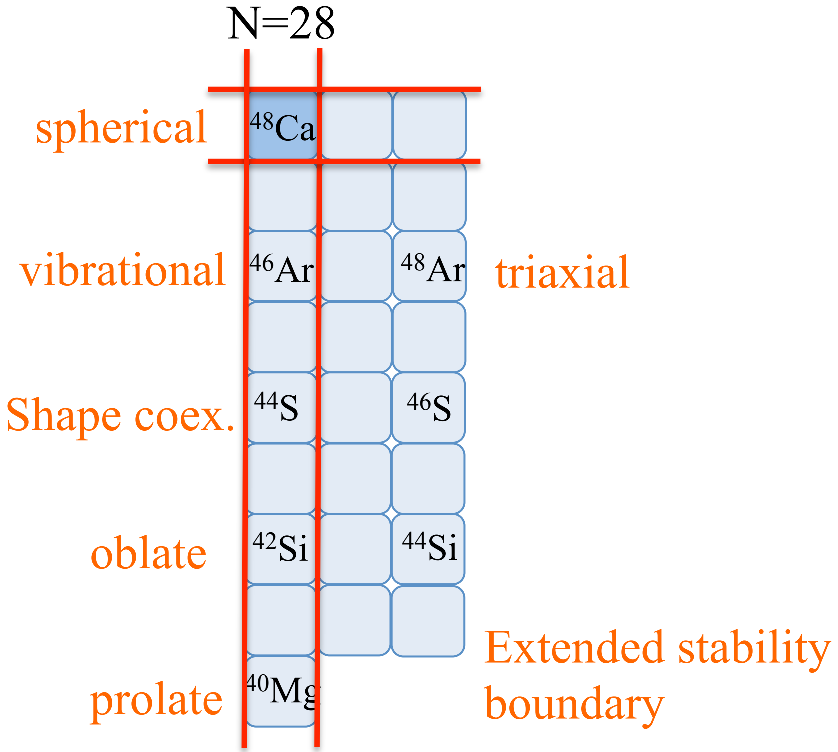
^{28}O

$d_{3/2}$ -1.85MeV

$s_{1/2}$ +0.3MeV

-1.5MeV

$d_{5/2}$ -2MeV


N=28

spherical ^{48}Ca

vibrational ^{46}Ar ^{48}Ar triaxial

Shape coex. ^{44}S ^{46}S

oblate ^{42}Si ^{44}Si

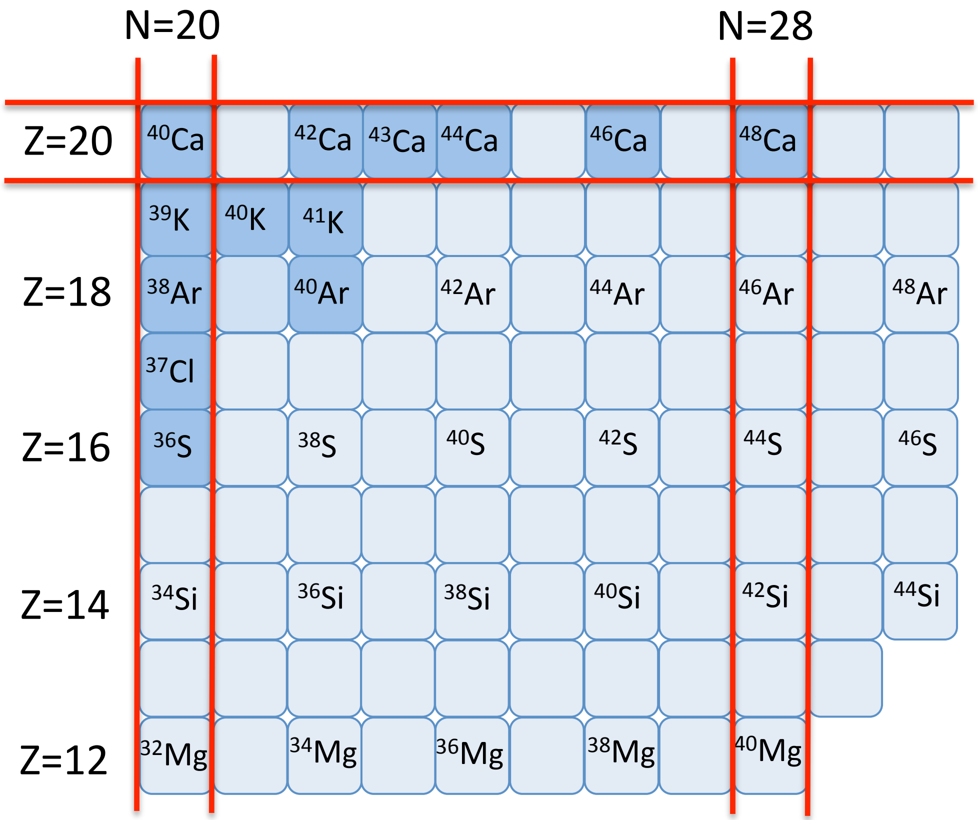
prolate ^{40}Mg

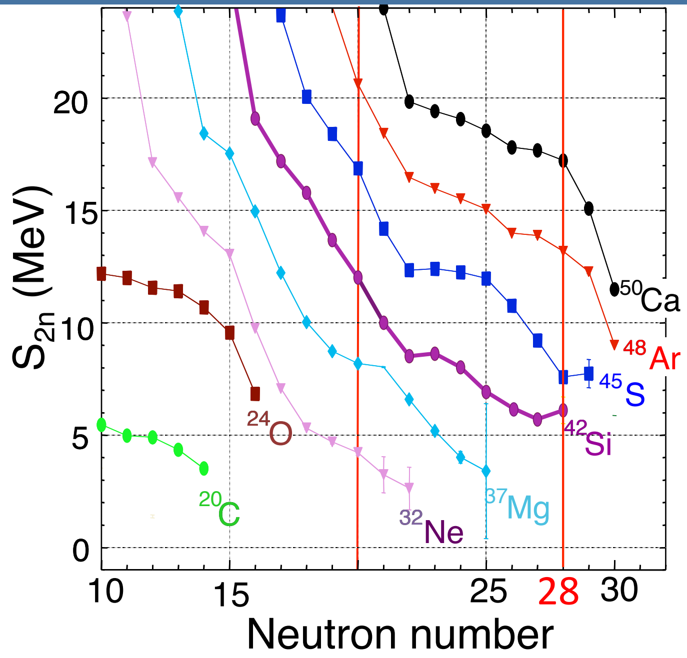
Extended stability boundary

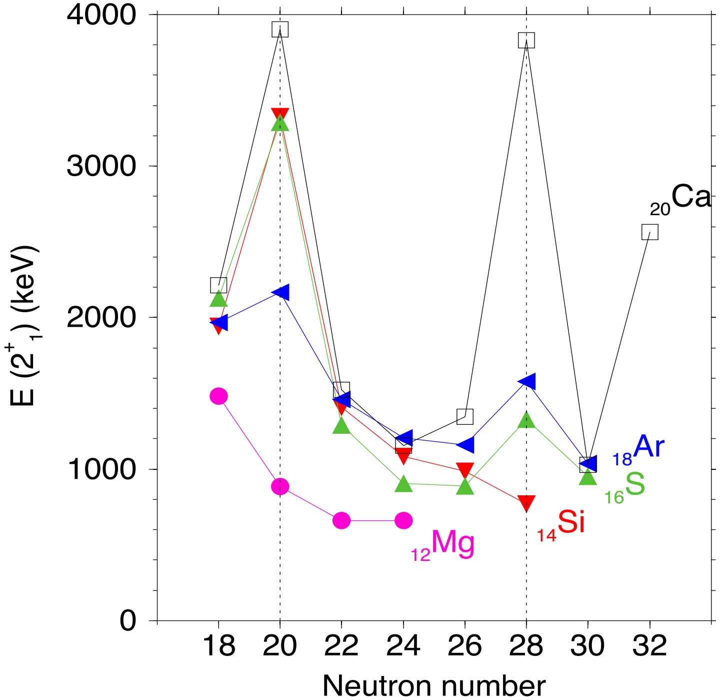
Favors quadrupole excitations -> deformation

