Testing the validity of the Spin-orbit force
Nuclear forces at the drip-line

O. Sorlin (GANIL, Caen, France)

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

PART 1:

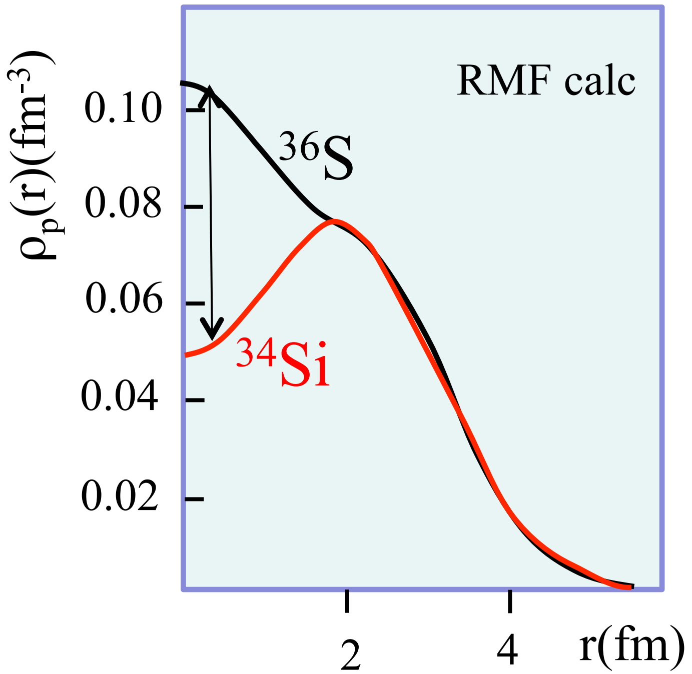
The ^{34}Si a bubble nucleus ?
Probing the neutron SO interaction using the ^{34}Si nucleus
Experimental results on (d,p) reaction
Interpretation, discussion
The ^{34}Si nucleus as a tool to study nuclear matter incompressibility ?!

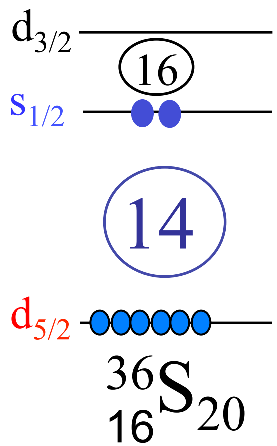
PART 2:

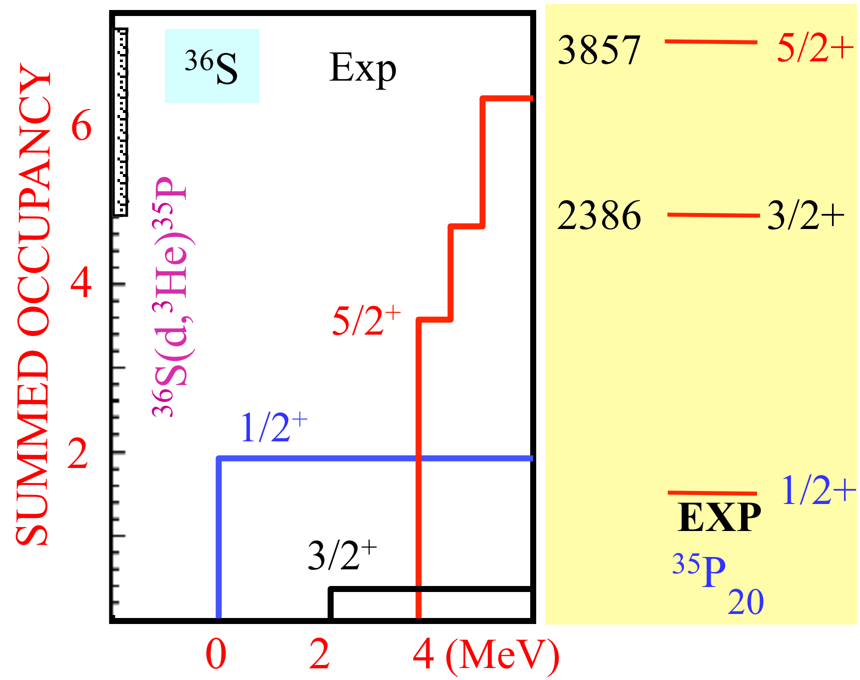
Are proton neutron interactions changing at drip line ?
- Motivation
- The $d_{5/2} - d_{3/2}$ proton neutron interaction in ^{26}F
- Two experimental techniques
- Interpretation/perspectives

$^{34}_{14}$Si a bubble nucleus ?

Grasso et al, PRC 79 (2009)







Khan et al. PLB 156 (1985)

In ^{34}Si, the $s_{1/2}$ orbit should be empty ➔ proton central density depletion

Correlations determined from SM lead to $\Delta s_{1/2}$=1.45

Occupancy of this orbit should be determined using ^{34}Si(-1p) knock out at NSCL

This will provide the amplitude of the proton bubble.

Probing the spin-orbit interaction using the ^{34}Si nucleus

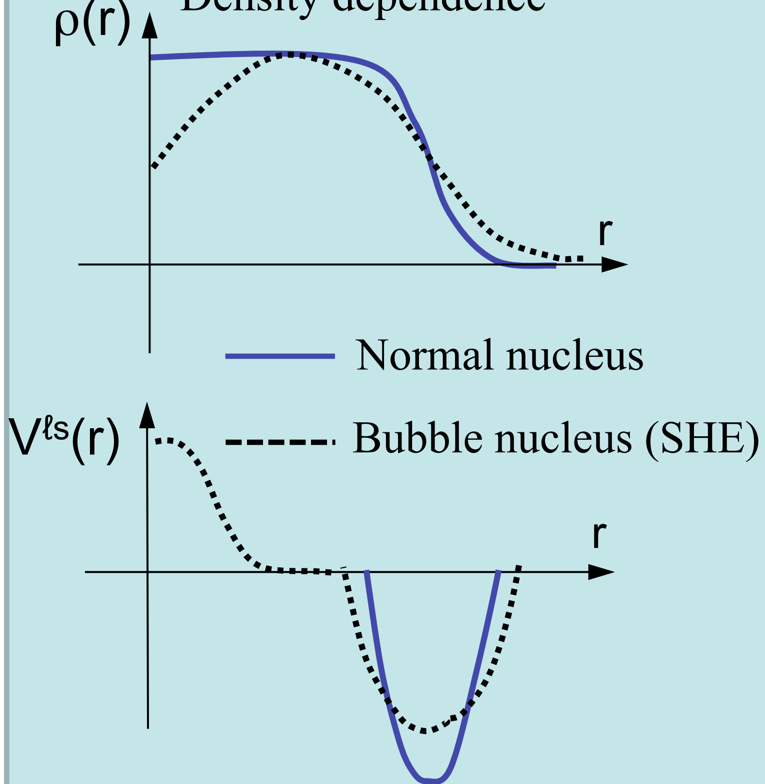
> the mean field theories

> the shell model approach

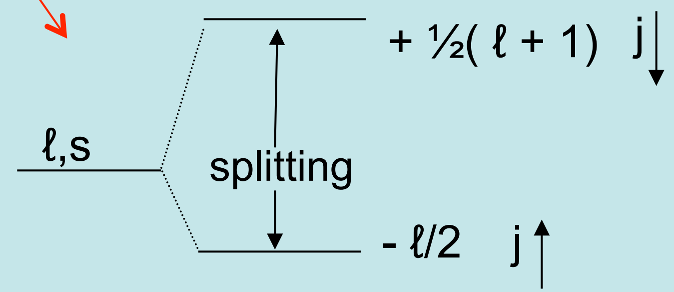
The spin orbit (SO) interaction in Mean Field models

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

Density dependence



- 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

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

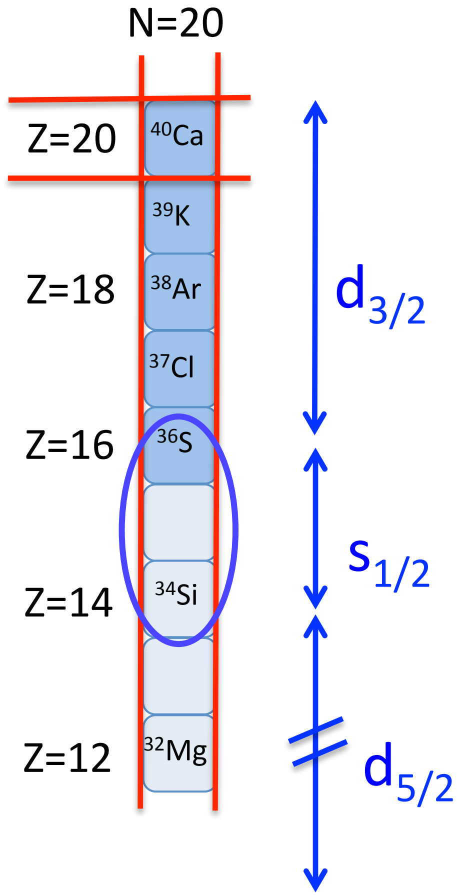
$$W_1 / W_2 \approx 1 \quad (RMF)$$

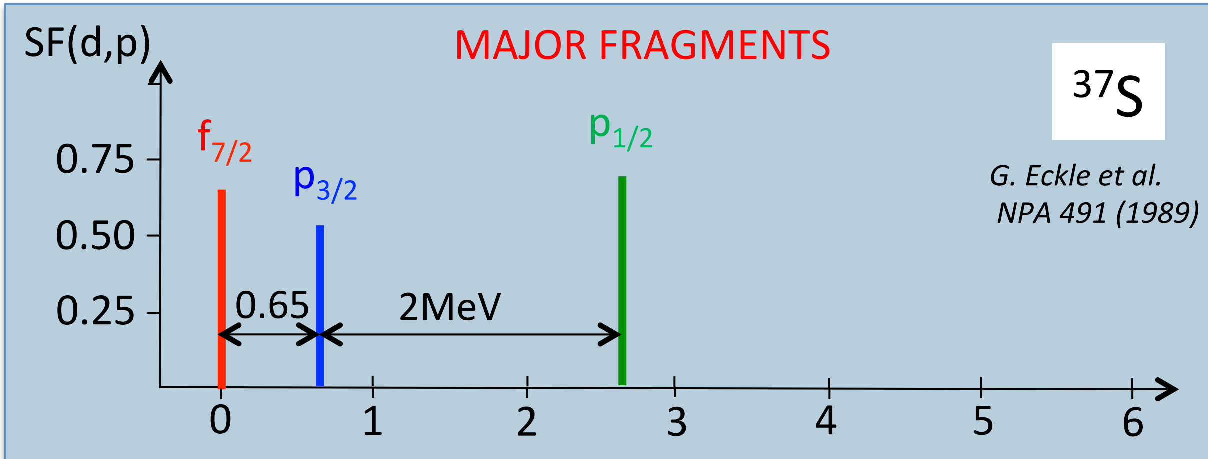
No isospin dependence in RMF

Reduced SO splitting in bubble nucleus for orbits probing the interior of the nucleus !

Reduction magnified in RMF approaches

Probing the two-body SO interaction





^{35}Si

Change of SO splitting ?

