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

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

PART 1:

Introduction to the SO interaction

- Historical picture -> magic numbers
- The SO in the Relativistic Mean Field approach
- Role at drip line and in Superheavy nuclei

A ‘bubble’ nucleus to probe the validity of the SO interaction

- ^{34}Si a bubble nucleus
- Predictions
- Use of transfer reaction
- Interpretation

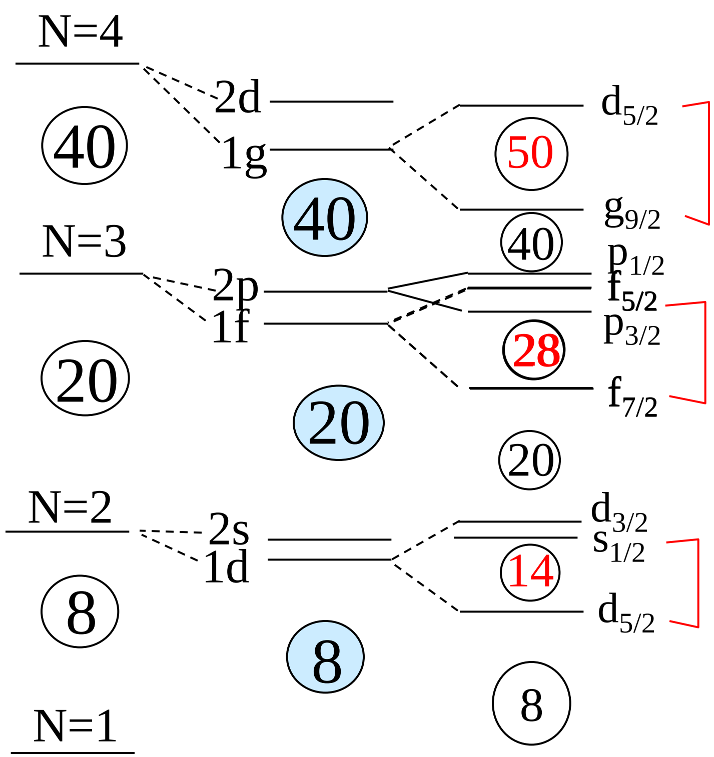
PART 2:

How 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
- Intepretation

The Spin orbit interaction: definition, effects

Spin orbit force and magic numbers



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

Spin Orbit
6, 14, 28, 50, 82, 126

M. Goppert-Mayer, Haxel et al.
Nobel prize 1949

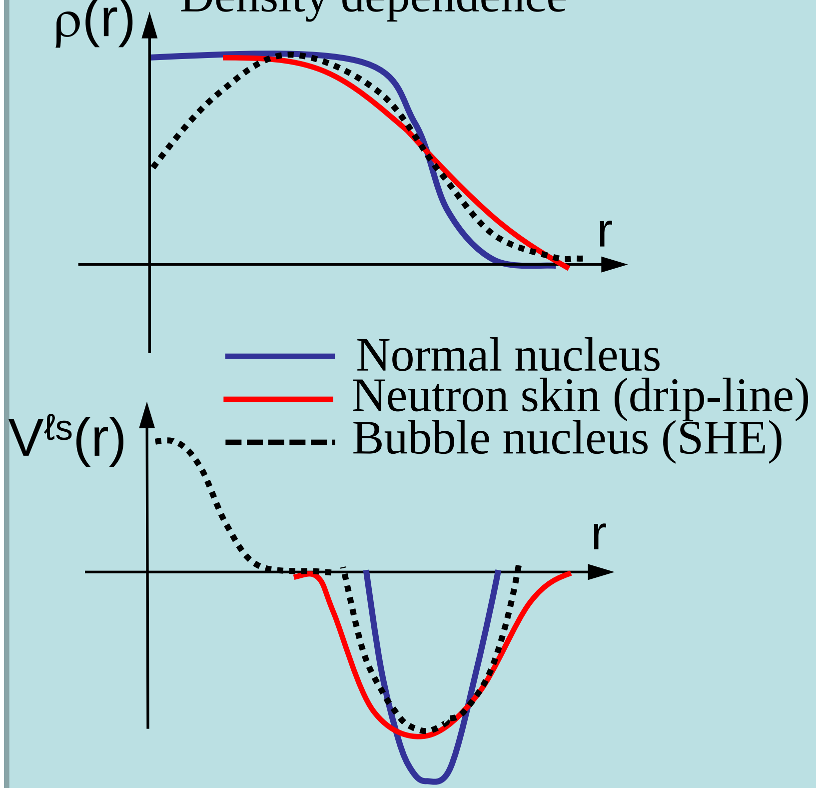
$$V^{\ell s}(r) = -v\left[\frac{\partial \rho\,(r)}{\partial r}\right]\vec{\ell}\cdot\vec{s}$$

The SO interaction has been introduced to account for the existence of large shell gaps (magic numbers) which could not be explained otherwise …

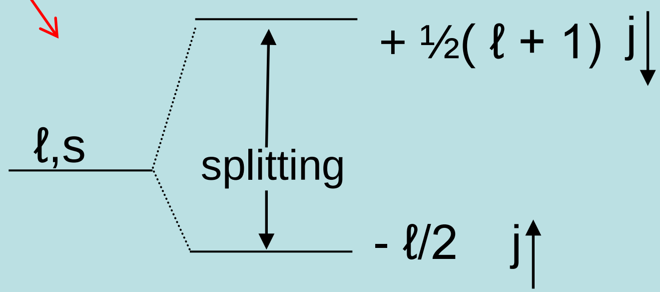
The spin orbit (SO) interaction in Mean Field models