Gaudefroy et al. PRL (2006)- ^{46}Ar
Force et al. PRL (2010)- ^{44}S
Bastin et al. PRL (2007) ^{42}Si
Baumann, Nature (2007) ^{40}Mg
Bhattacharyya et al.2008 PRL 101 (2008) ^{48}Ar

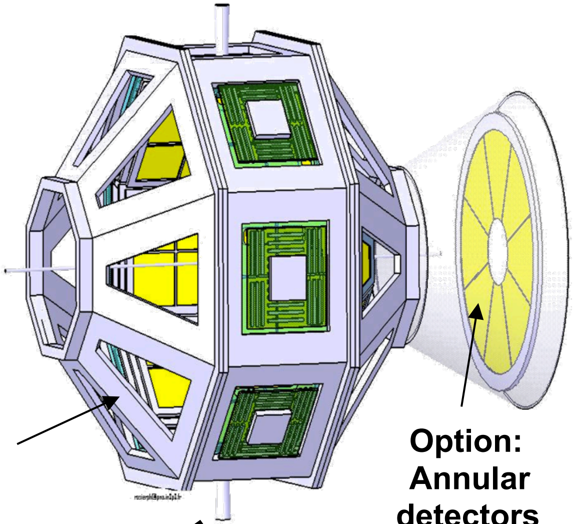
From spherical to deformed shapes at N=28





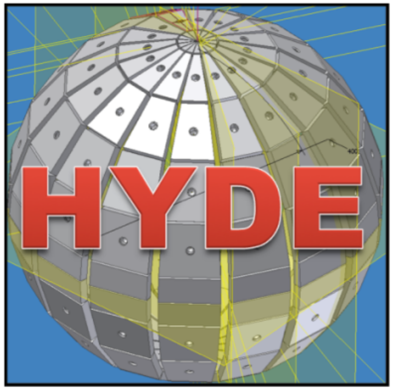


New generation detectors for direct reaction studies



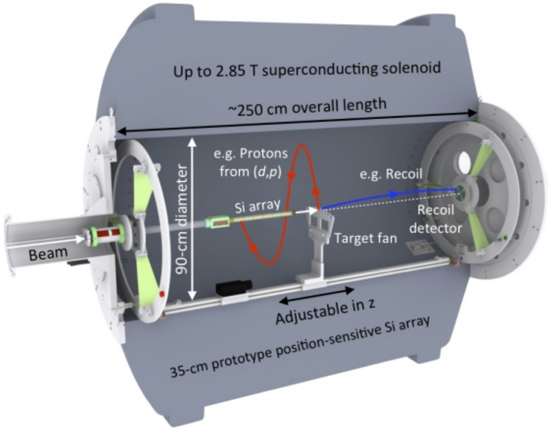
Trapezoidal shapes for endcaps

Option: Annular detectors



Silicon based

Solenoid spectrometer



Active Target

actar TPC

Conclusions

Selected experimental data spanning over large N/Z enable to probe major shell changes such as reduction of N=28 shell gap, and p SO splitting

Transfer reactions allow to follow the evolution of shell gaps and their origin from nn or pn interactions.

Decomposition of the monopole terms reveal which parts of the interaction play decisive roles, i.e. central, tensor, two-body SO

^{34}Si bubble nucleus used to determine two-body SO interaction
to test the validity of mean field models

^{24}Ne used to reveal a total disruption of the N=28 gap further from stability

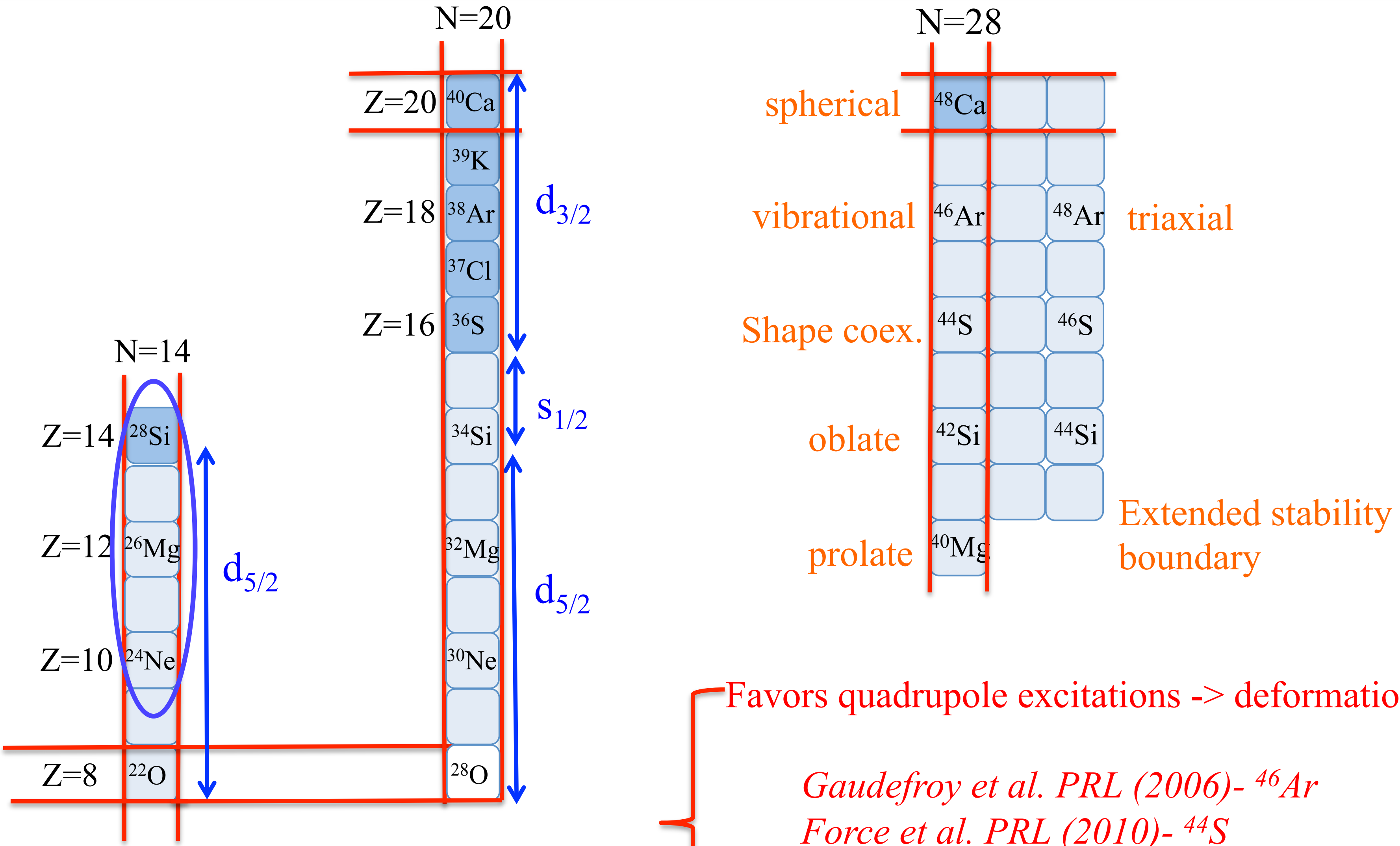
Expected increasing role of the neutron $p_{3/2}$ orbit near ^{28}O

Similar forces expected at play in other regions of the chart of nuclides ….