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

Pure two-body SO force *See Nowacki, Smirnova, Otsuka*

Determination of the p SO splitting in ^{35}Si

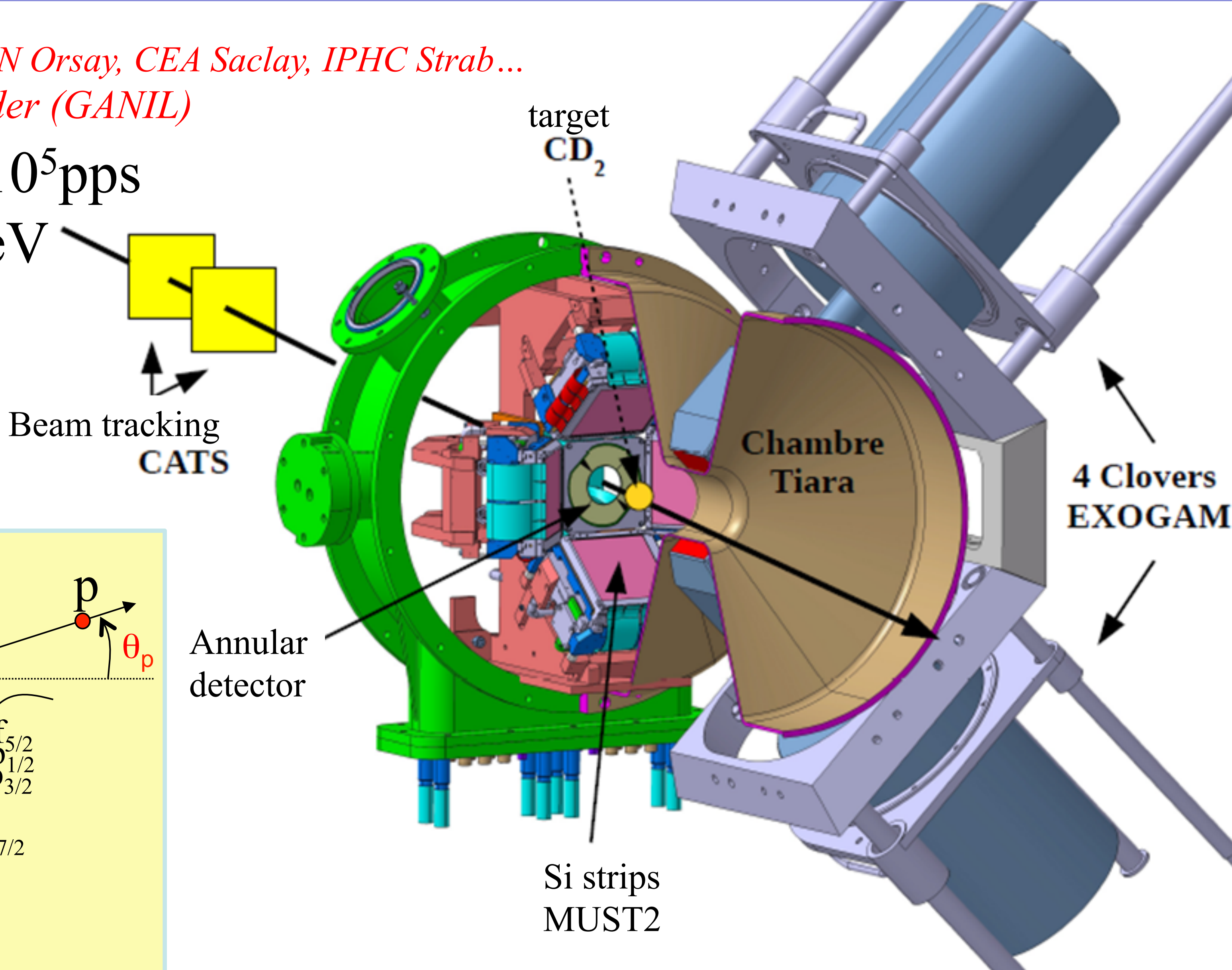
Experimental set up to study the $^{34}Si(d,p)^{35}Si$ reaction

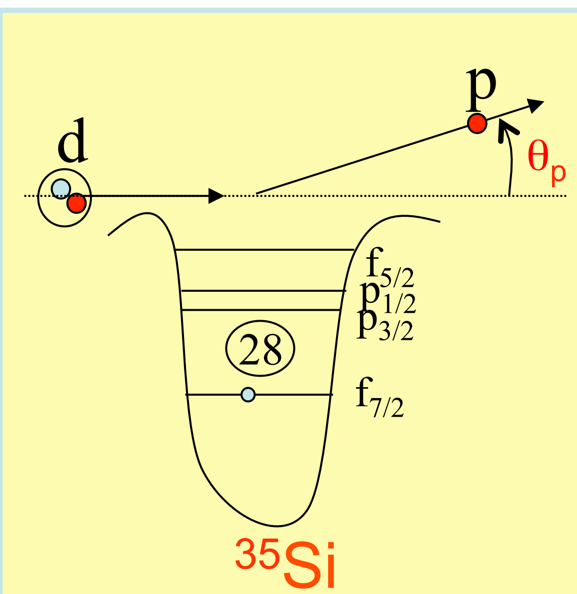
Collab. GANIL, IPN Orsay, CEA Saclay, IPHC Strab…

PHD G. Burgunder (GANIL)