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

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

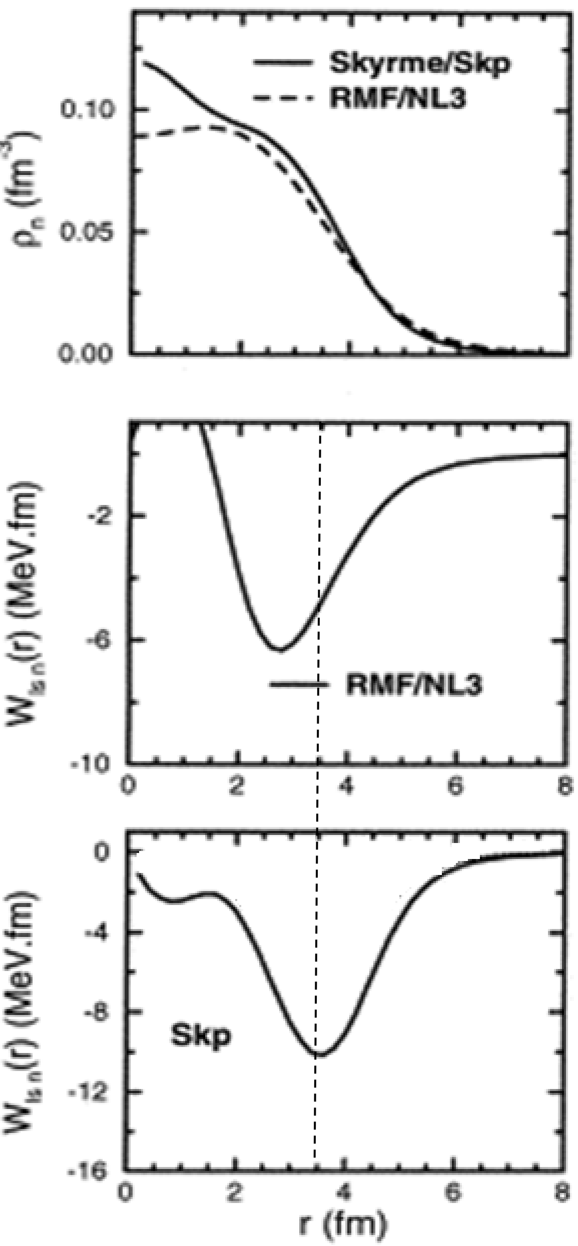
$$W_1 / W_2 \approx 2 \quad (MF)$$

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

No isospin dependence in RMF

The spin orbit interaction at the drip line

^{40}Ne



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

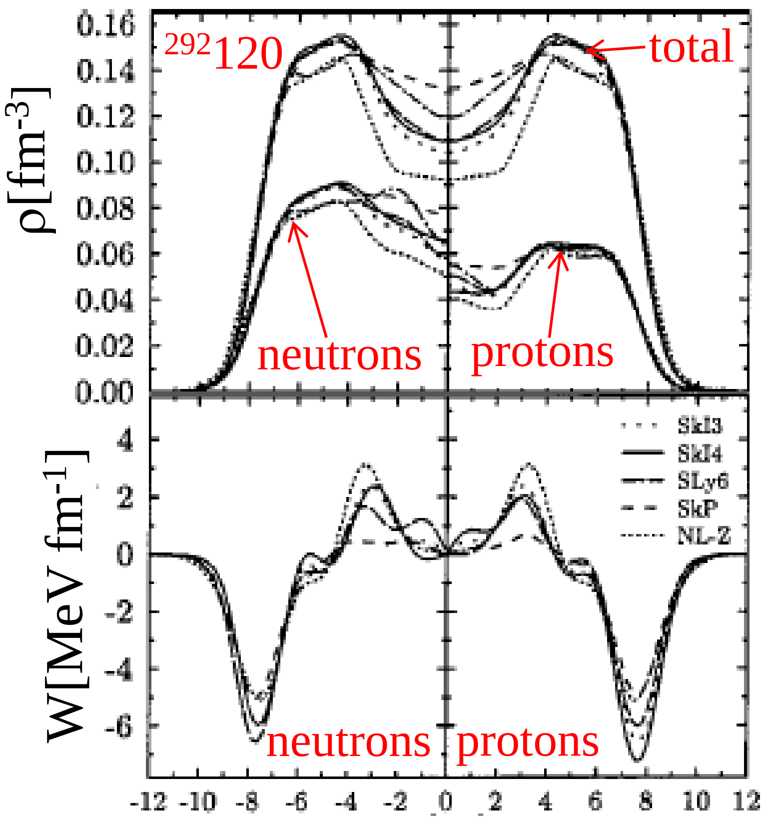
→ SO splitting weaker in RMF (comes from isospin dependence)

→Would affect the evolution of shell gaps differently

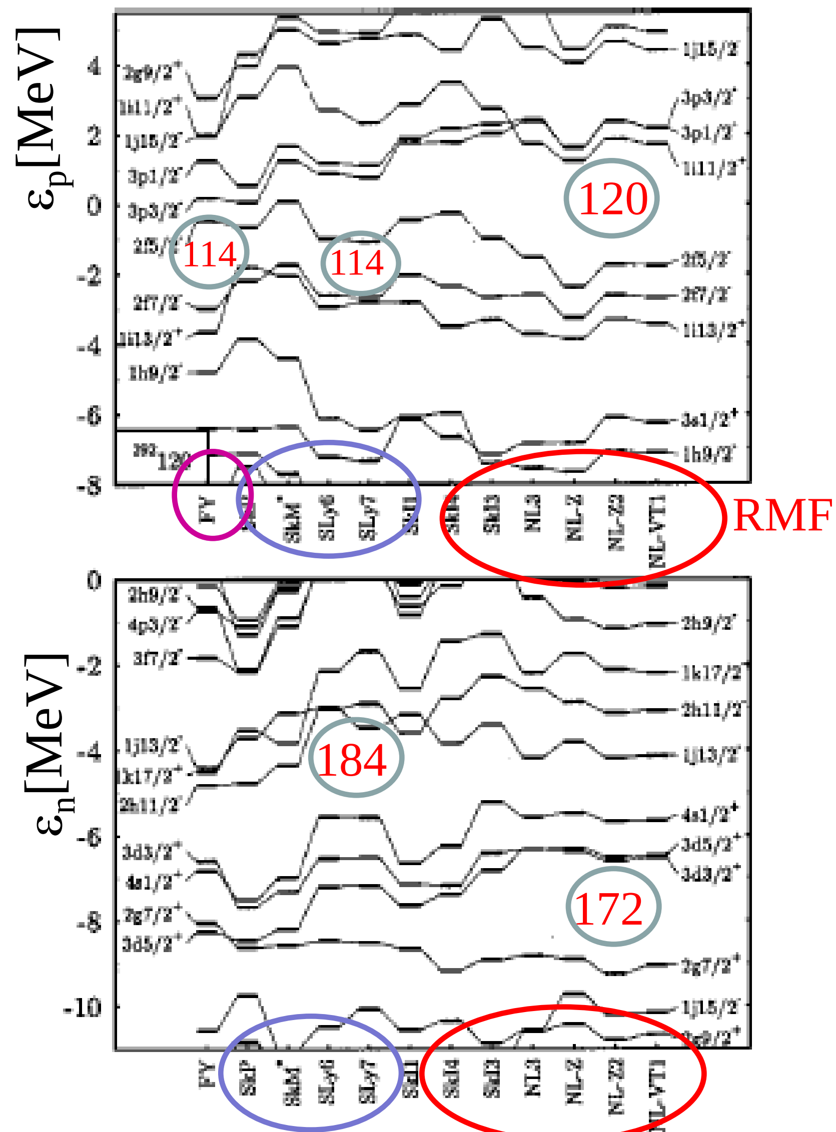
→ Consequence for the r process nucleosynthesis

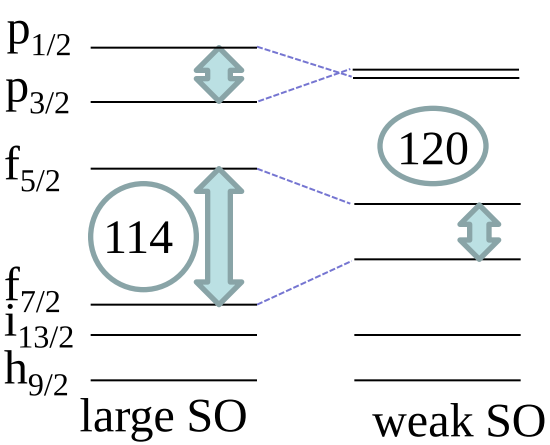
G. A. Lalazissis et al . Phys. Lett. B 418 (1998)