Sorlin and Porquet arXiv:1209.3377 (2012) for more details

Lecture ends here

Proton-neutron forces applied to the N=28 shell closure



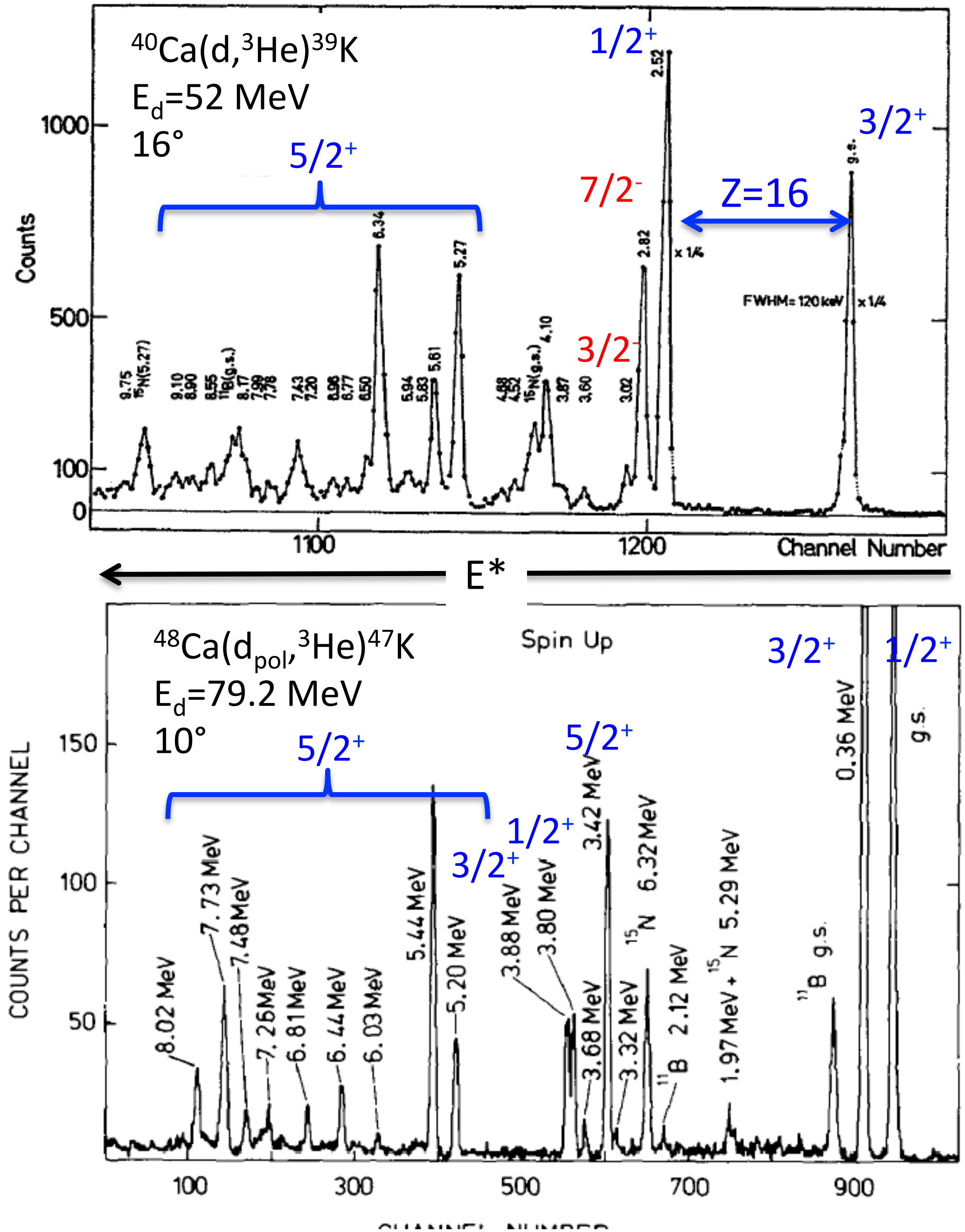
Global reduction of the N=28 shell gap
Induced by nuclear forces

Favors quadrupole excitations -> deformation

Gaudefroy et al. PRL (2006)- ^{46}Ar
Force et al. PRL (2010)- ^{44}S
Bastin et al. PRL (2007) ^{42}Si
Baumann, Nature (2007) ^{40}Mg

Probing the occupied proton orbits in ^{48}Ca and ^{40}Ca

^{48}Ca: Banks et al. NPA 437 (1985) 381
^{40,48}Ca: Doll et al. NPA 263(1976)210