^{34}Si, 2.10^5pps

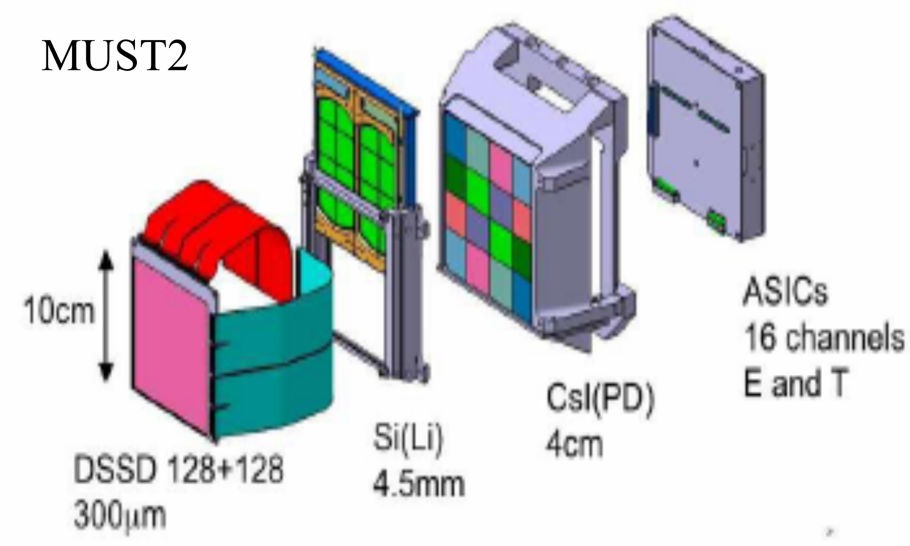
20A.MeV

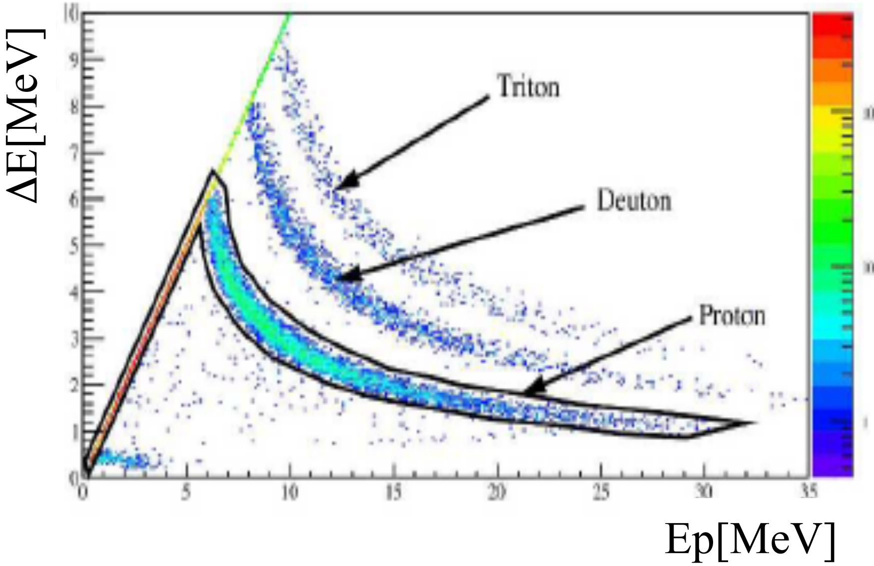


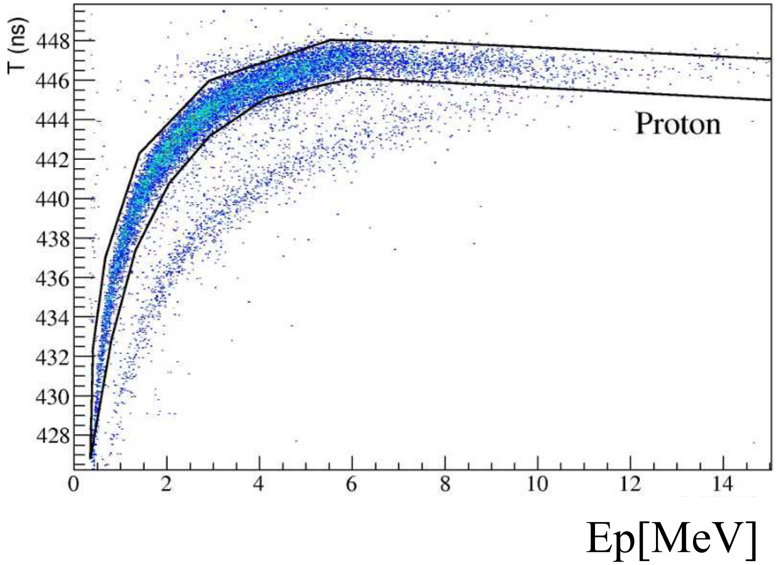


Copyright E. Rindel IPN Orsay

Proton time and energy spectra using MUST2

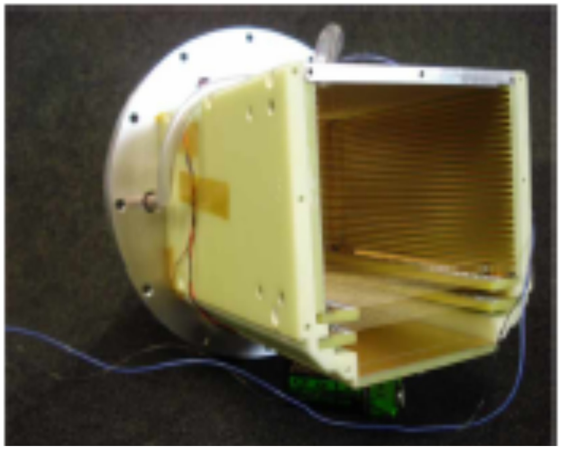


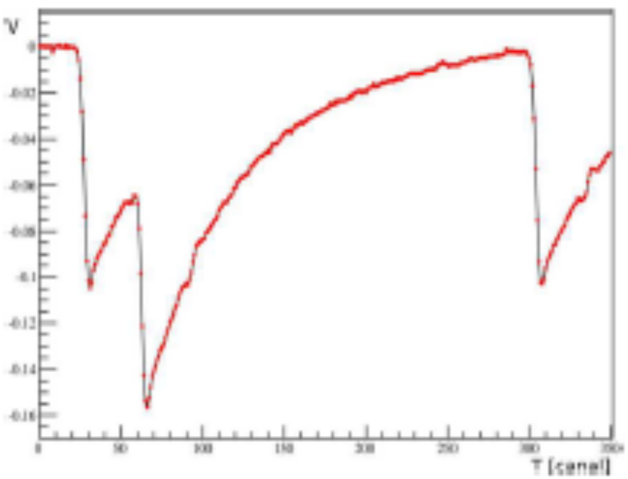


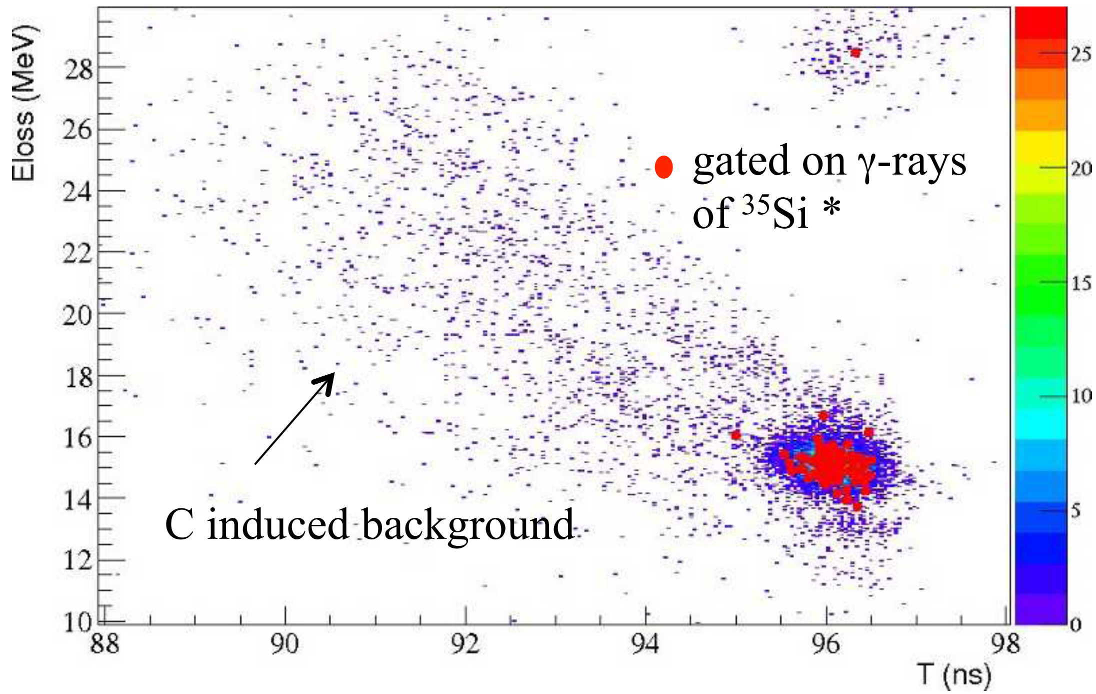


Identification of the Si nuclei

Ionization chamber (CHIO)
C. Spitaels (GANIL),

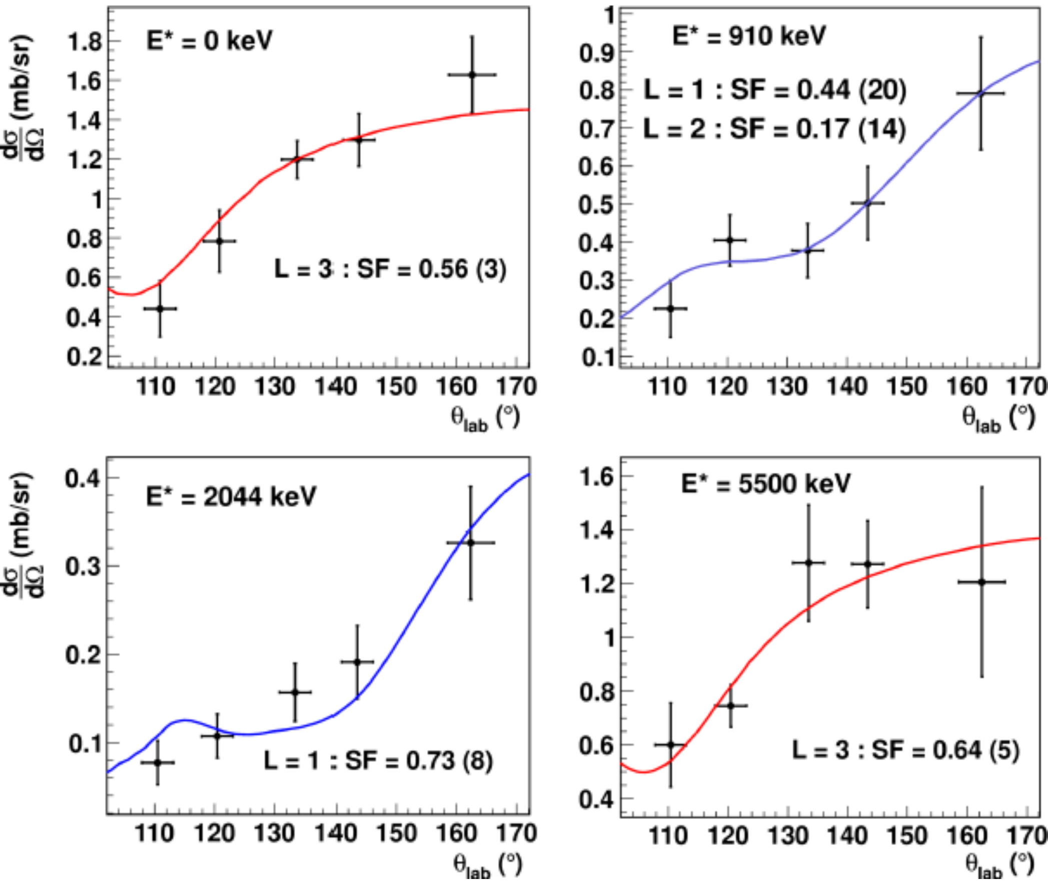


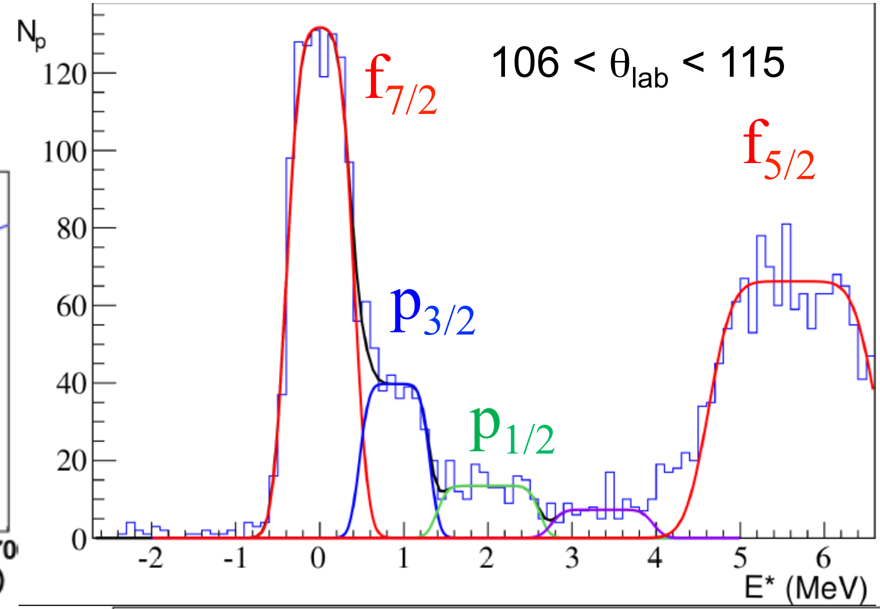


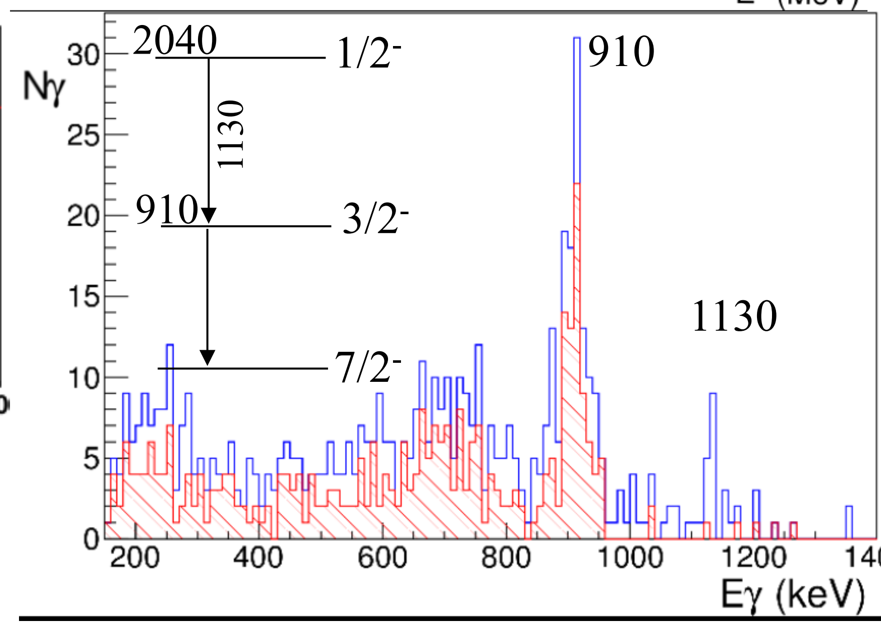


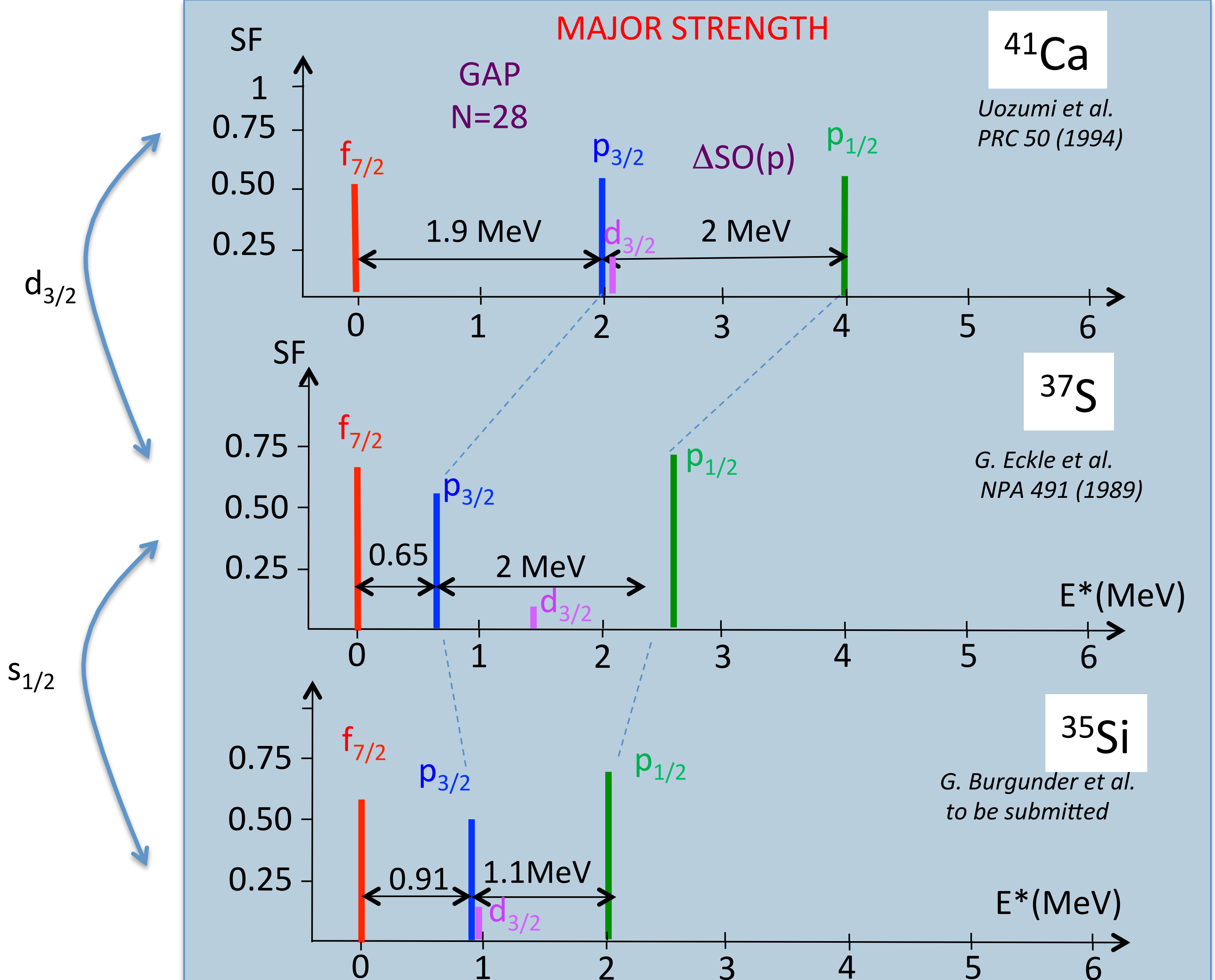
CF_4 gas
70 mbar
Rise time 250ns,
Fall time 1.5 µs
digitized every 10ns