Spin orbit interaction and superheavy elements



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



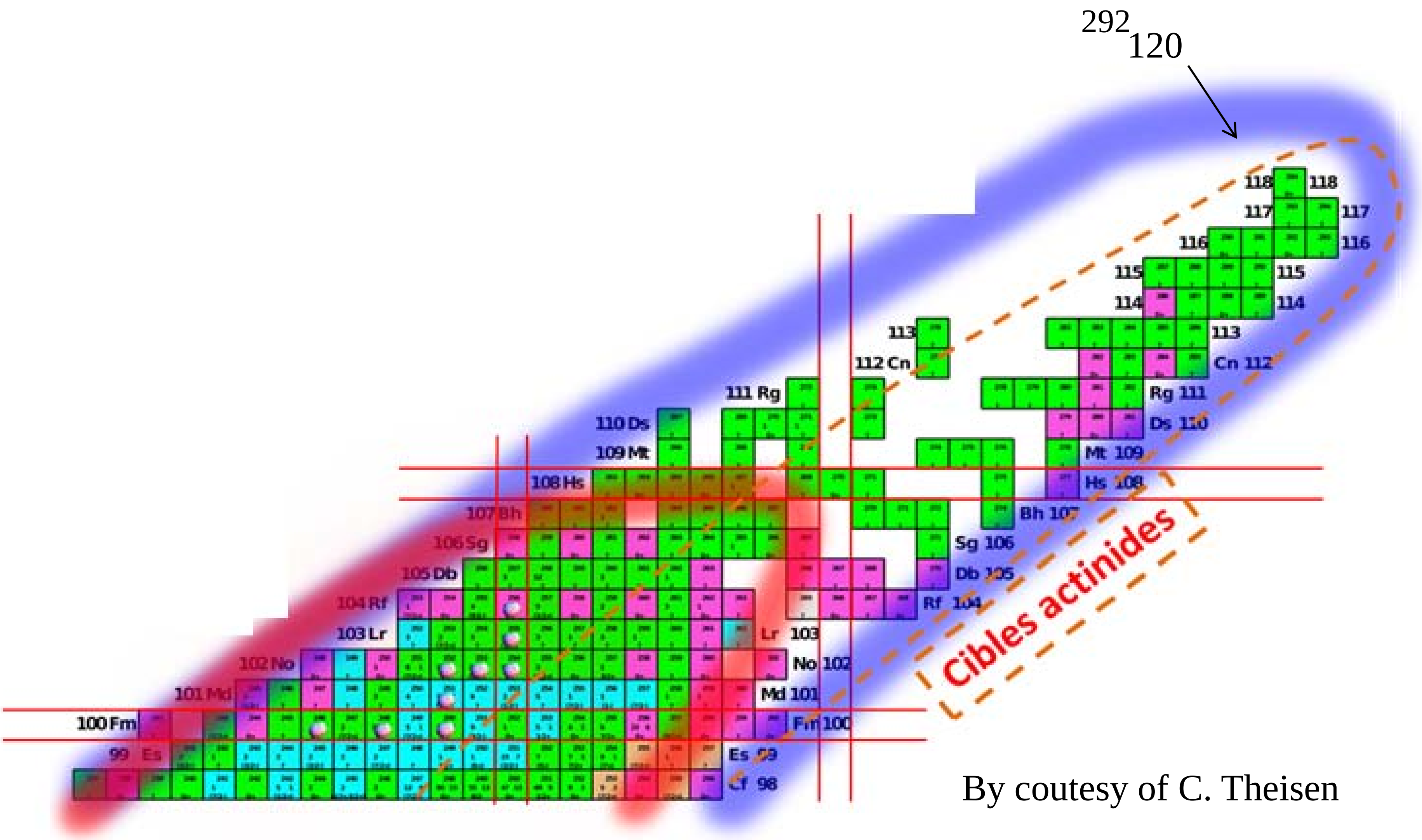


Size of gaps depends on strength of the SO force

Island of SHE favoured at Z~120 in RMF

Agrees with *Morjean et al. PRL 101 (2008)*

Superheavy nuclei anticipated with the S3 project at GANIL



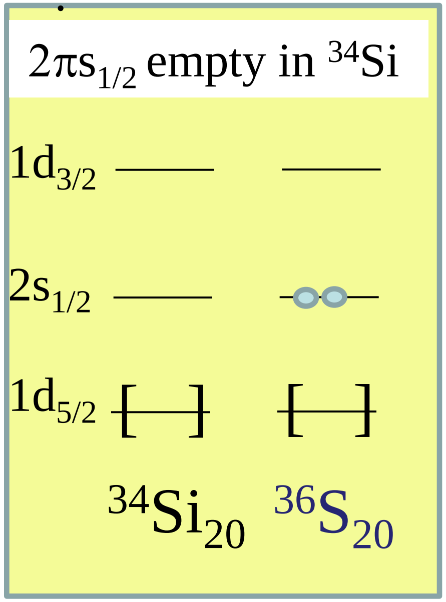
By coutesy of C. Theisen

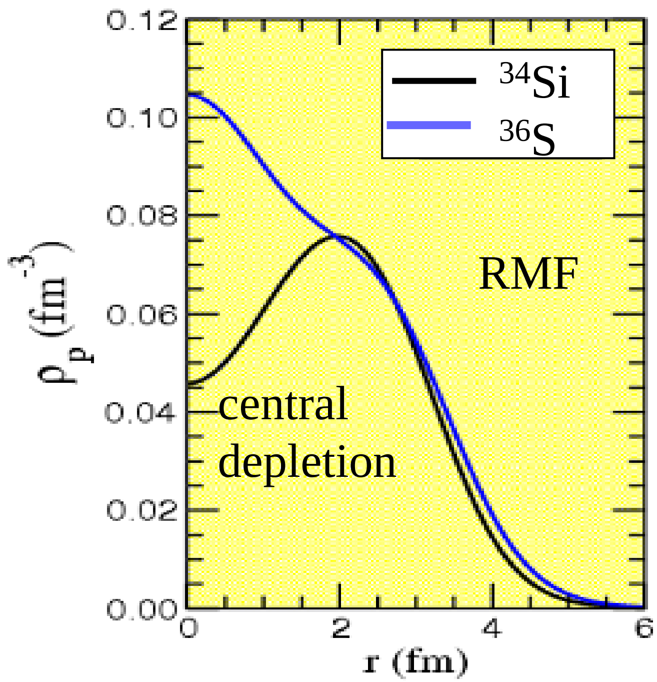
How to test the validity of the spin-orbit interaction ?

- Density dependence
- L.S
- Isospin dependence

Probing the SO interaction using a bubble nucleus

^{34}Si a 'bubble' nucleus, Grasso et al *PRC 79 (2009)*



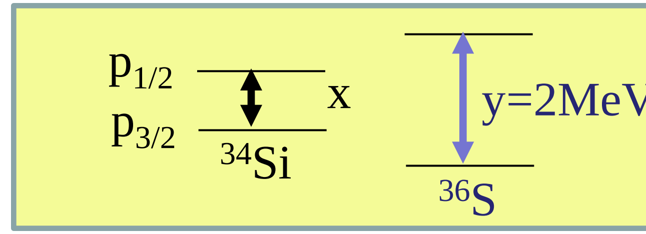


The ^{34}Si exhibits a large central depletion compared to ^{36}S.

Orbits probing the interior of nucleus strongly affected

Test of density dependence of the SO force
by determining the change of $p_{3/2}$-$p_{1/2}$ splitting between ^{34}Si / ^{36}S

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



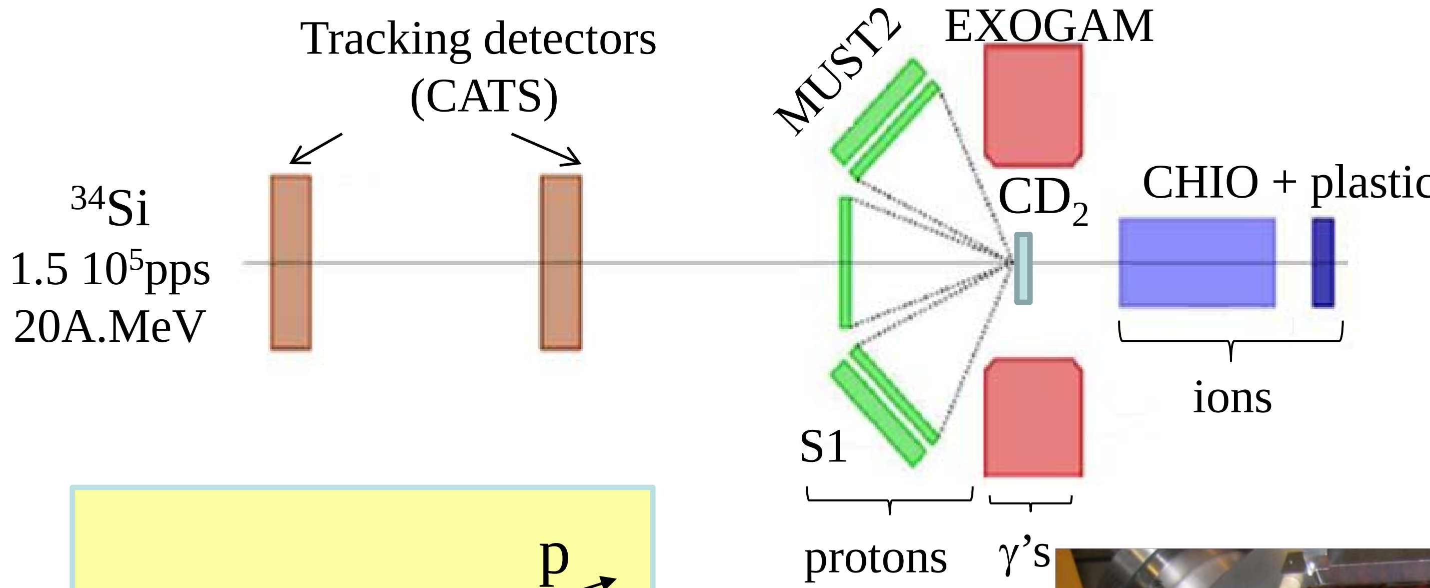
$$\Delta_n(SO) = y-x$$

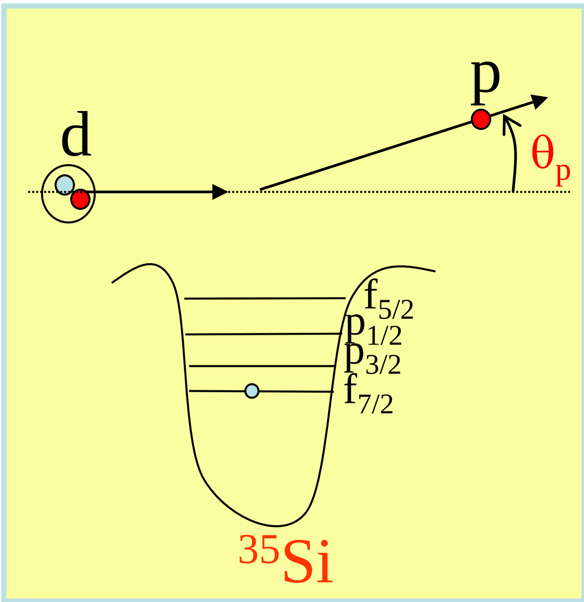
$$\Delta_n SO/SO\ (\%) = \frac{Diff}{Mean} = \frac{y-x}{(x+y)/2}$$

Predictions	$\Delta_n SO/SO$ ($p_{3/2}$-$p_{1/2}$)
RMF/ NL3	95%
MF Skyrme	40%
SM	40 %
VlowK	20-40% cutoff dependent