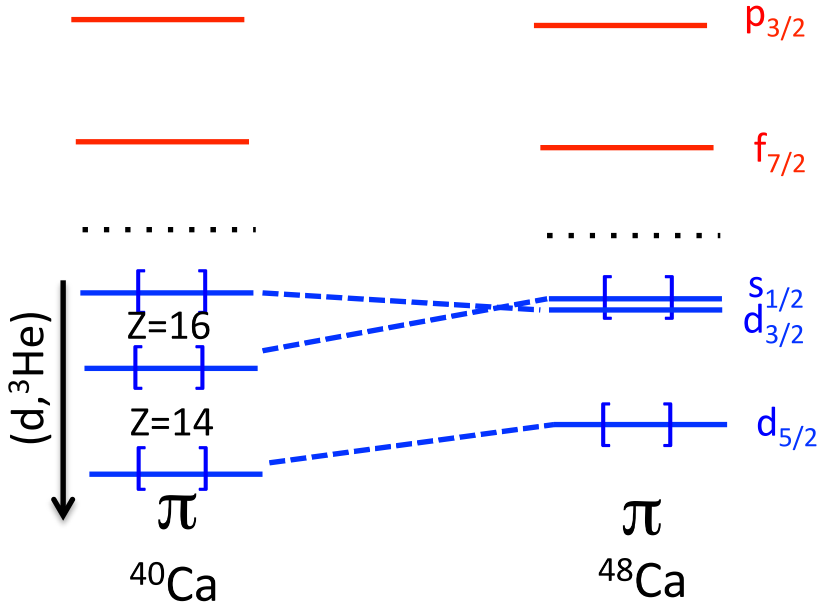


An inversion between the $s_{1/2}$ and $d_{3/2}$ orbits occurs in ^{48}Ca

Degeneracy at N=28

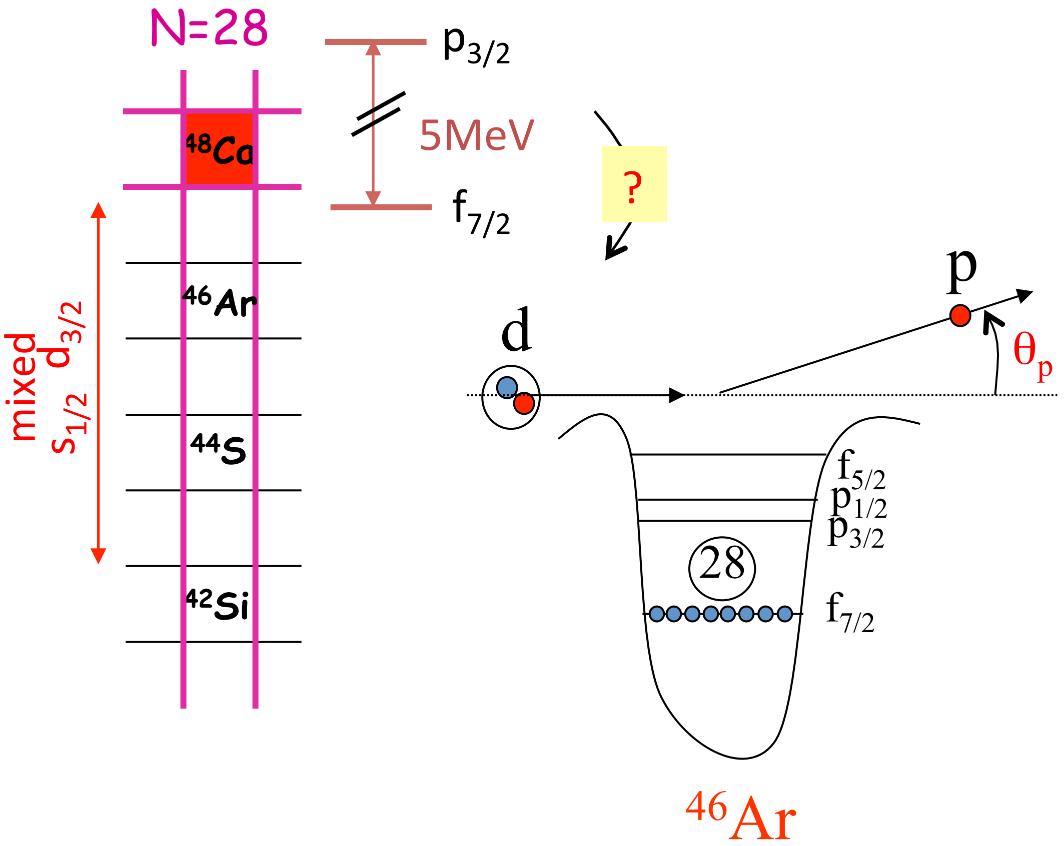
➔Role of proton-neutron forces

The $d_{5/2}$ strength is very fragmented

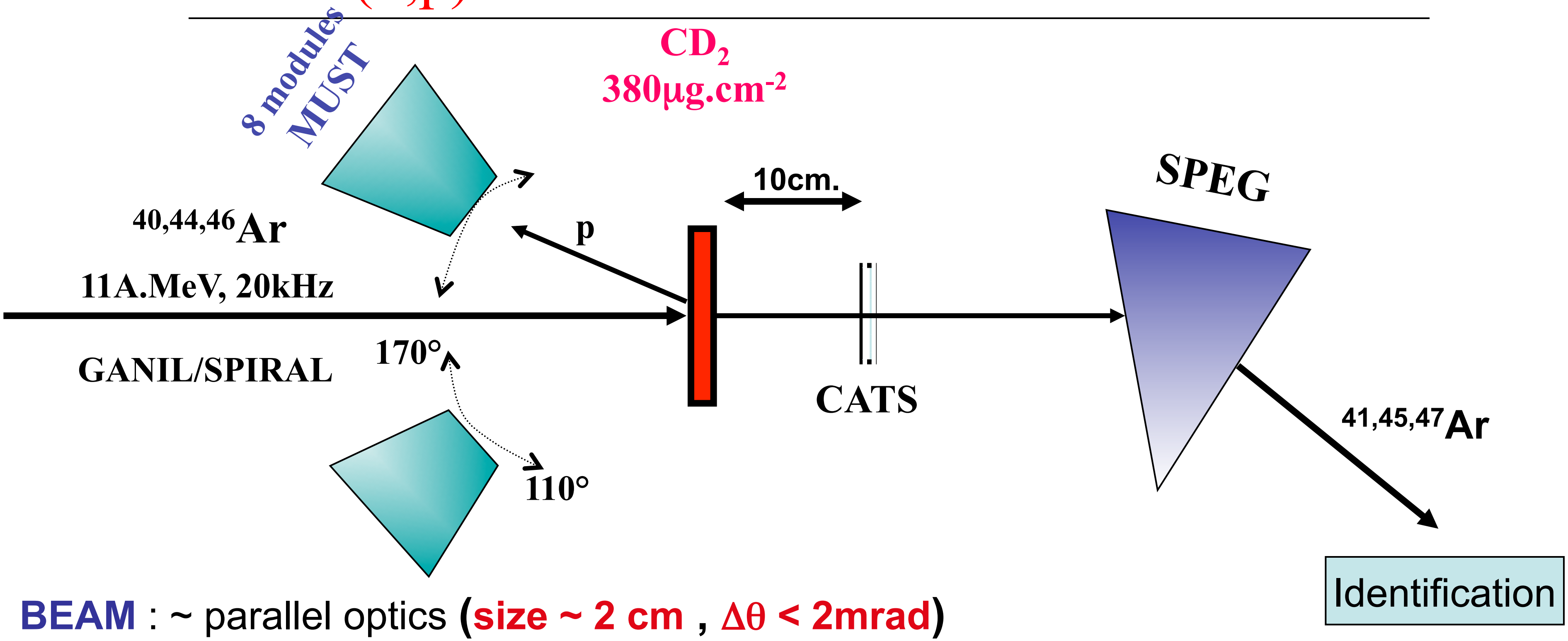


Evolution of the N=28 shell gap and SO splittings below ^{48}Ca

→ Use of transfer (d,p) reaction with ^{46}Ar beam
Collab. IPNO Orsay, GANIL,CEA saclay
L. Gaudefroy et al. Phys. Rev. Lett. 97 (2006)



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



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

CATS : -**beam**-tracking detector

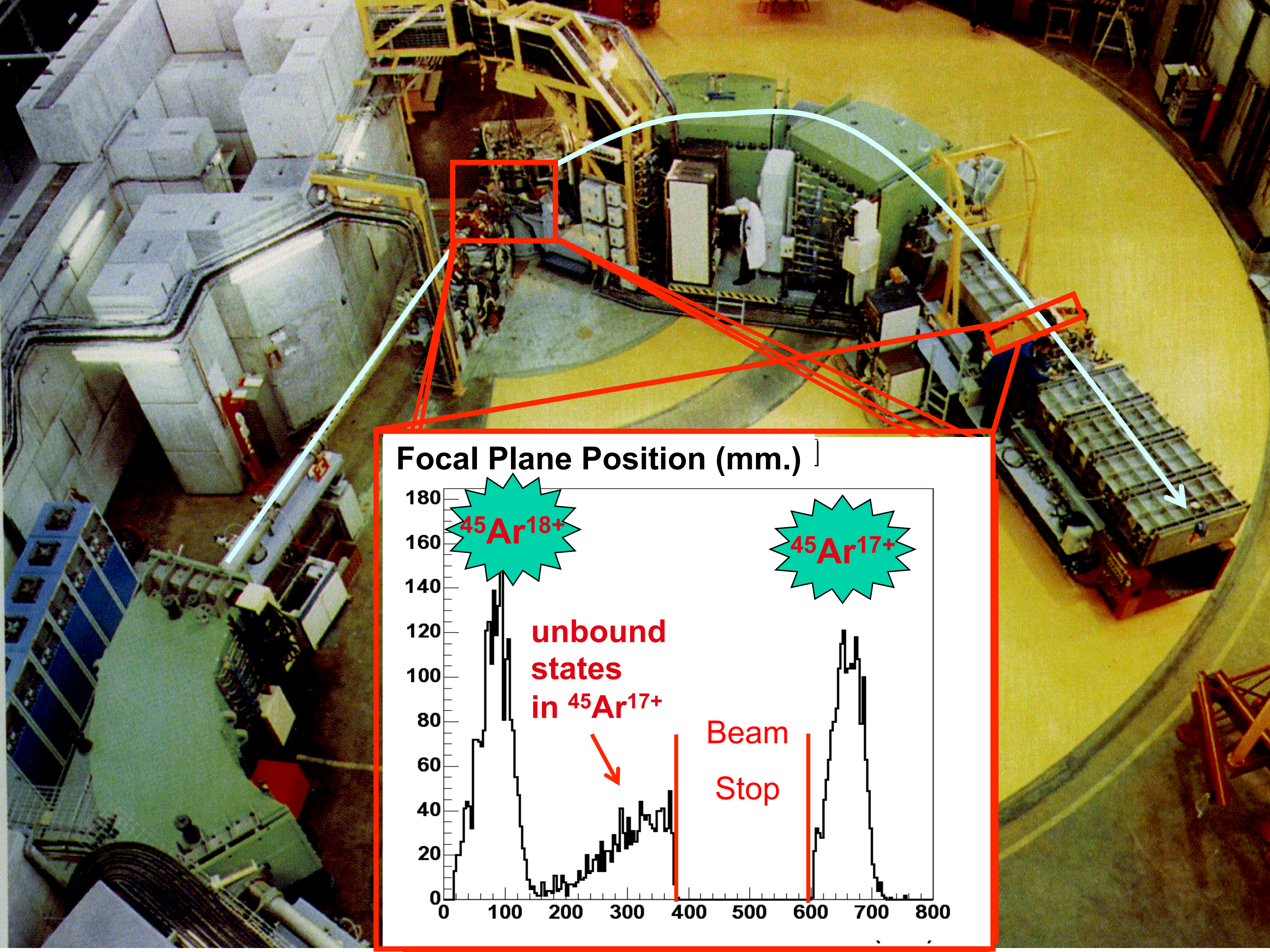
- Proton **emission point**.
  resolution : ~1 mm