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









Taking correlations into account :

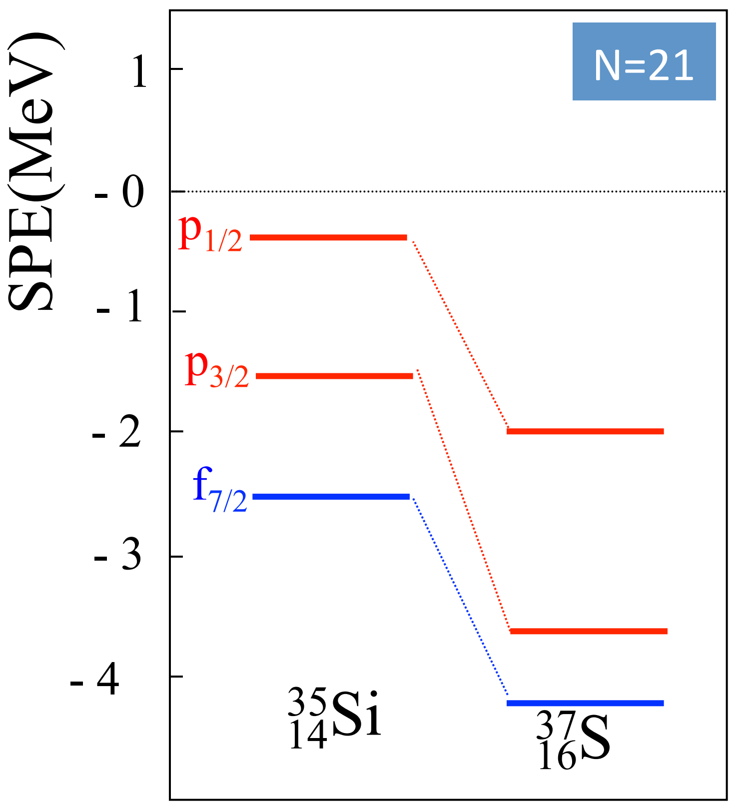
$$\delta(SO\ p) \approx 1.45 \left(V 2s_{\frac{1}{2}} 2p_{\frac{3}{2}}{}^{pn} - V 2s_{\frac{1}{2}} 2p_{\frac{1}{2}}{}^{pn} \right) \approx -400keV$$

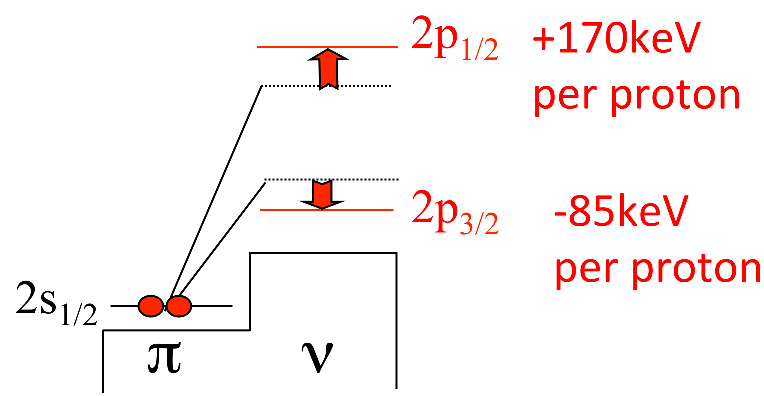
Large change in p SO splitting

Two-body SO interaction

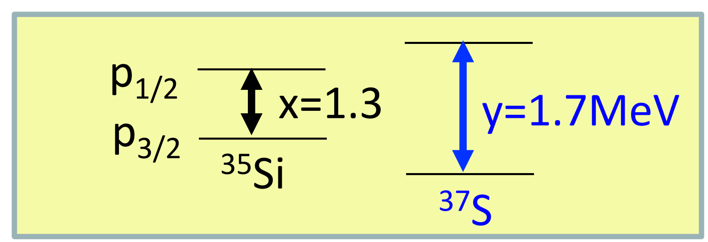
Evolution of SPE from two-body SO interaction

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





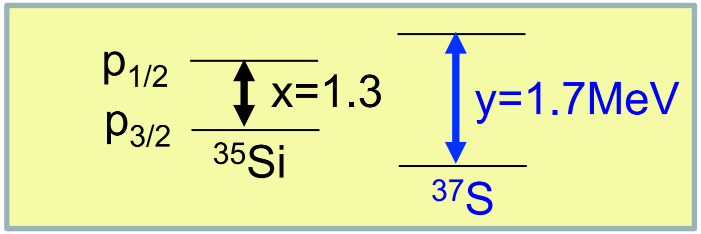
Increase of the SO splitting due to the two- body SO interaction



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

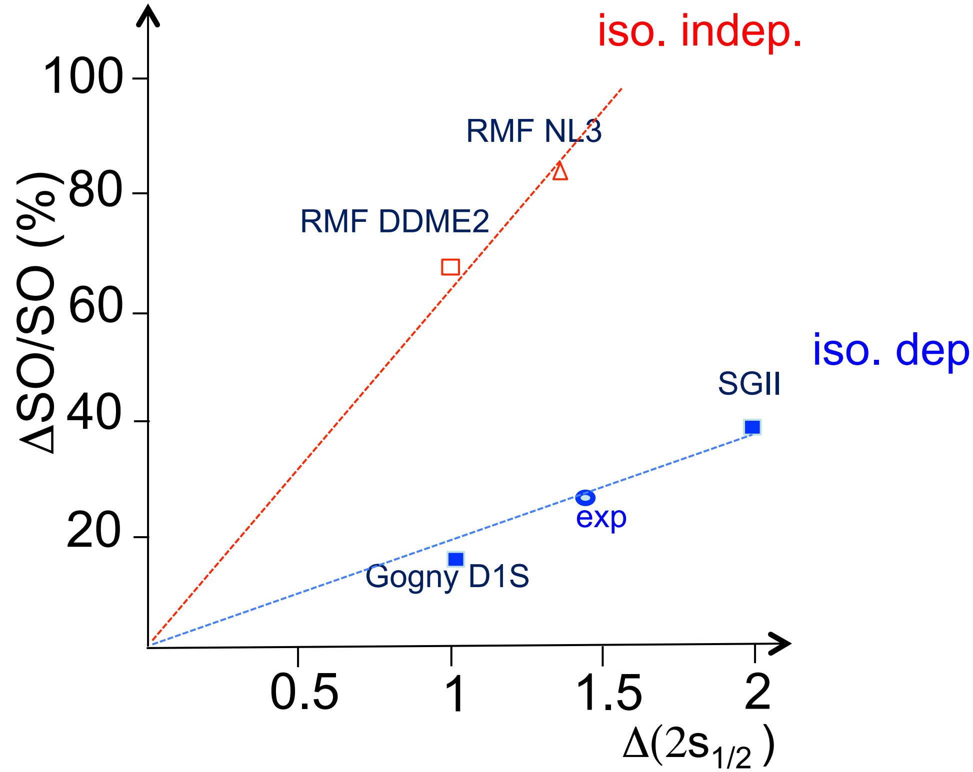
Modification of the SO splitting in a bubble nucleus

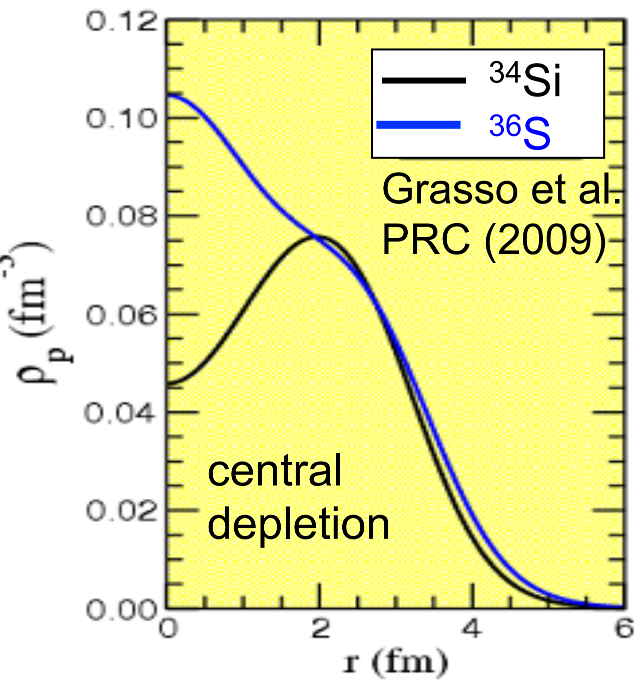
Change of $\nu(p_{1/2}-p_{3/2})$ splitting



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

for $\Delta s_{1/2}$ = 1.45 (tbc @NSCL)





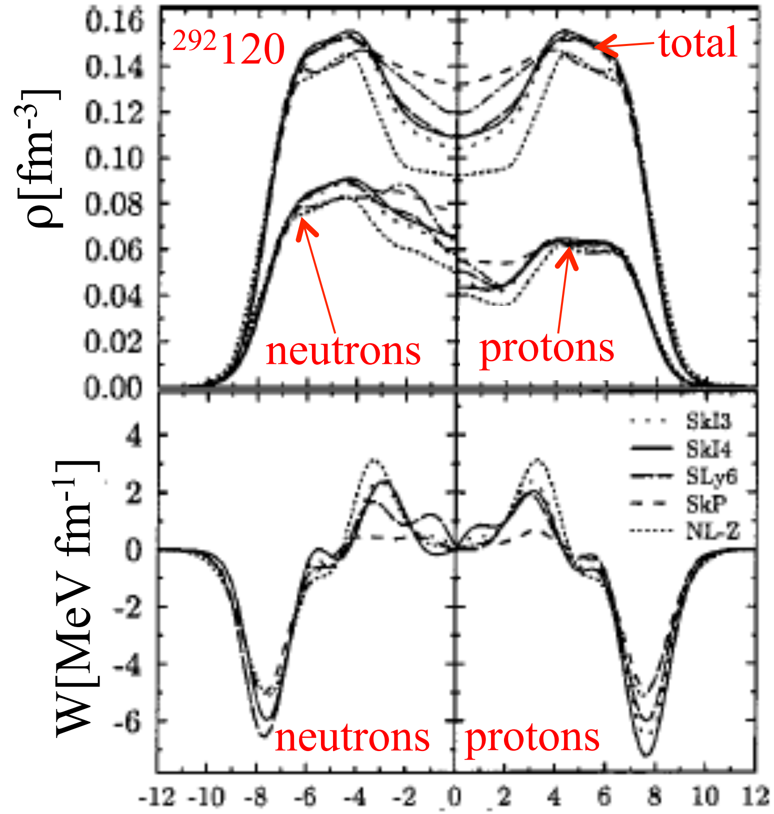
$$W_\tau^{\ell s}(r) = -\left[W_1 \frac{\partial \rho_\tau(r)}{\partial r} + W_2 \frac{\partial \rho_{\tau'\neq\tau}(r)}{\partial r}\right] \vec{\ell}\cdot\vec{s}$$