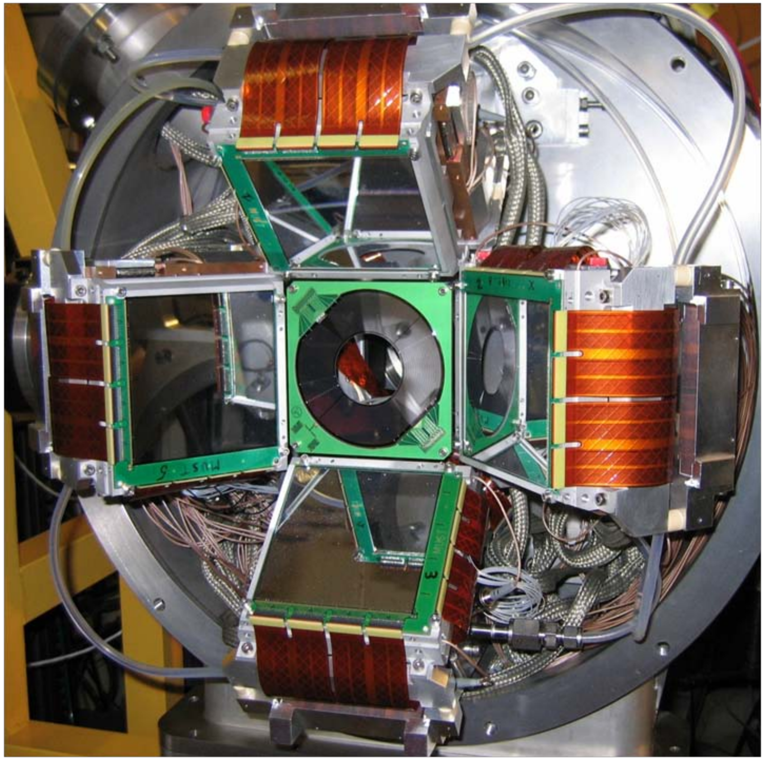
Assuming 2 protons removed from $2s_{1/2}$