MUST : -**Si Strip** detector

-Proton **impact localisation**
resolution : 1 mm; size 6 x 6 cm^2

-Proton **energy** measurement.
resolution : 50 KeV

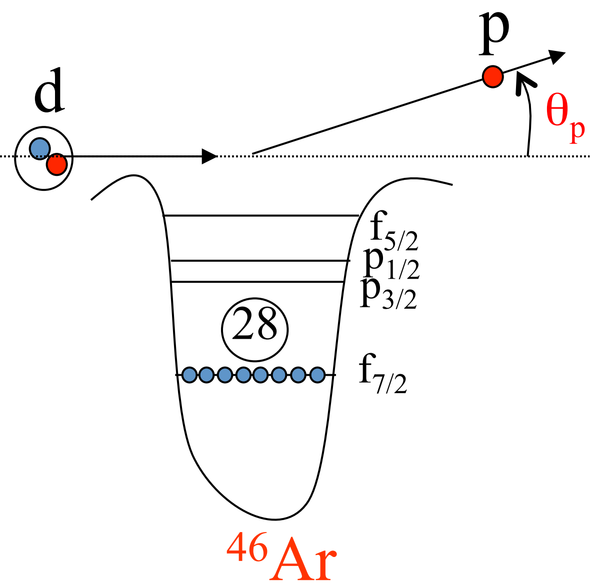
SPEG : Energy loss spectrometer : **recoil ion** identification→transfert-like products


Focal Plane Position (mm.)
$^{45}Ar^{18+}$
$^{45}Ar^{17+}$
unbound states in $^{45}Ar^{17+}$
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}Ar(d,p) transfer reaction with SPIRAL1 +MUST

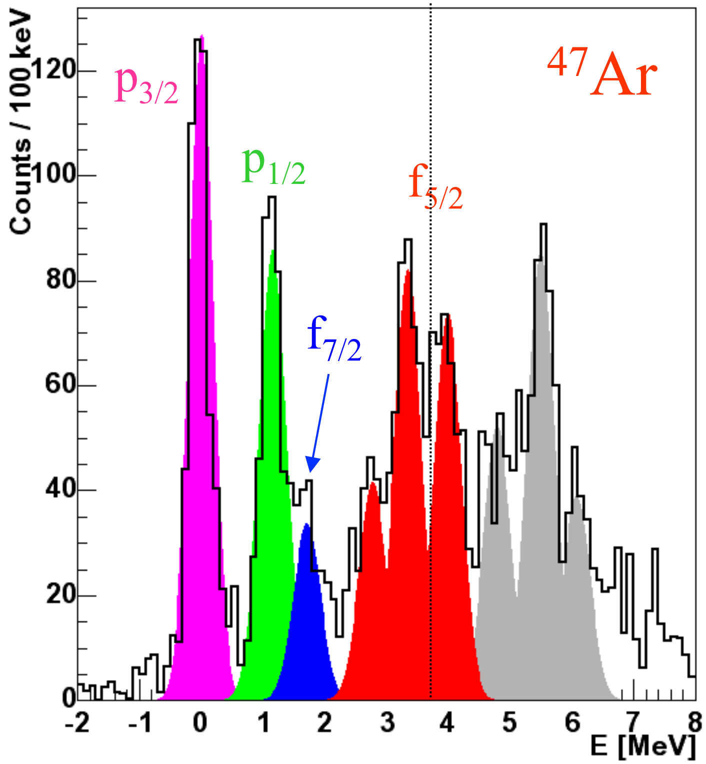
L. Gaudefroy PRL 97 (2006)