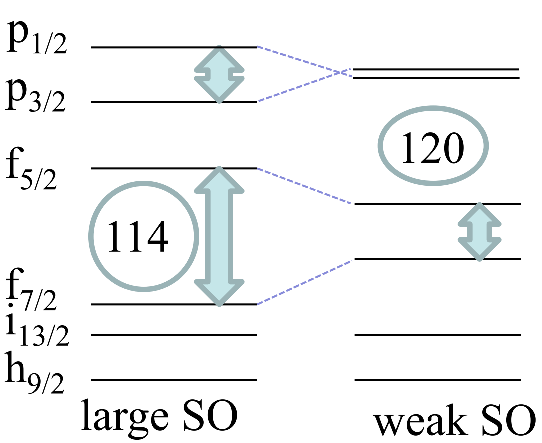
$W_1 / W_2 \approx 2 \quad (MF)$ isospin dependence

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

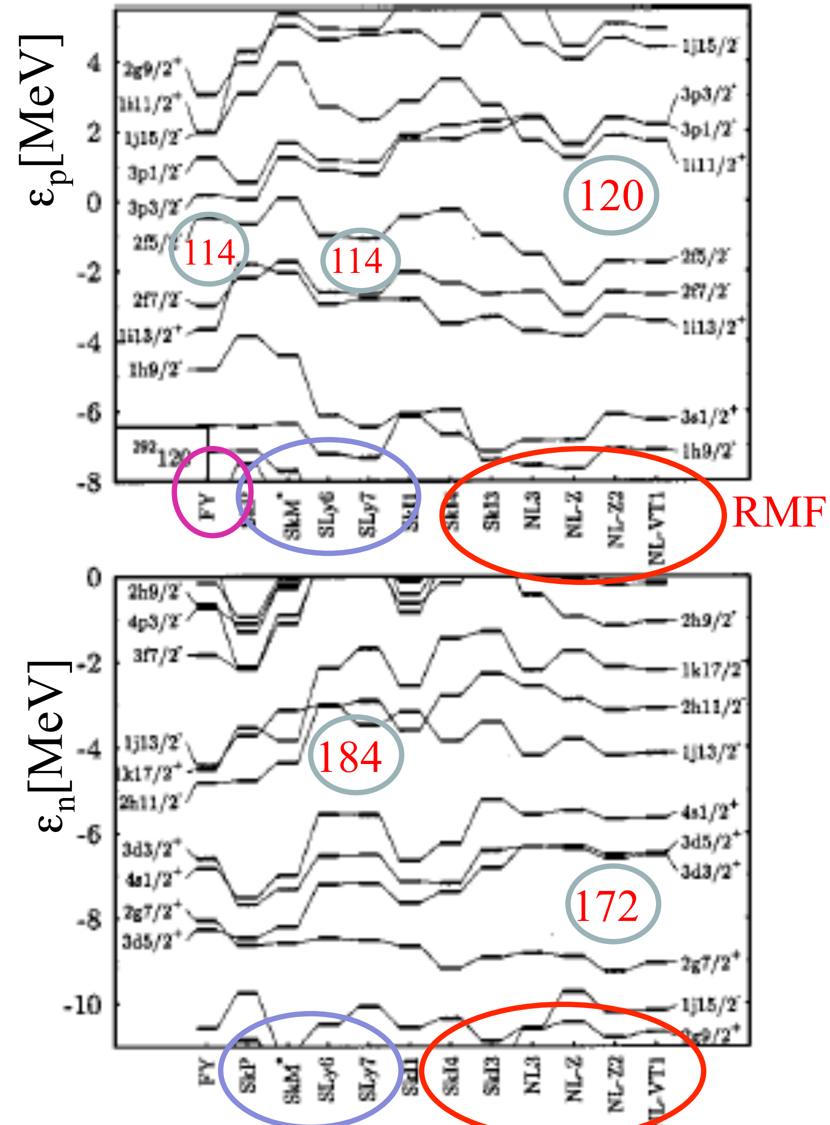
Exp. favors density AND isospin dep. of SO interaction
Anticipate consequences for drip line and SHE nuclei …

Spin orbit interaction and superheavy elements





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

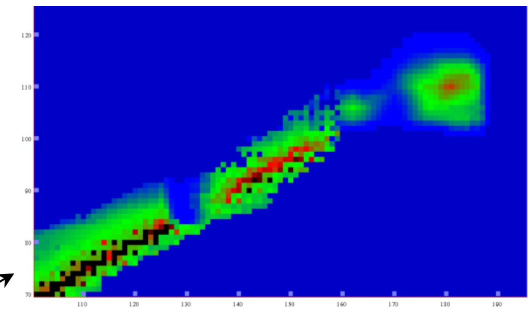


Size of gaps depends on strength of the SO force

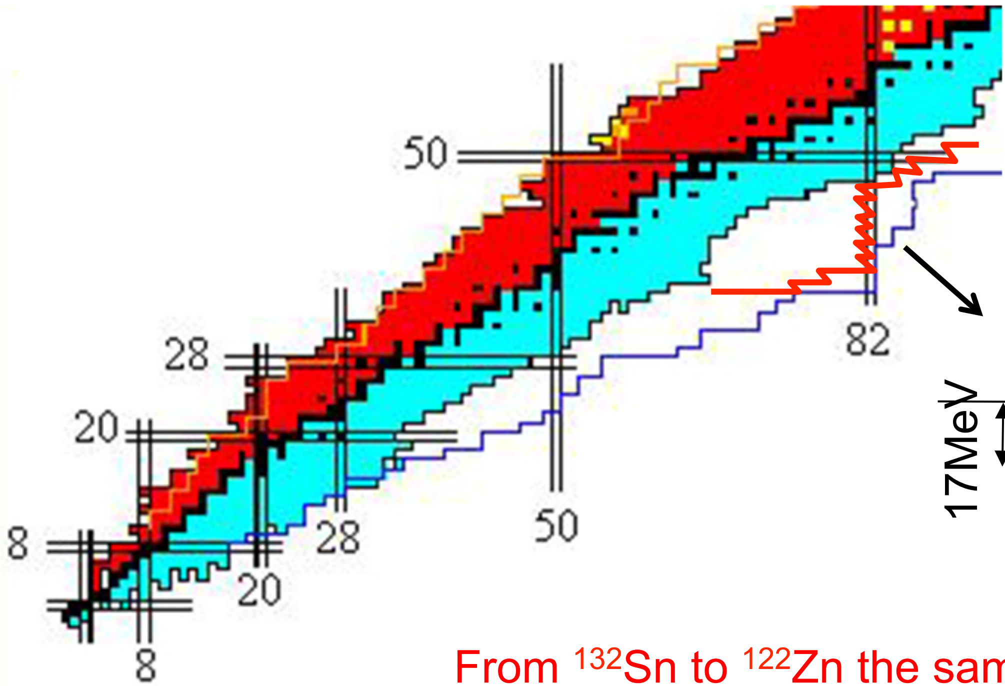
Island of SHE favoured at Z~120 in RMF

Studying proton-neutron interactions at the drip line

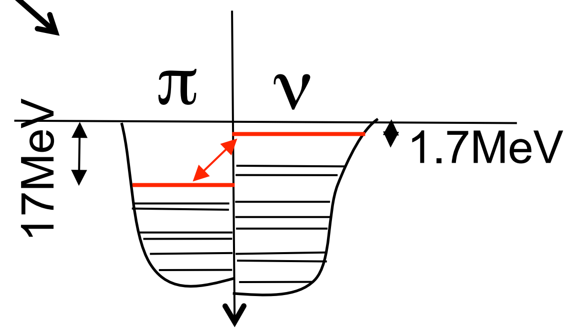
Nuclear forces at large proton-neutron asymmetry energy



Superheavy nuclei



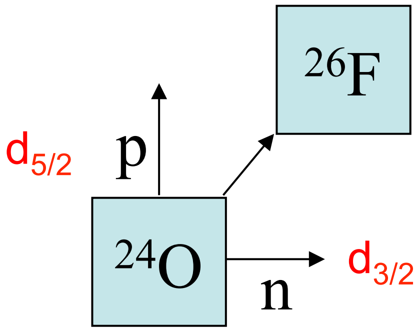
Rapid neutron capture
Explosive nucleosynthesis



From ^{132}Sn to ^{122}Zn the same proton $g_{9/2}$ orbit intervene
-> Same pn interactions involved !
But change in binding energy asymmetry.

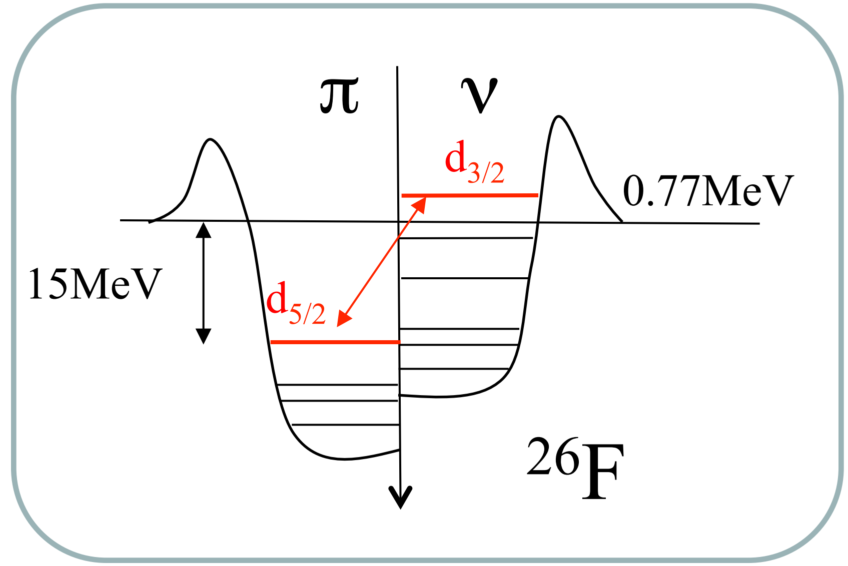
Do proton-neutron interactions change at large p-n binding energy asymmetry ?

Are proton-neutron interactions similar at drip line ?

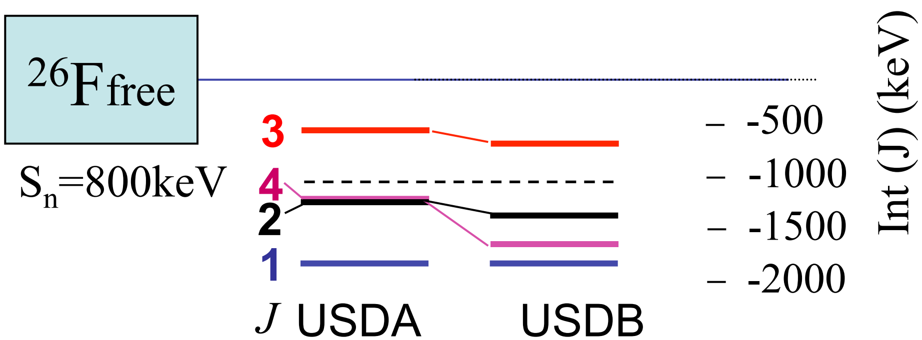


$V^{pn}\,(d_{3/2}d_{5/2})$

J=1,2,3,4



^{25}O unbound, Hoffman PRL 100 (2008)
^{26}F g.s. J=1 from beta-decay, Reed et al. PRC
3^+ : Frank et al., PRC (2011)
Masses: Jurado PLB 649 (2007)