Experimental set up for $^{34}Si(d,p)^{35}Si$



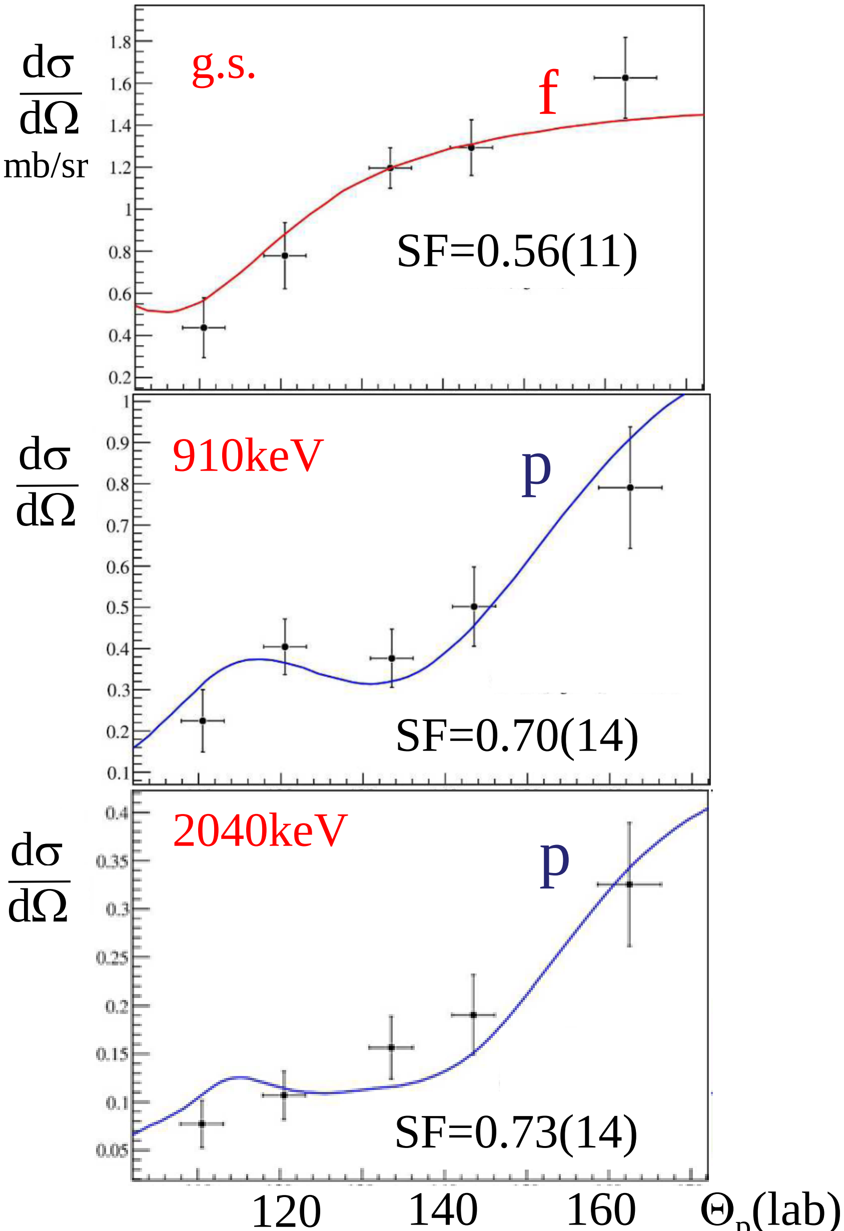


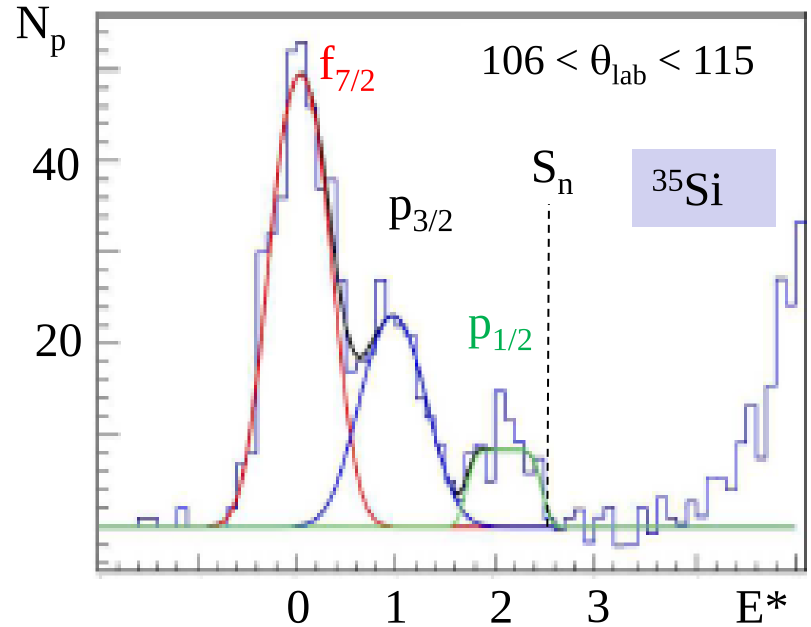
Reaction in inverse kinematics

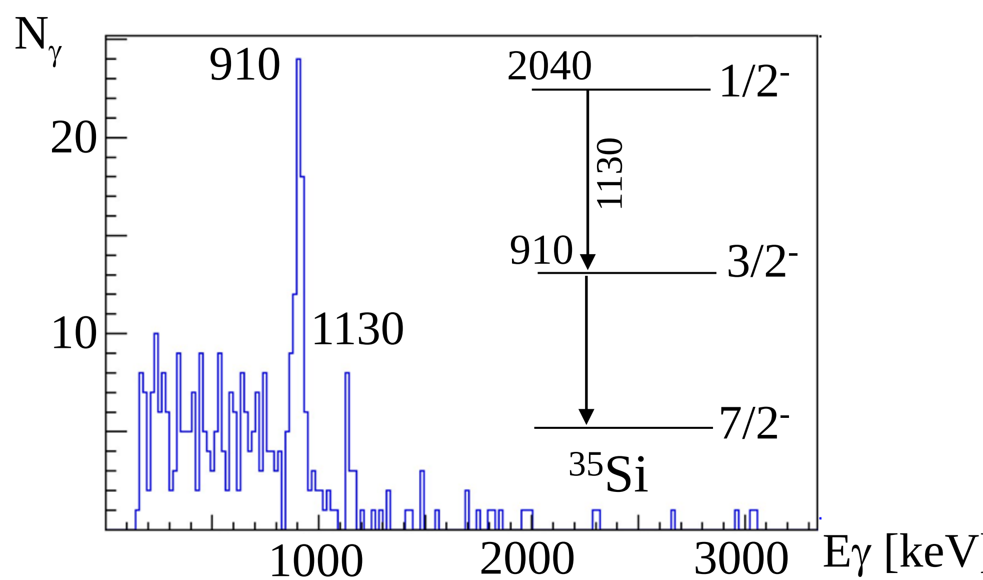


GANIL, IPN Orsay,CEA Saclay, IPHC Strasbourg

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

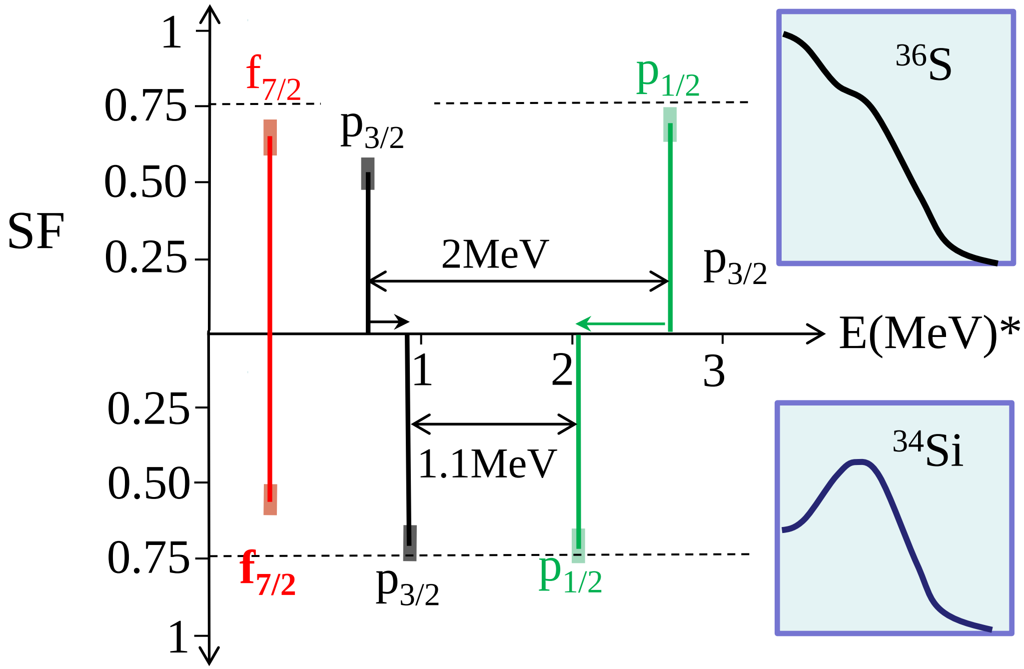






$J=3/2^-$, agrees with Nummela et al. PRC (2001)

INTERPRETATION (1)



- Reduction of observed SO splitting between ^{36}S and ^{34}Si by about 55%
  → Qualitatively agrees with density dependence of the SO

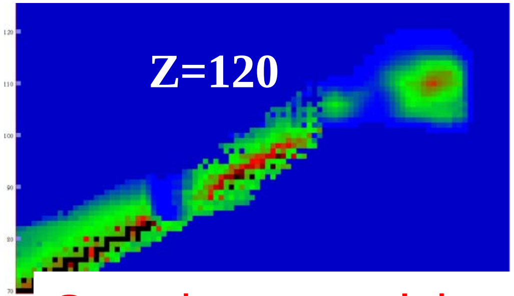
- Asymmetric shift of the p components → Expected from an $\ell \cdot \mathbf{s}$ coupling

Isospin dependence → seems between MF and RMF but depends on change in occupancy

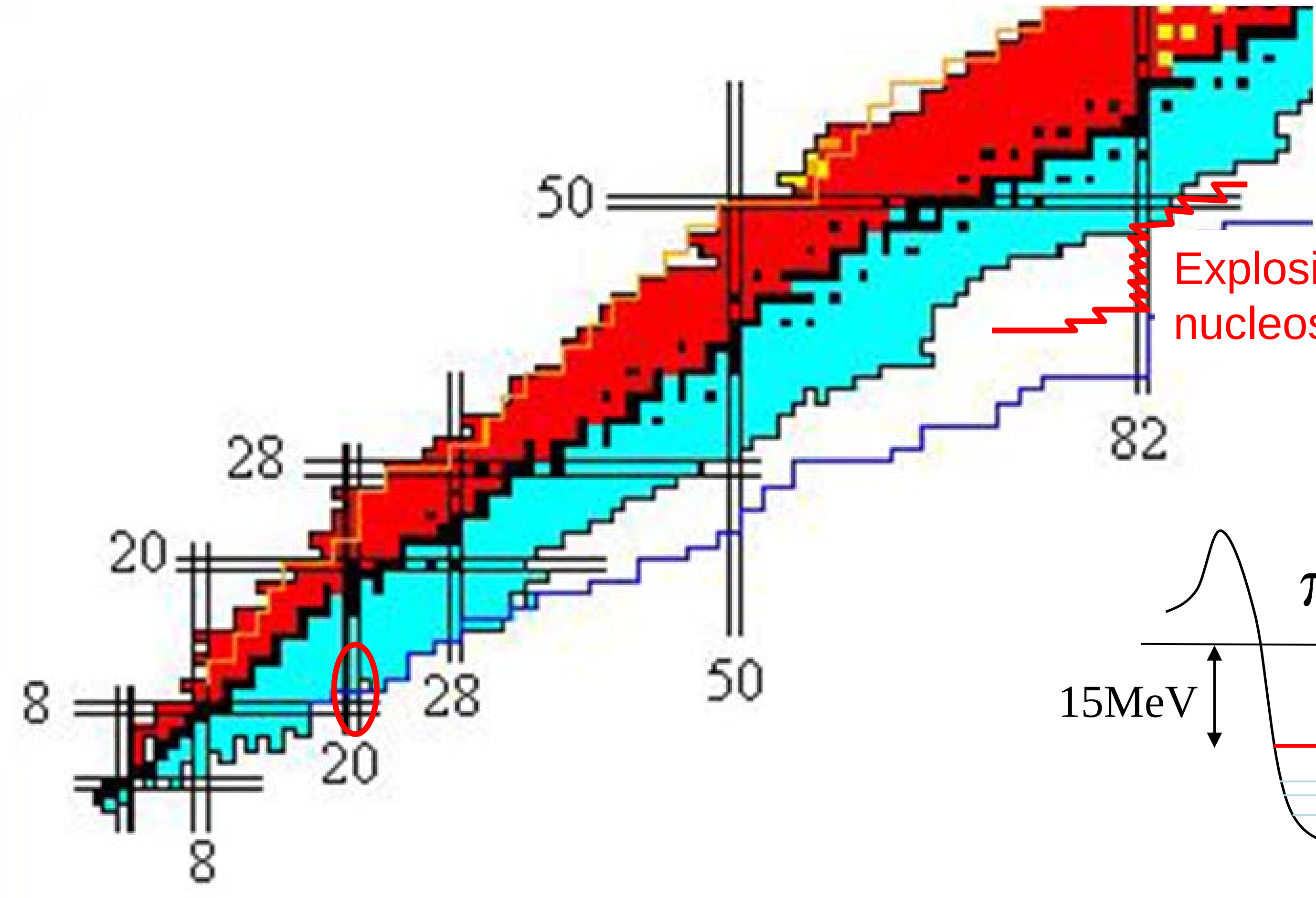
! Consider the effect of correlations on the SO splitting value
Work in progress using Shell Model calculations (F. Nowacki)