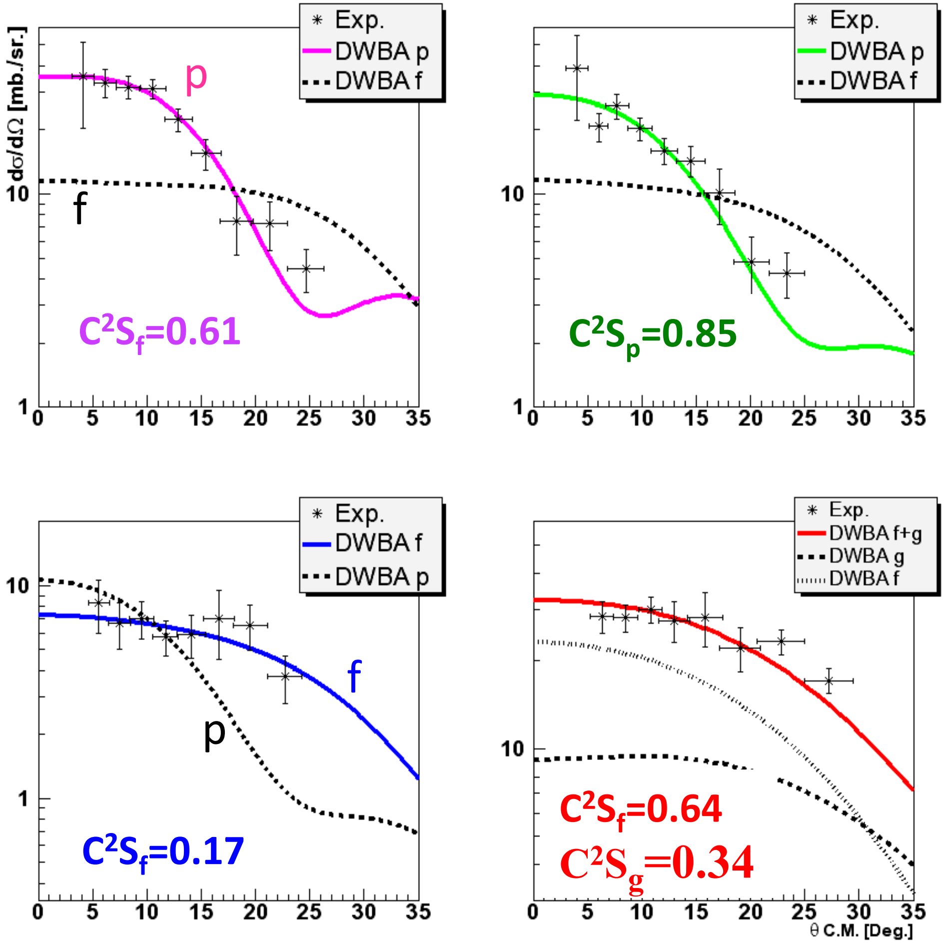


^{46}Ar is not a good closed core

Correlations should be taken into account

N=28 reduced by 330Kev





COMPARISON WITH SM CALCULATIONS

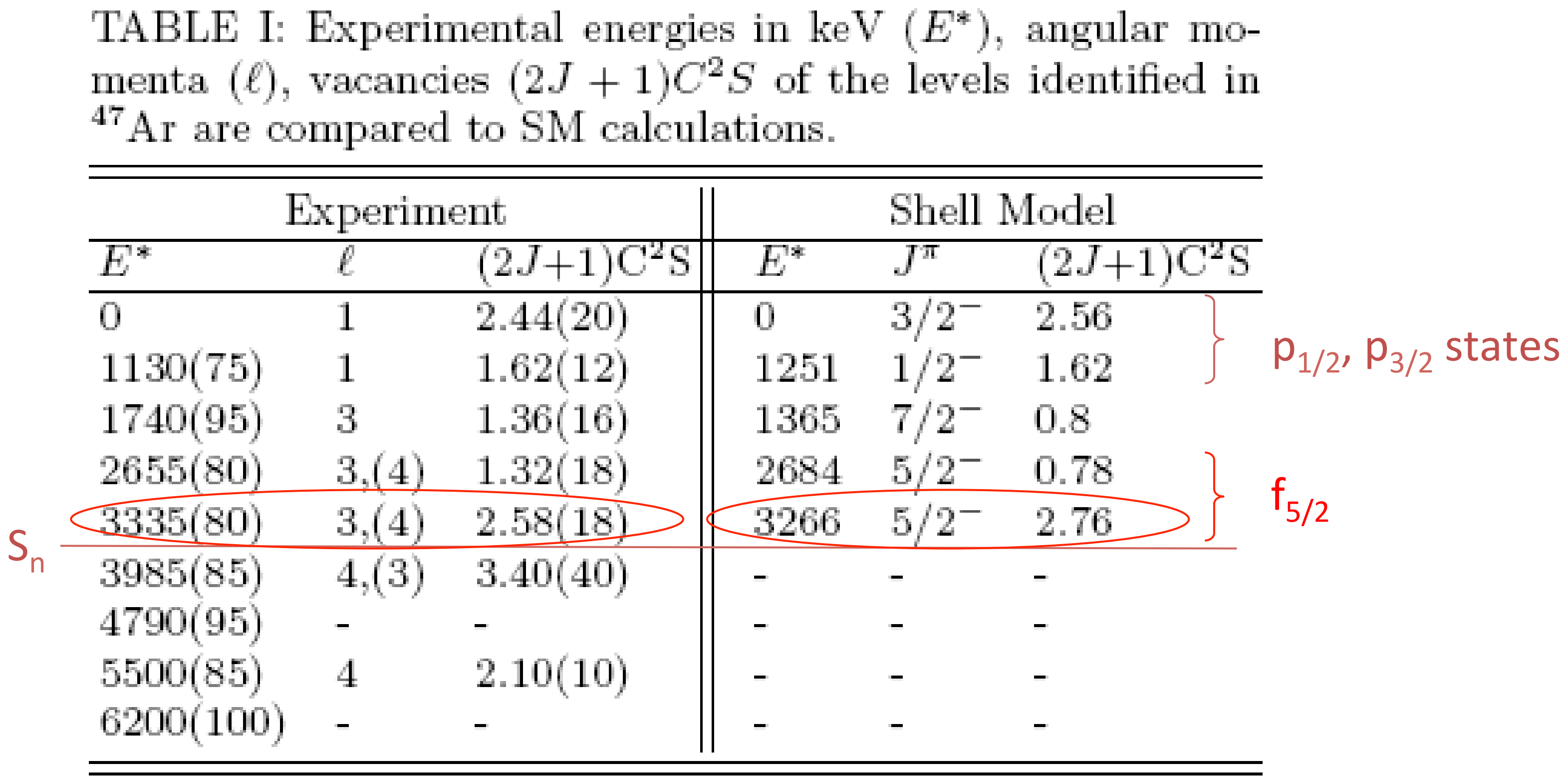


TABLE I: Experimental energies in keV (E^*), angular momenta (ℓ), vacancies $(2J+1)C^2S$ of the levels identified in ^{47}Ar are compared to SM calculations.

Experiment			Shell Model		
E^*	ℓ	$(2J+1)C^2S$	E^*	J^π	$(2J+1)C^2S$
0	1	2.44(20)	0	$3/2^-$	2.56
1130(75)	1	1.62(12)	1251	$1/2^-$	1.62
1740(95)	3	1.36(16)	1365	$7/2^-$	0.8
2655(80)	3,(4)	1.32(18)	2684	$5/2^-$	0.78
3335(80)	3,(4)	2.58(18)	3266	$5/2^-$	2.76
3985(85)	4,(3)	3.40(40)	-	-	-
4790(95)	-	-	-	-	-
5500(85)	4	2.10(10)	-	-	-
6200(100)	-	-	-	-	-

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

$f_{5/2}$

S_n

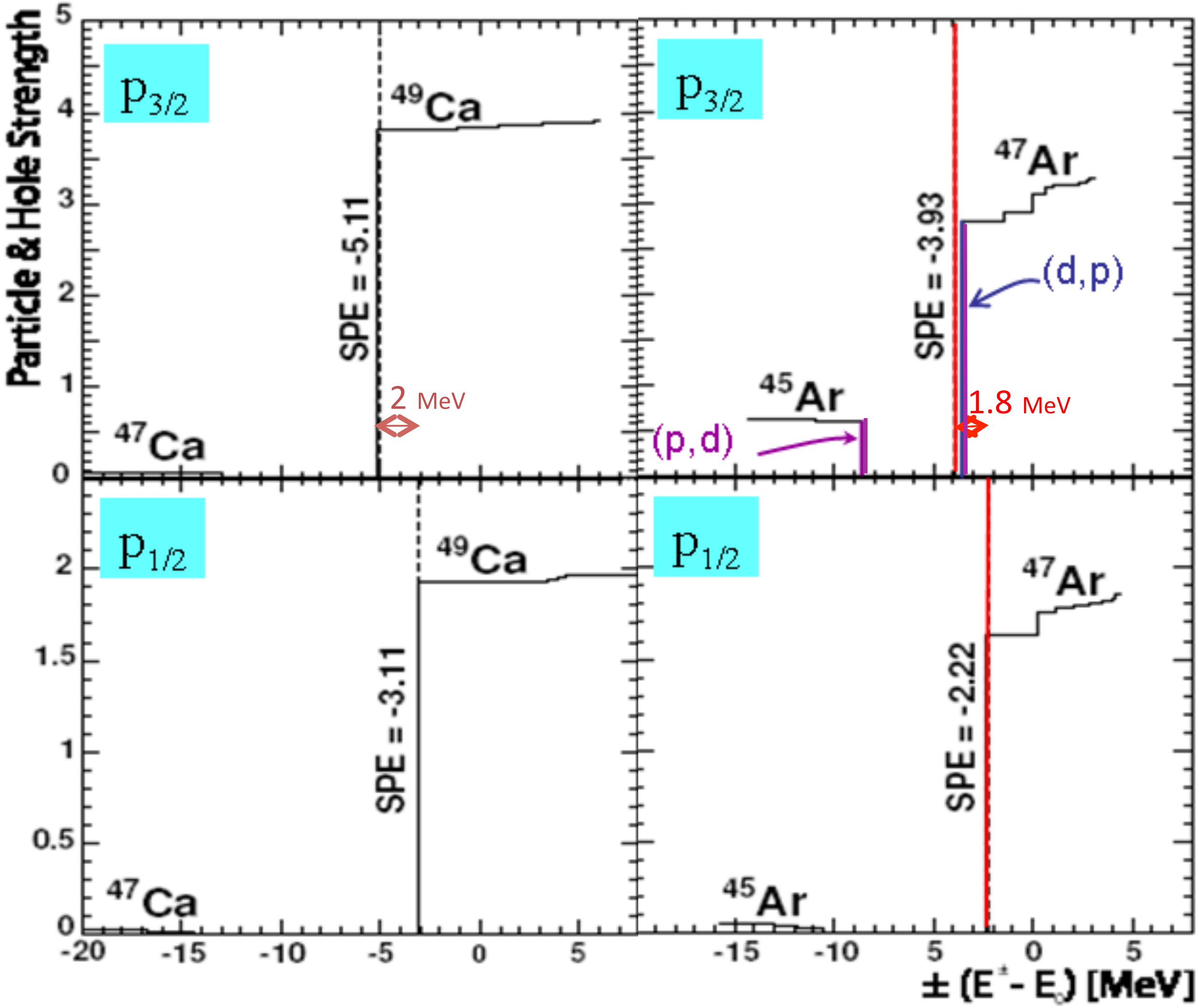
From SPDF-U (Nowacki), TBME at N=21

->Fine tuning of monopoles to reproduce the main part of the experimental SPE strength