Shell Model, Brown

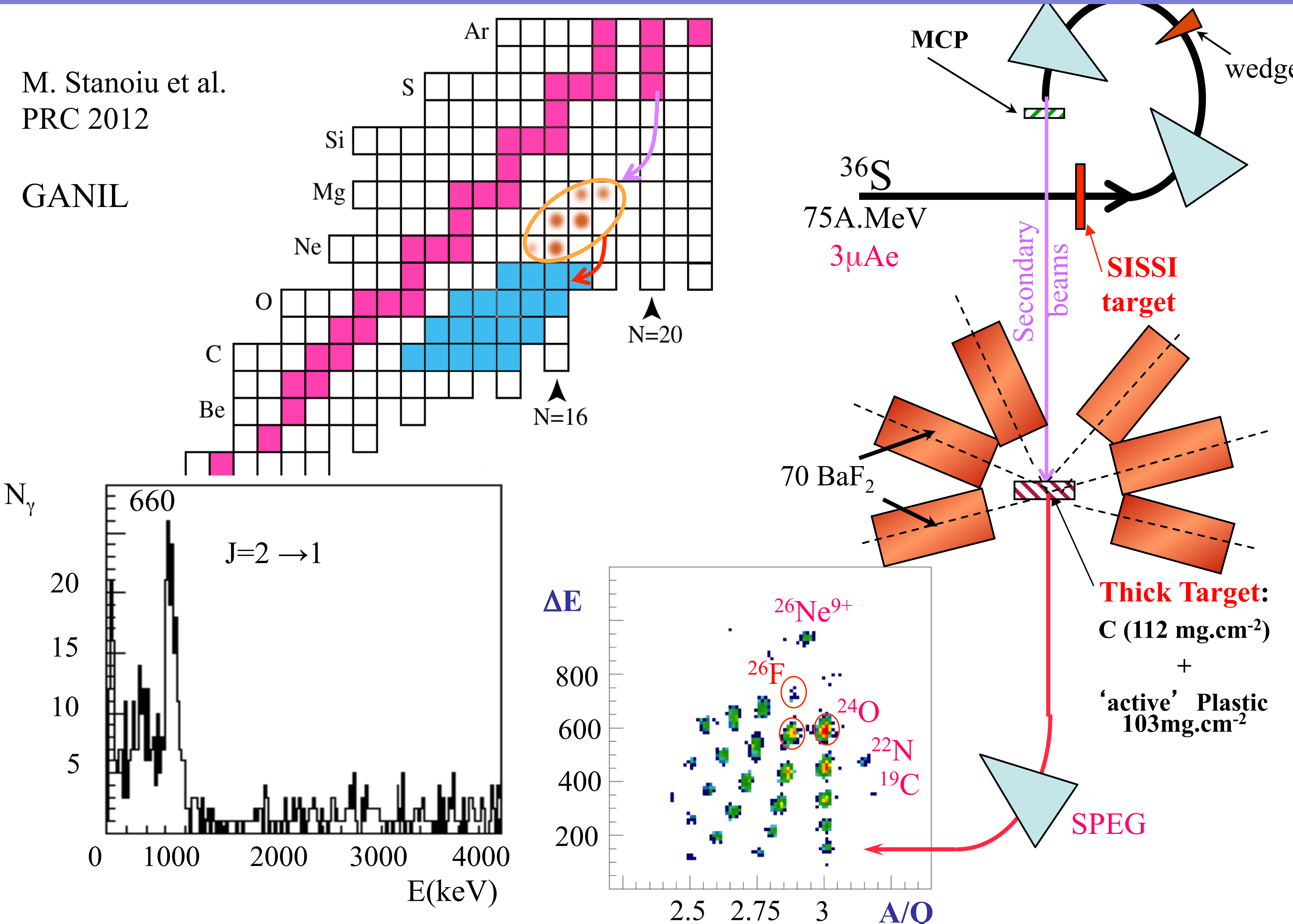
Search for J=2, 4 states using different experimental techniques

Compare experimental binding energies in ^{26}F to those predicted by Shell Model using effective forces constrained closer to stability → need spectroscopy of ^{26}F.

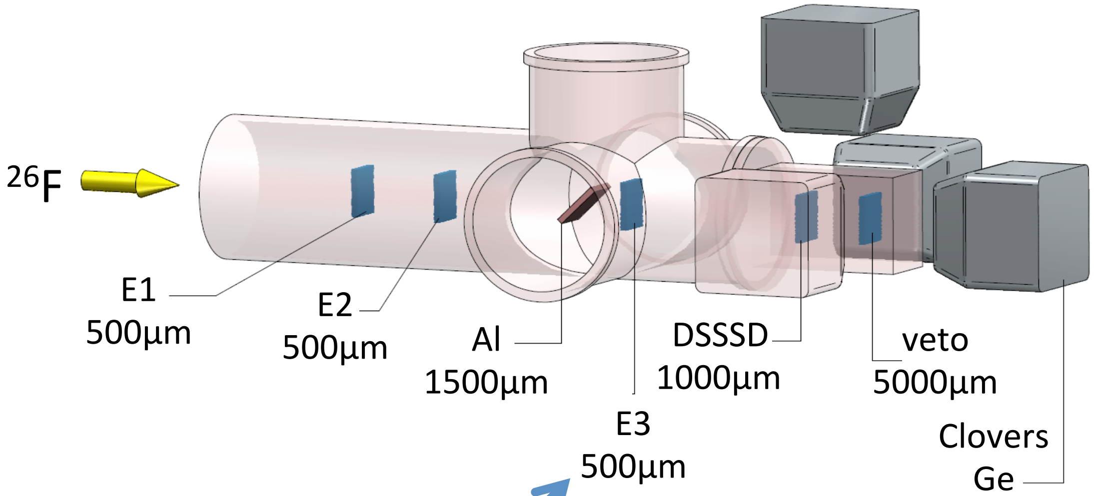
Search for J=2 excited state in ^{26}F

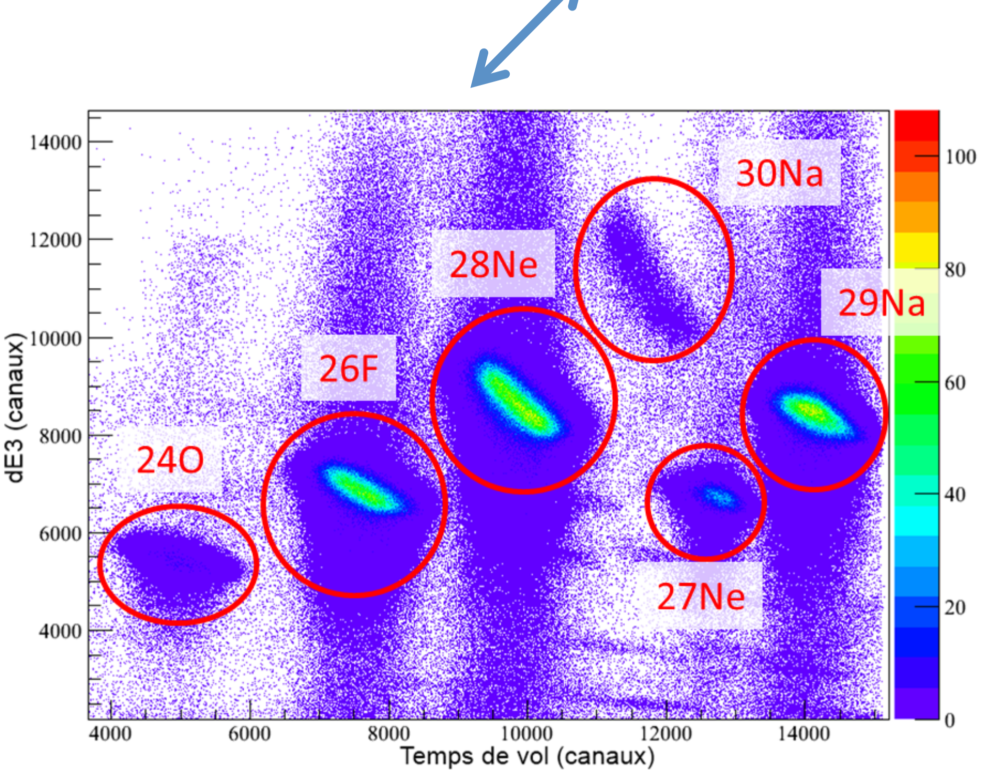
M. Stanoiu et al.
PRC 2012

GANIL



Search for the isomeric 4^+ state in ^{26}F





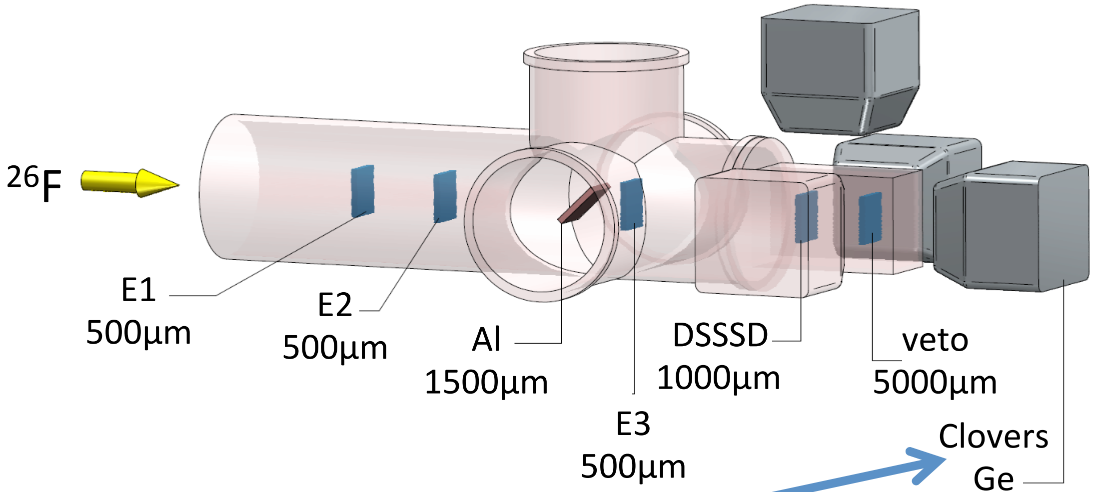
A. Lepailleur (PhD thesis, GANIL)