Studying proton-neutron interactions at the drip line

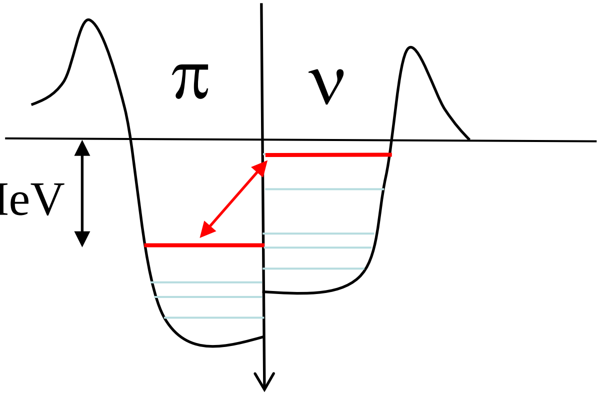
MOTIVATIONS



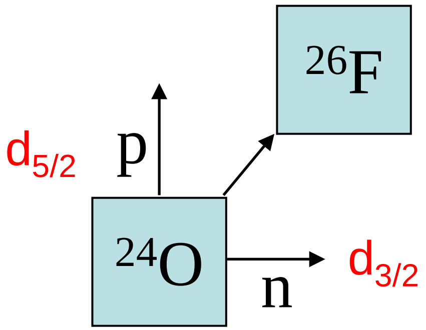
Superheavy nuclei



Explosive nucleosynthesis

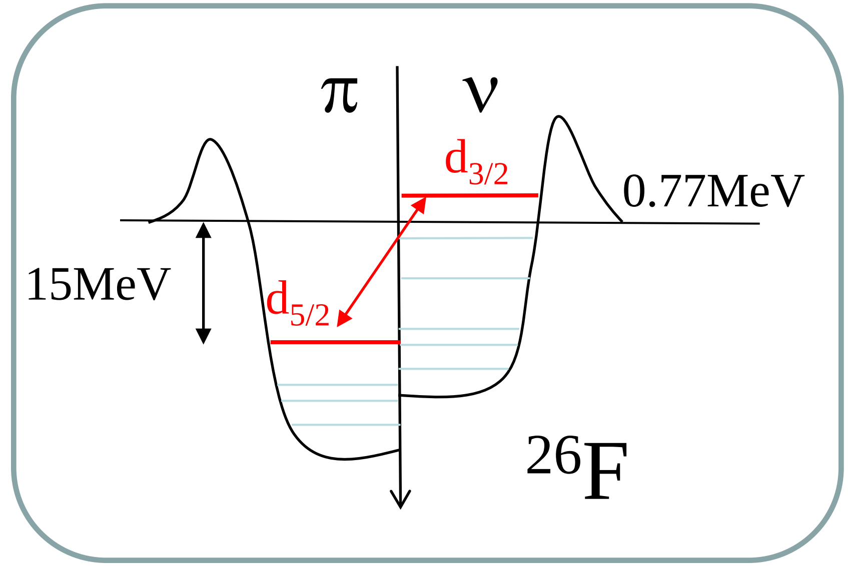


Are proton-neutron interactions similar at drip line ?

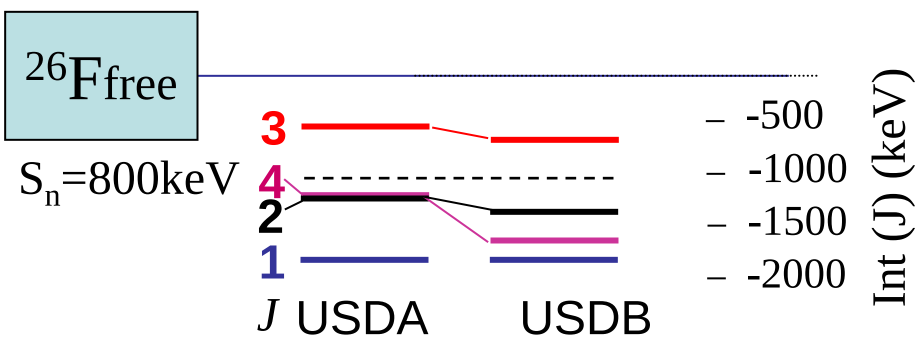


$V^{pn}(d_{3/2}d_{5/2})$

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. (NSCL) 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.
accepted in PRC 2012

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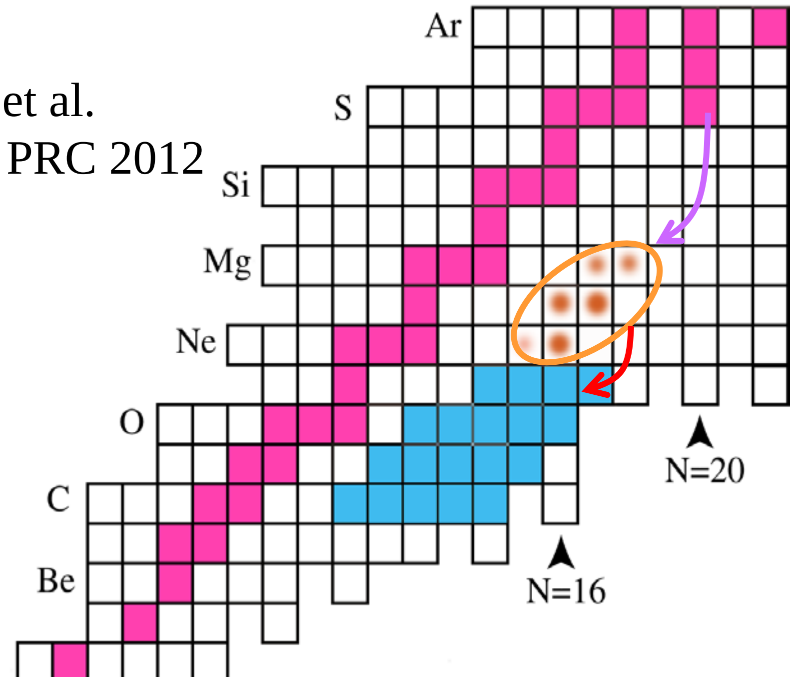
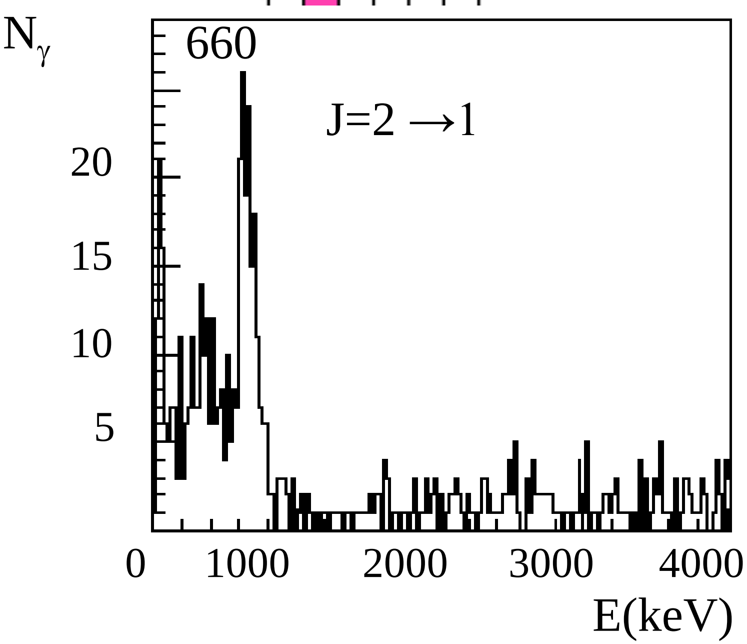
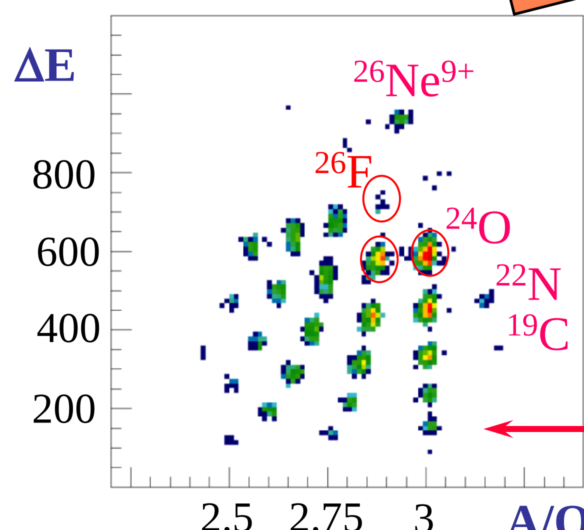
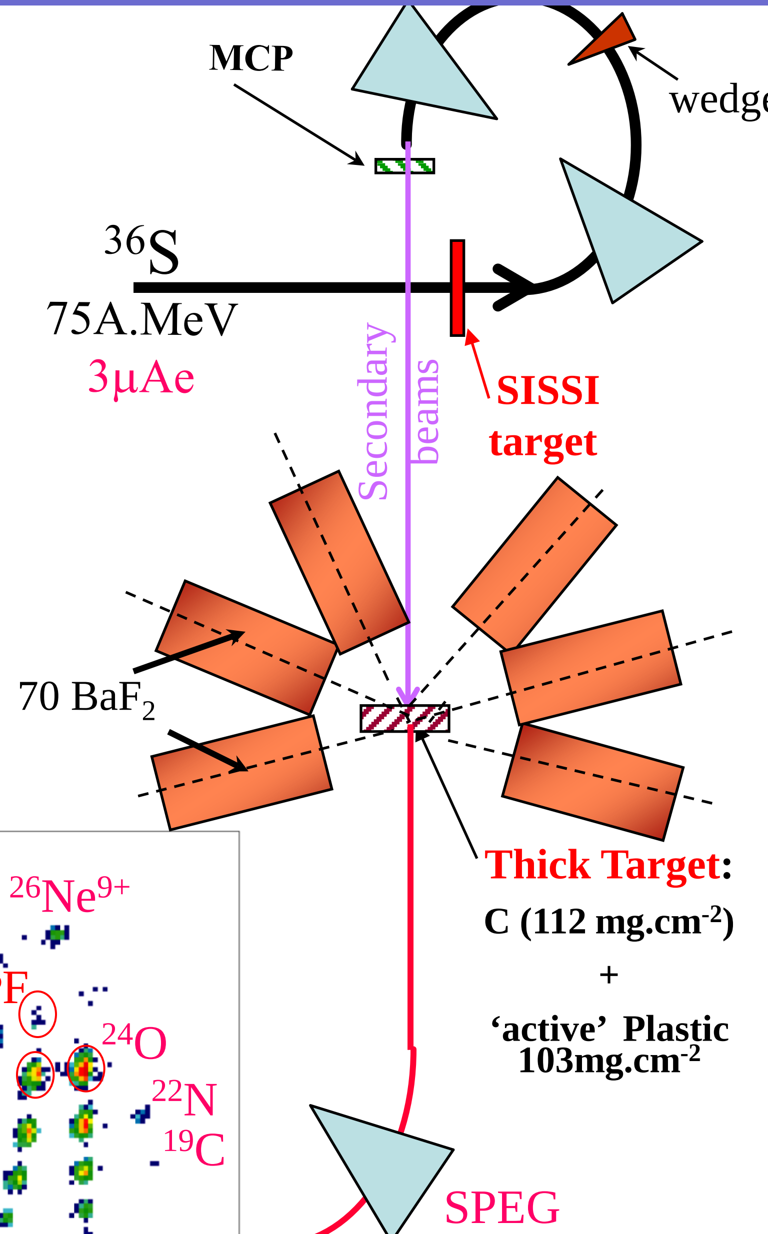
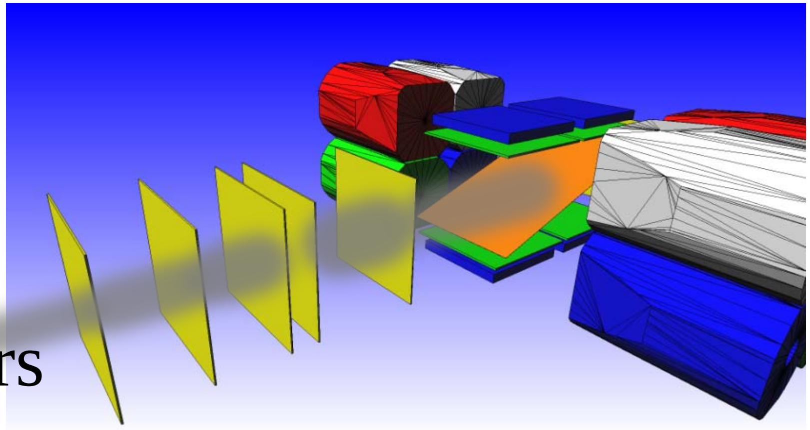