->Assume that the treatment of correlations is correct, check for (d,p) and (p,d)

Deduce the change in SPE's between ^{49}Ca to ^{47}Ar

Effects of correlations on the fragmentation of states



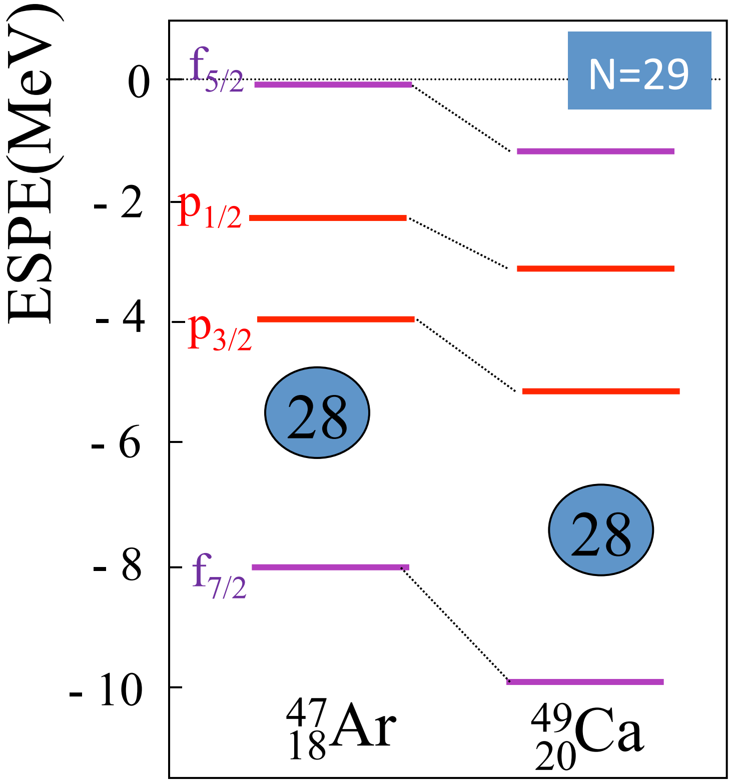
EXP
Particle strength : transfer reaction ^{46}Ar(d,p)^{47}Ar
Hole strength: ^{46}Ar(-1n) Gade et al. PRC 71, 051301 (R) 2005

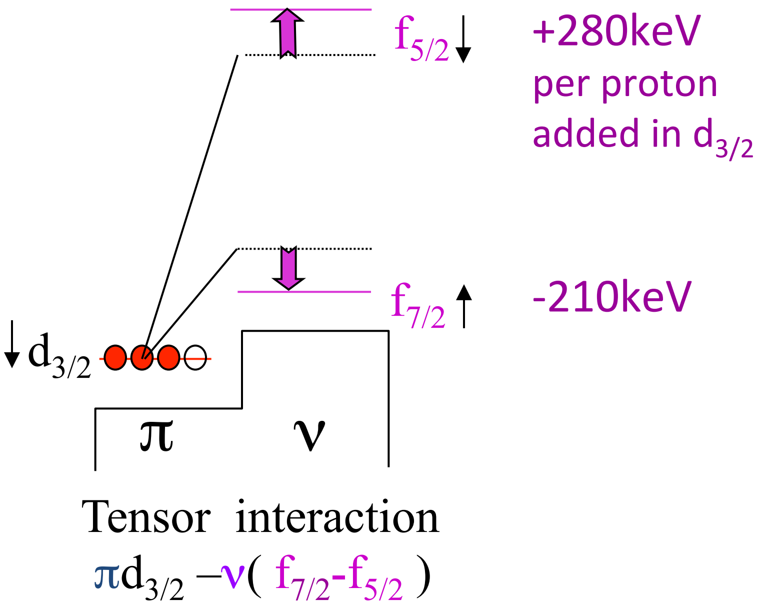
THEORY : *Signoracci and Brown ; Gaudefroy, …Nowacki et al PRL 2007*

Variation of single particle energies from tensor forces

-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 → tensor forces ?





Tensor interaction

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

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

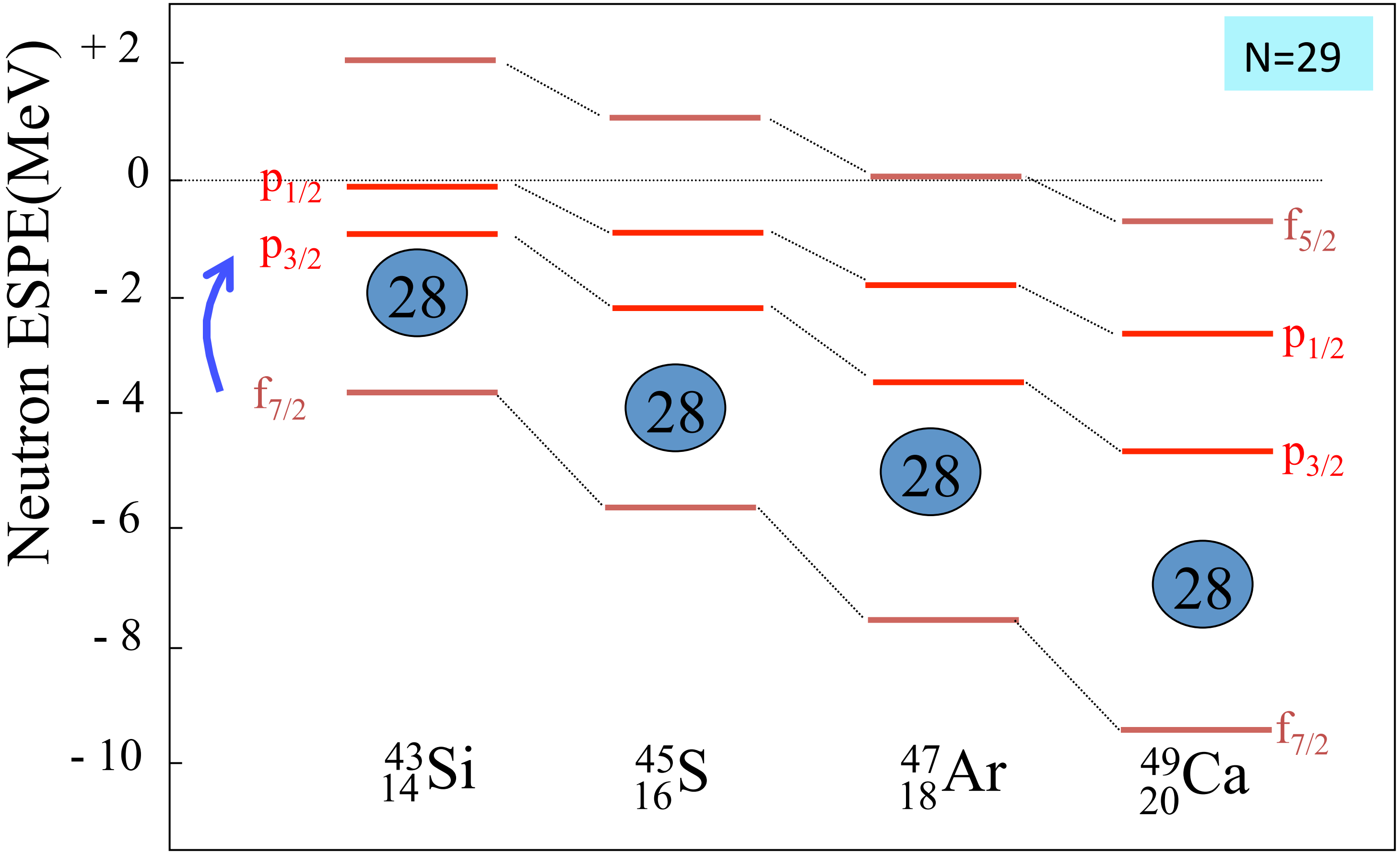
Expect a change of the f7-f5 SO splitting by 2MeV between ^{41}Ca and ^{37}S, NOT AS LARGE, WHY ?