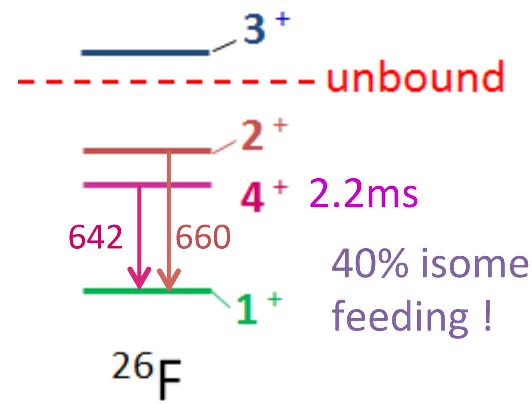
^{28}Ne : 10.4/s

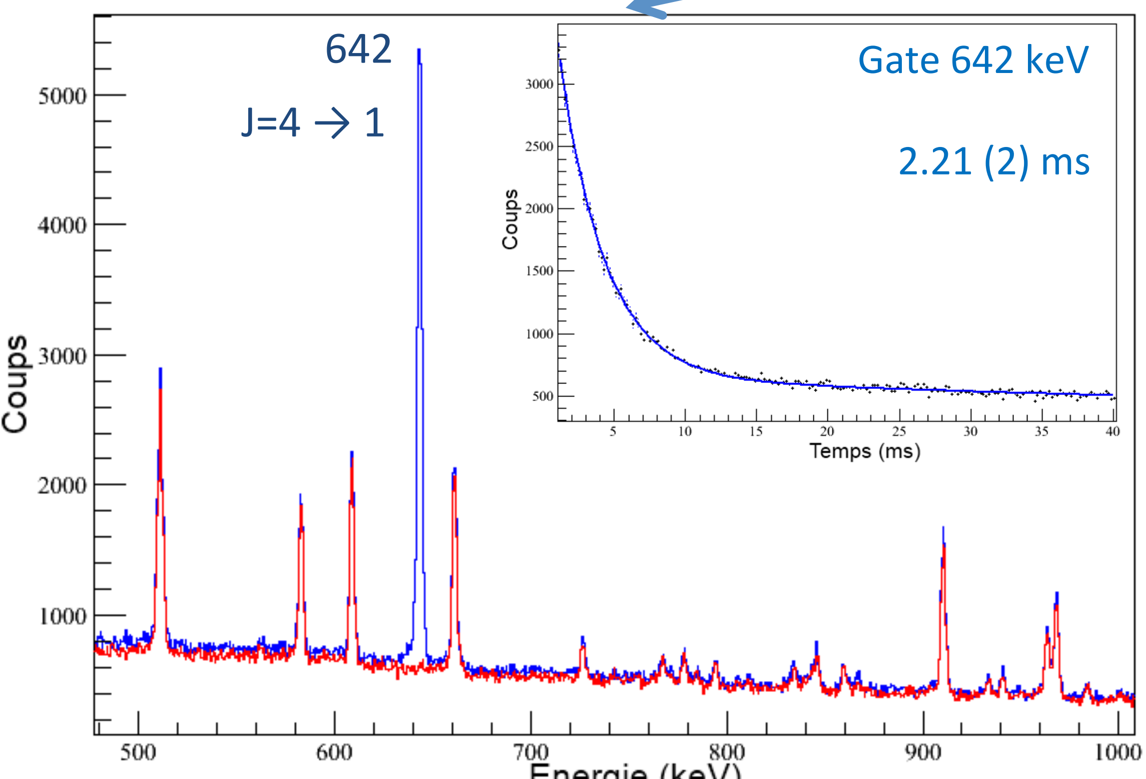
^{26}F : 5.5/s

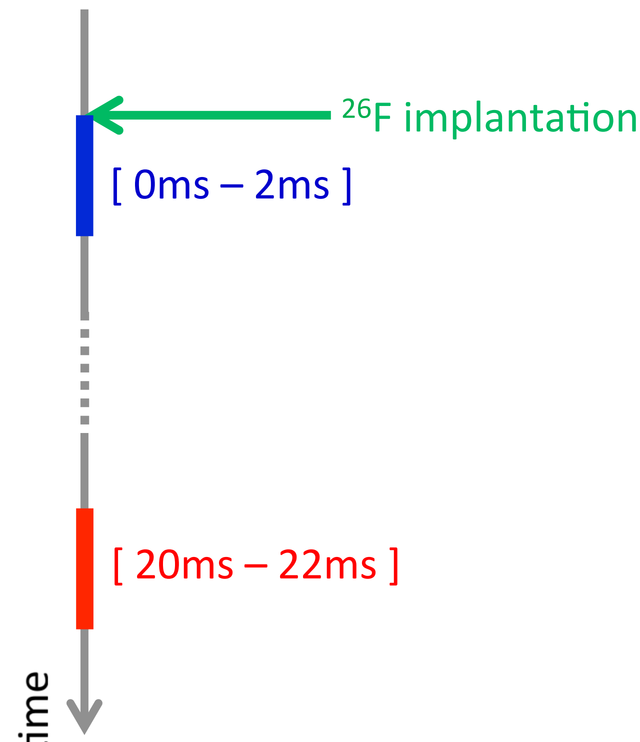
^{24}O : 0.058/s

Showing of this isomeric 4^+ state in ^{26}F



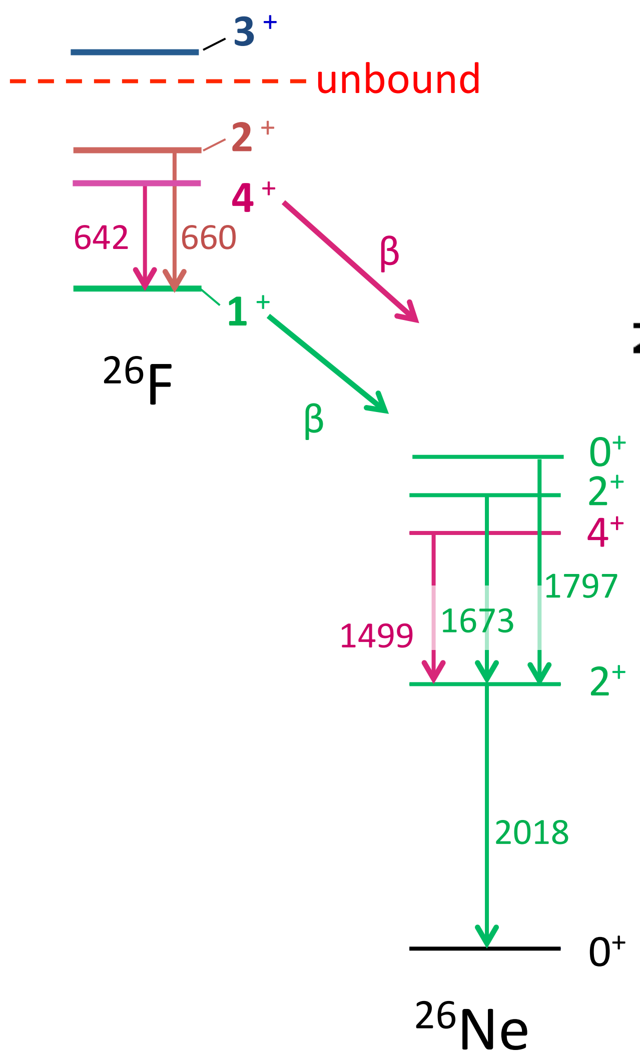


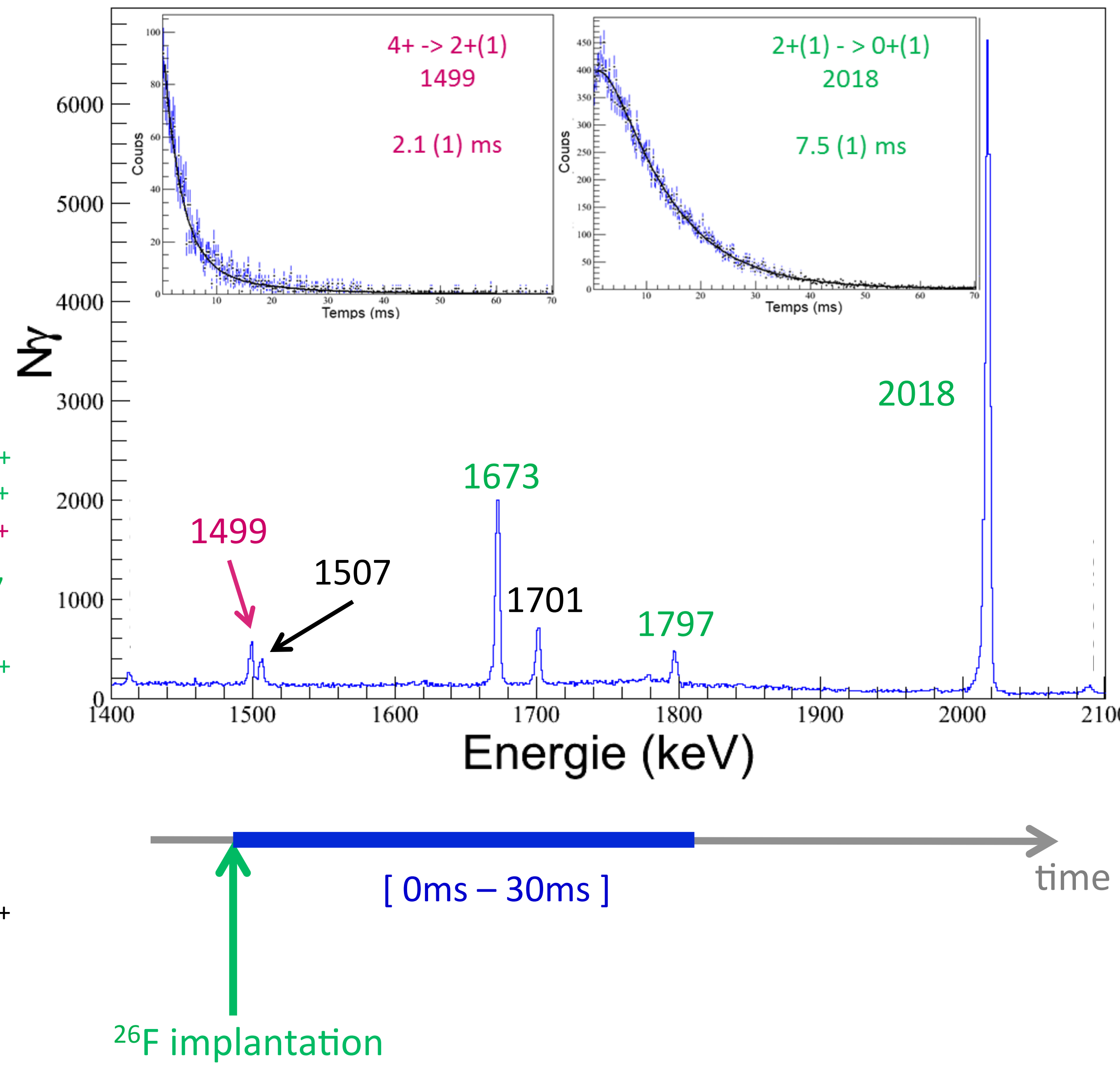




Study of the beta decay of ^{26}F

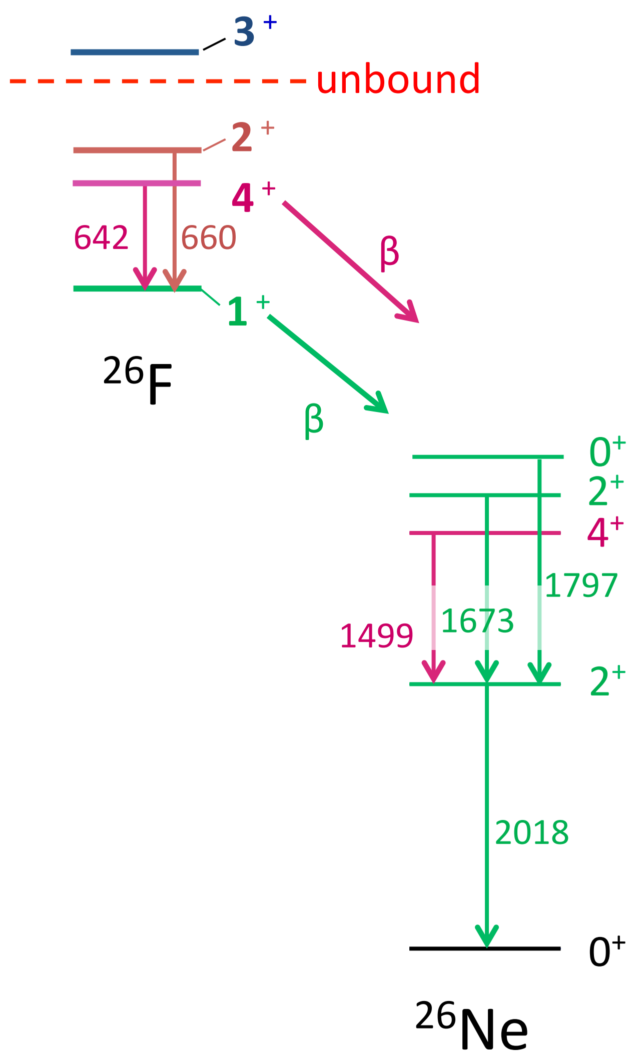
β-decay selection rules :
ΔJ = 0 , ±1

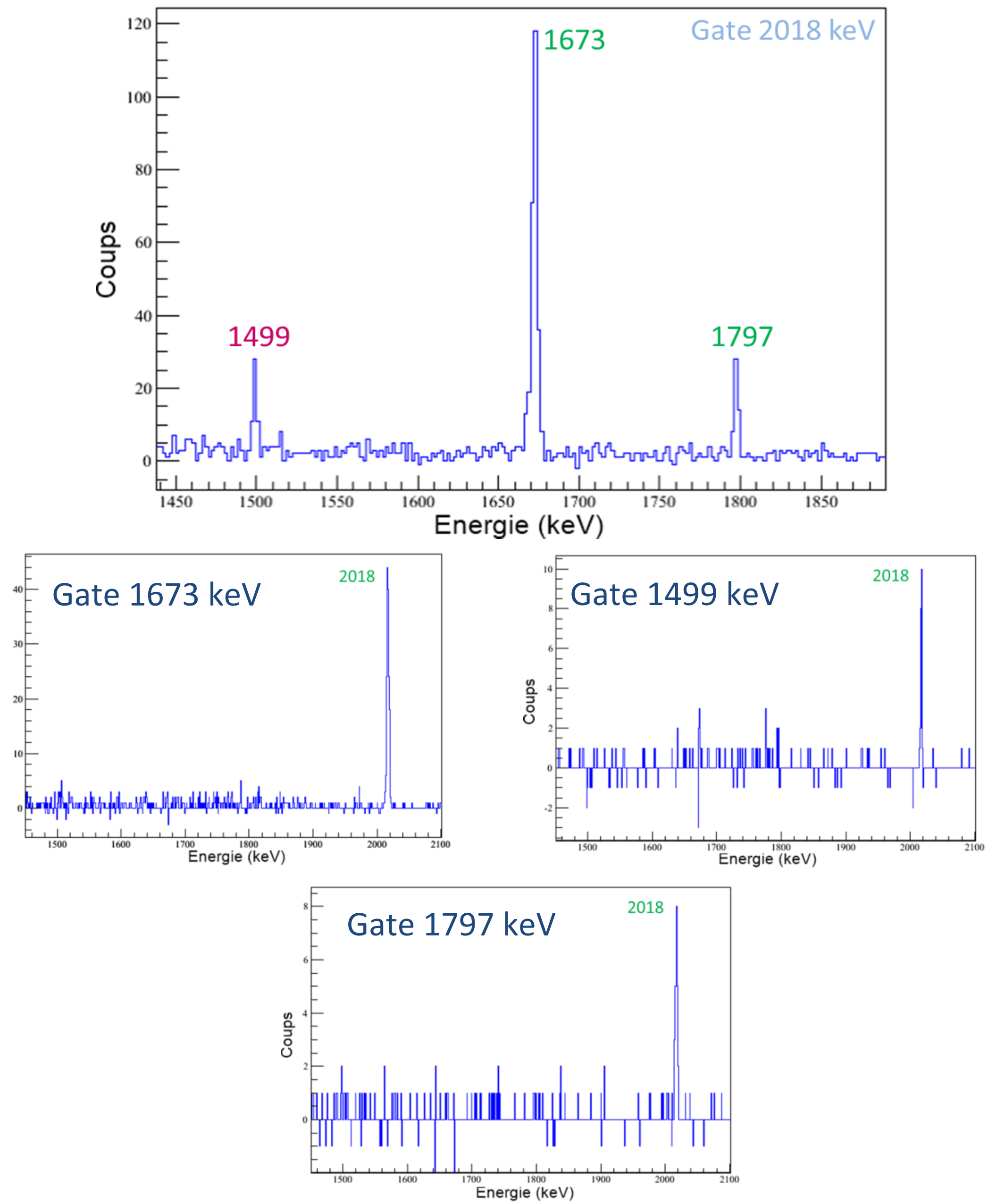




Study of the beta decay of ^{26}F

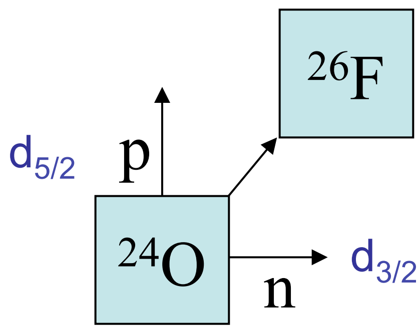
β-decay selection rules :
$\Delta J = 0 , \pm 1$

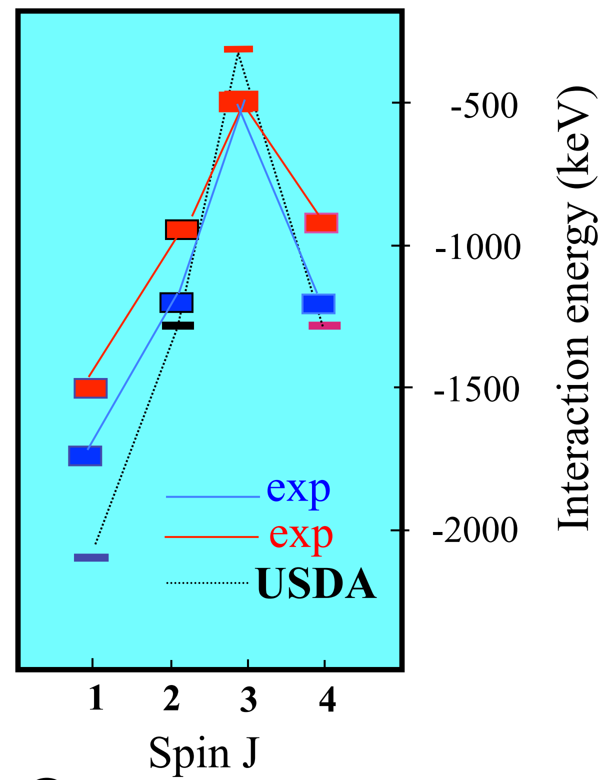


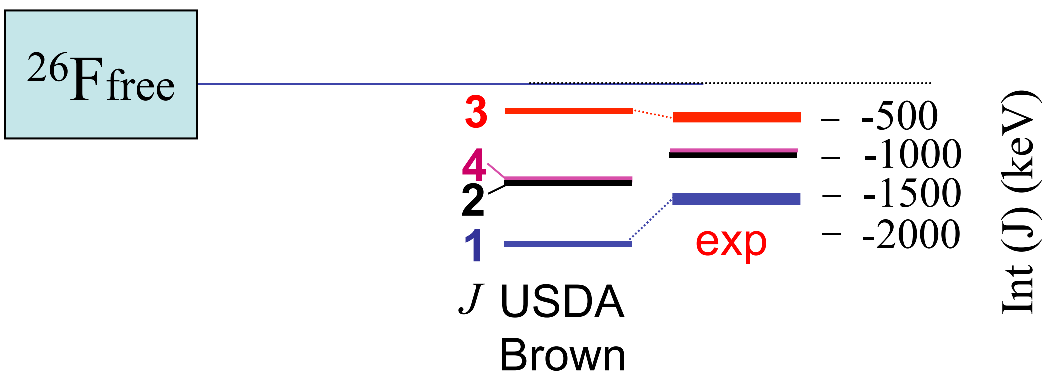


Proton-neutron interaction $d_{5/2}d_{3/2}$ in ^{26}F

$V^{pn}(d_{5/2}d_{3/2})$







Assuming 40% isomer

Reduced interaction as compared to Shell Model
+ Global shrink of levels -> reduced residual interaction
Use proper treatment of continuum …

Conclusions & Perspectives

PART 2 :