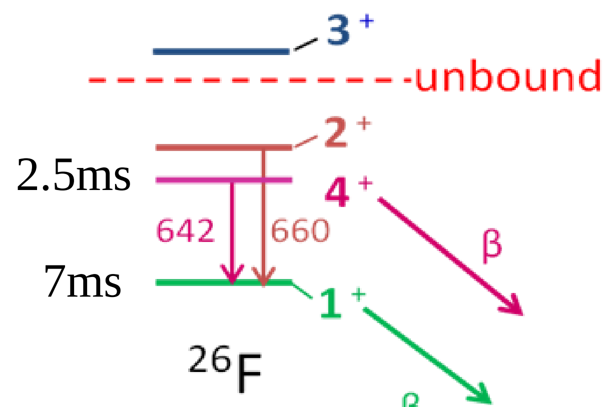


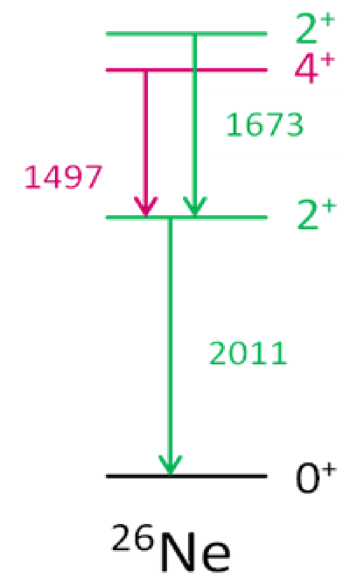


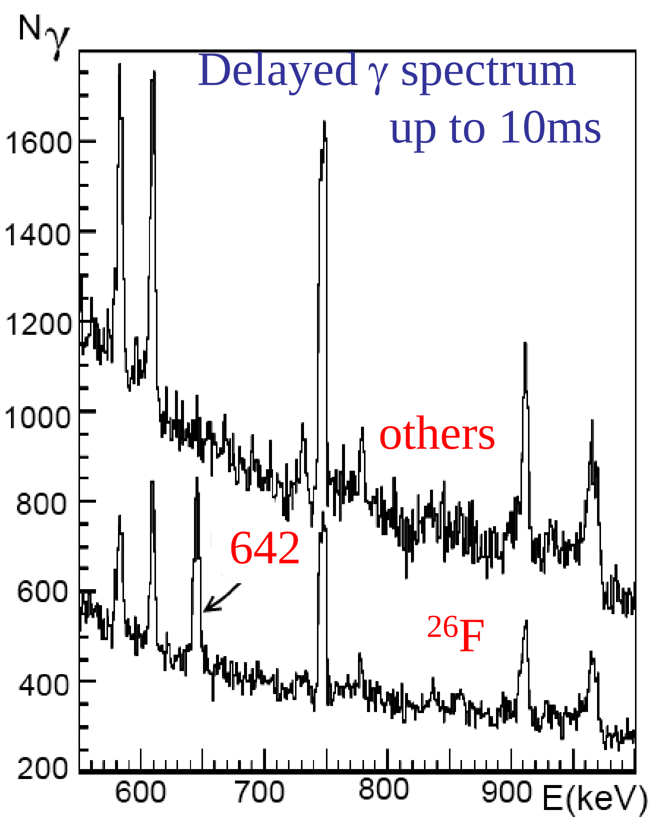


Searching for a 4^+ isomer in ^{26}F …

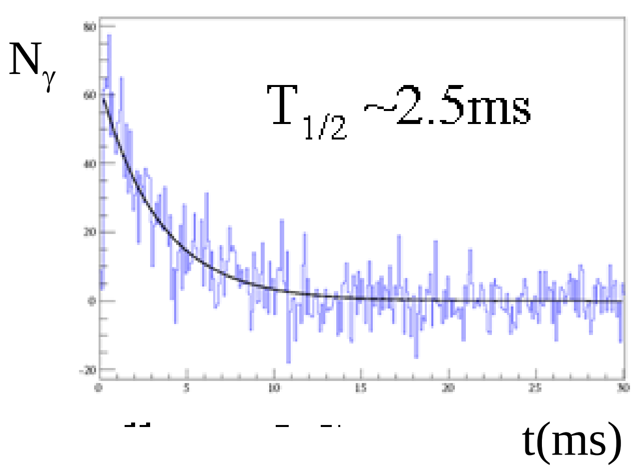








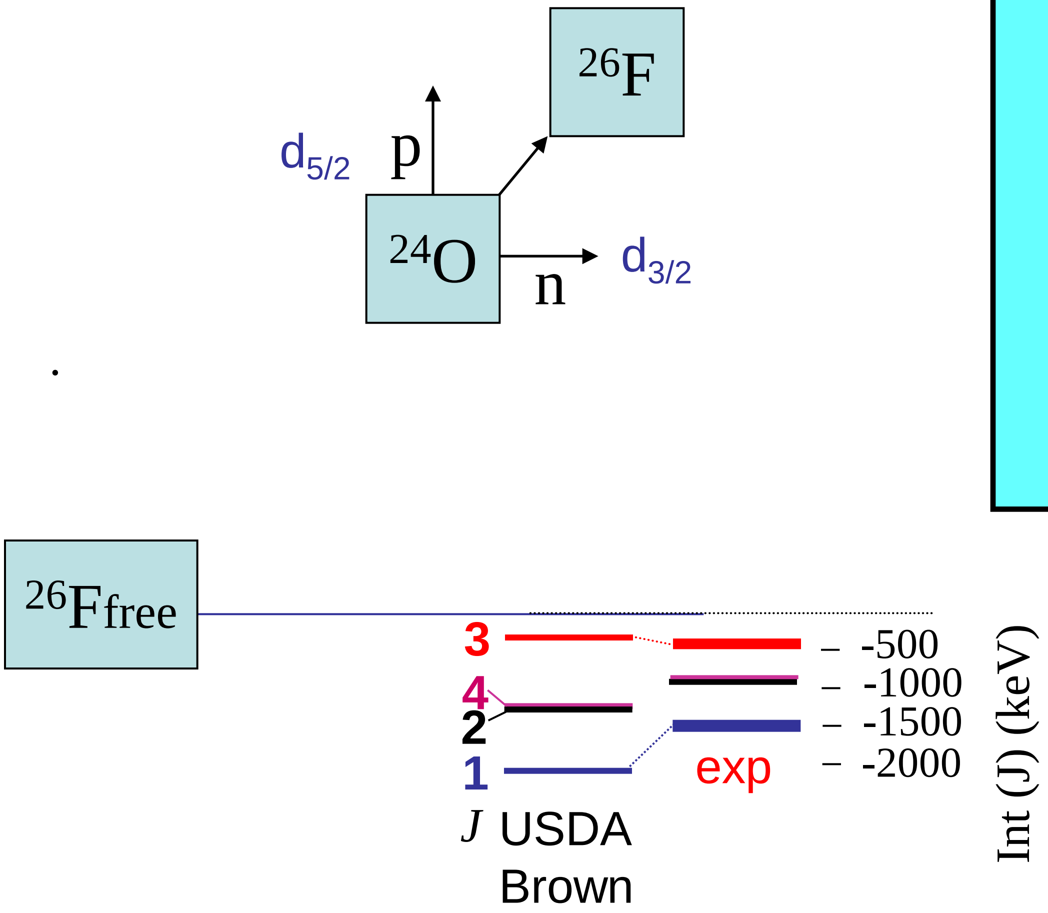
Compatible with M3 transition !
J=4 →1

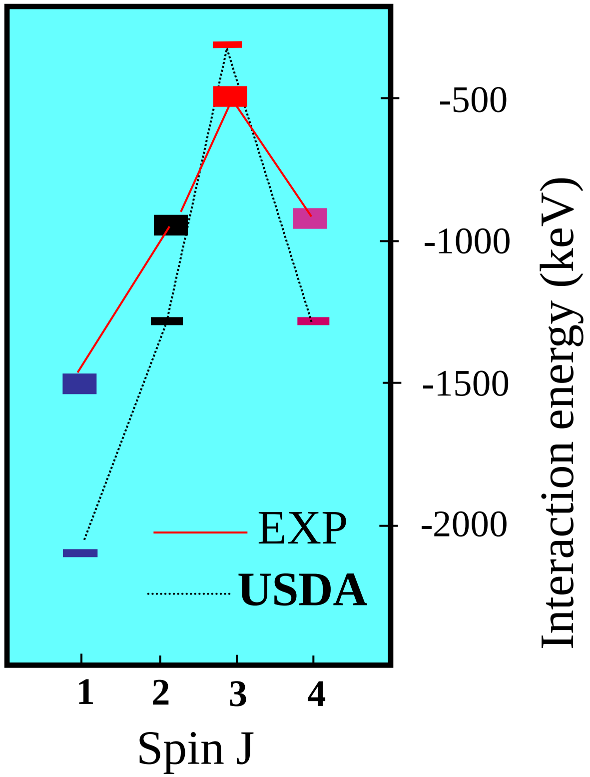


A. Lepailleur, O.S. et al.
GANIL

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

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





~30% reduced interaction as compared to Shell Model !

+ Global shrink of levels

Use proper treatment of continuum …Work in progress (G. Hagen)

Conclusions & Perspectives

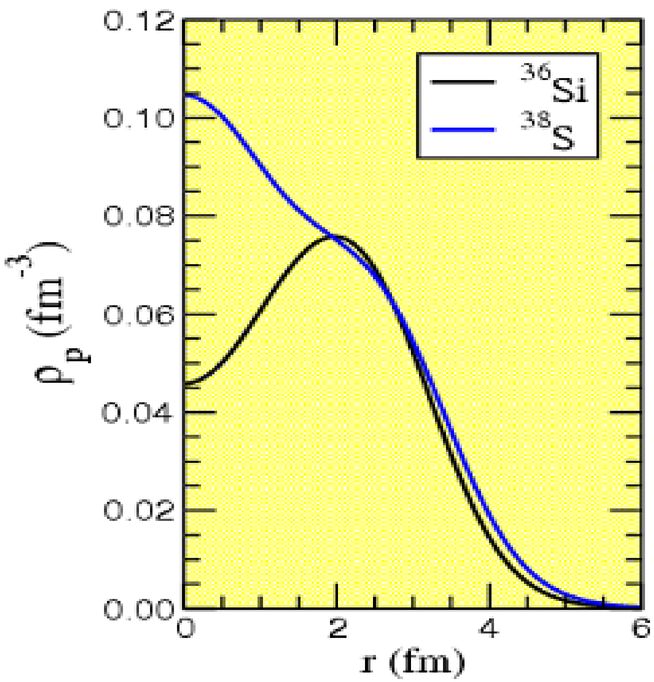
PART 1:

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

Change of the neutron $p_{3/2}$-$p_{1/2}$ splitting by ~55% between ^{36}S and ^{34}Si.

So far exp value fall in between MF and RMF pedictions !

Determine the amplitude of the bubble