The f5 orbit lies in the continuum in ^{37}S,then the tensor-induced mechanism may be perturbed…

Extapolated SPE between ^{49}Ca and ^{43}Si …

derived from experimentally-constrained monopole variations

Including ^{46}*Ar(-1n) Gade et al. PRC 71, 051301 (R) 2005*



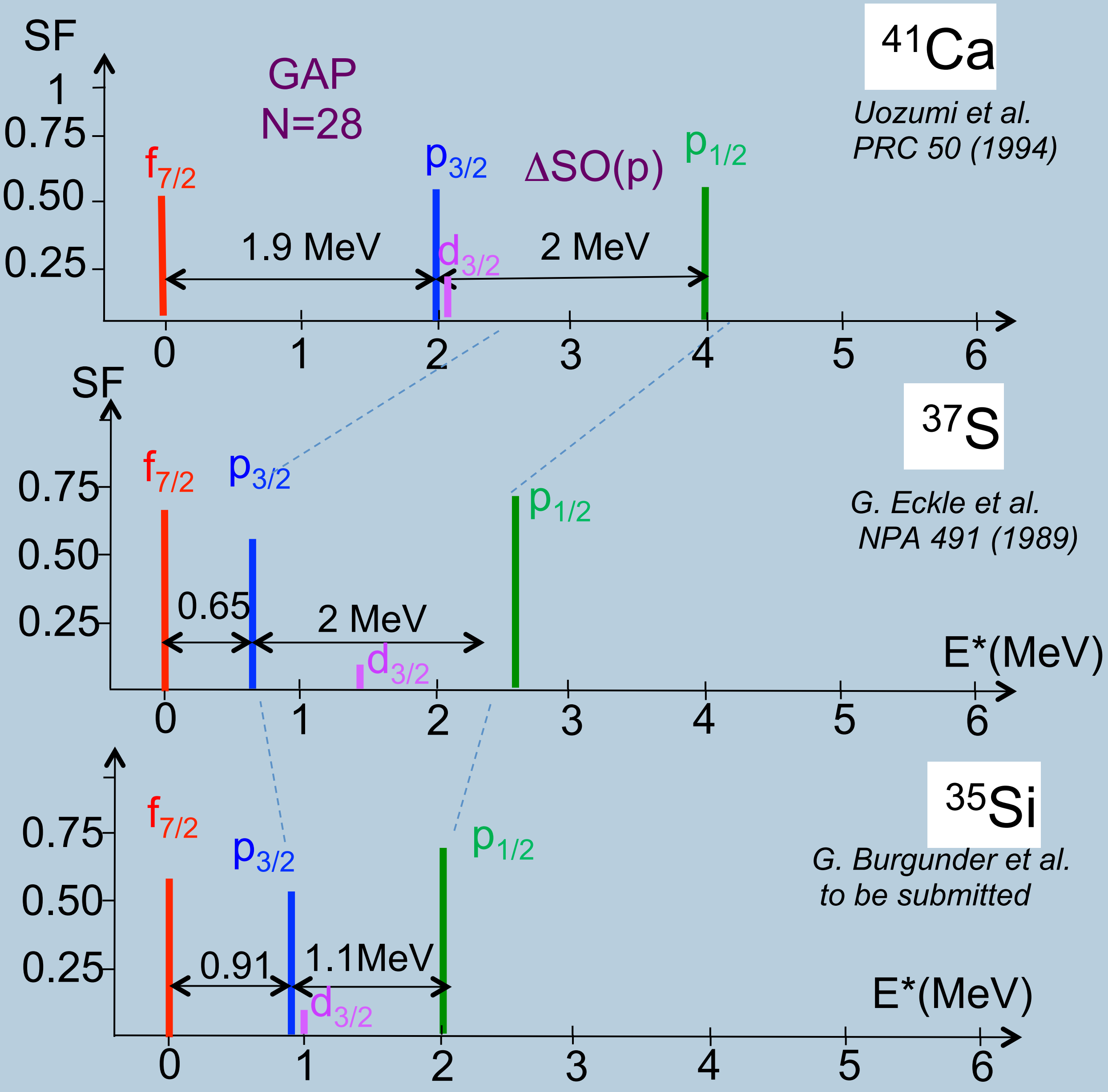
-A shrink of neutron SPE's is occurring gradually when N>>Z

> Enhanced collectivity expected

What happens when drip-line is reached ?

> determine properties of proton-neutron nuclear forces there

MAJOR STRENGTH

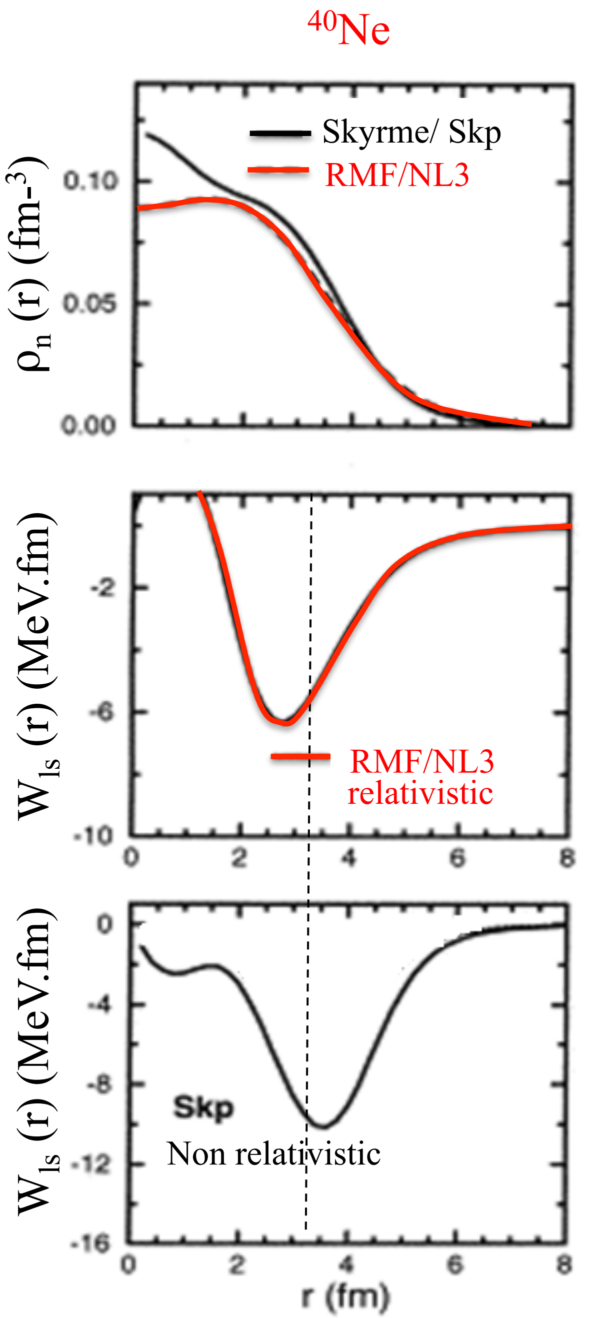


Uozumi et al.
PRC 50 (1994)

G. Eckle et al.
NPA 491 (1989)

G. Burgunder et al.
to be submitted

The spin orbit interaction at the drip line



MF and RMF calculations predict different behaviours of the SO interaction when reaching drip lines

→ SO splitting weaker in RMF (comes from isospin dependence)

→Would affect the evolution of shell gaps differently

→ Consequence for the r process nucleosynthesis

G. A. Lalazissis et al . Phys. Lett. B 418 (1998)

ESPE(MeV) for N=28 isotones