Determine spectroscopy of ^{26}F to infer the change of the proton-interaction close to drip line

→Global reduction of the interaction and residual interaction

→Should be taken into account to model $^{27\text{-}29}F$ isotopes

Check the atomic mass, confirm energy/spin assignment of the 3^+ unbound state

Systematics study of N=17 isotones to be carried out.

PART 1:

Use of a bubble nucleus ^{34}Si to probe the spin-orbit interactoion

Change of the neutron $p_{3/2}$-$p_{1/2}$ splitting by ~25% between ^{36}S and ^{34}Si.

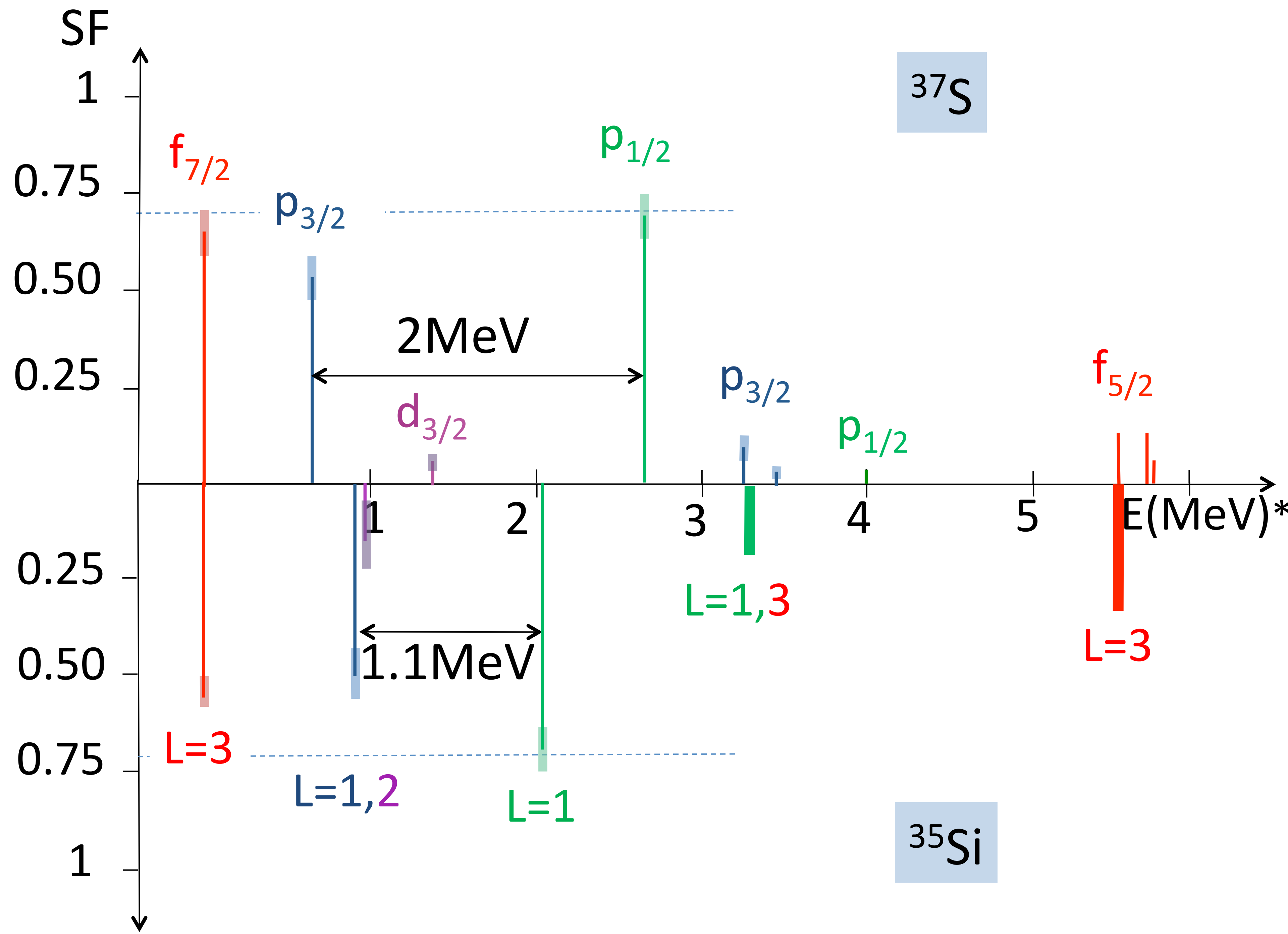
Unique way to determine the strength of two-body SO interaction

Exp value close to MF predictions -> isospin dep. of SO interaction

Determine the amplitude of the bubble (exp currently been analyzed)

Consequences for SHE ?...

Use bubble nucleus to study matter incompressibility at low ρ !



SF
1
0.75
0.50
0.25
0.25
0.50
0.75
1
f7/2
p3/2
p1/2
2MeV
d3/2
p3/2
p1/2
f5/2
1
2
3
4
5
E(MeV)*
L=1,3
L=3
1.1MeV
L=3
L=1,2
L=1
37S
35Si