Study the effect of fragmentation of sp states on this splitting (collab. F. Nowaki).



Consequences

Drip line, Location of the island of stability in SHE …

PART 2 :

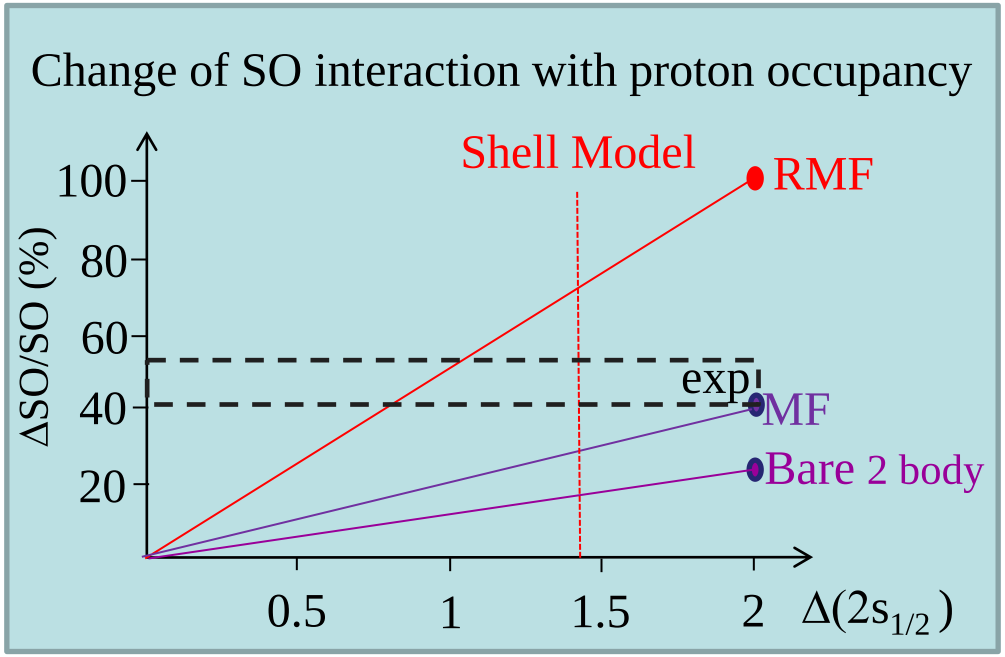
Use the spectroscopy of ^{26}F to infer the change of the proton-interaction close to drip line
→Reduction of the interaction by 30%

Check the atomic mass, confirm energy of unbound state(s) (collab. T. Aumann @LAND)

Look at the effect of the continuum to account for this reduced interaction (collab. G. Hagen)

END OF TALK, After are extras…

INTERPRETATION (2)



The use of 2-body V_{lowK} bare forces cannot itself account for the observed SO change

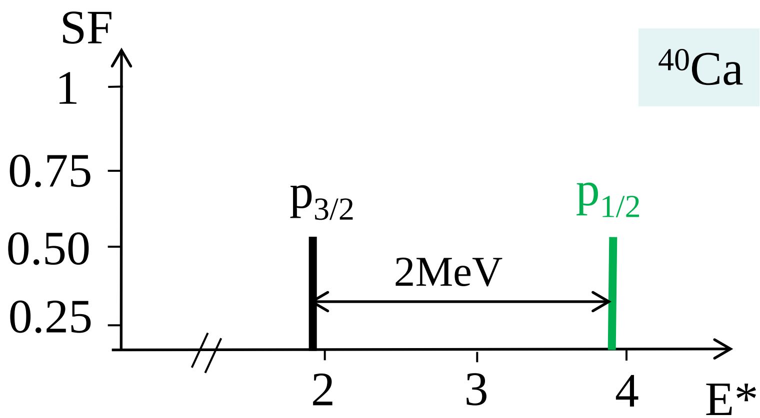
The Mean Field (MF) model seems not to be adequate

The Relativistic Mean Field model would be adequate if $\Delta s_{1/2}$ =1 (i.e. the bubble is moderate)

→Otherwise new ingredients needed in the theory!

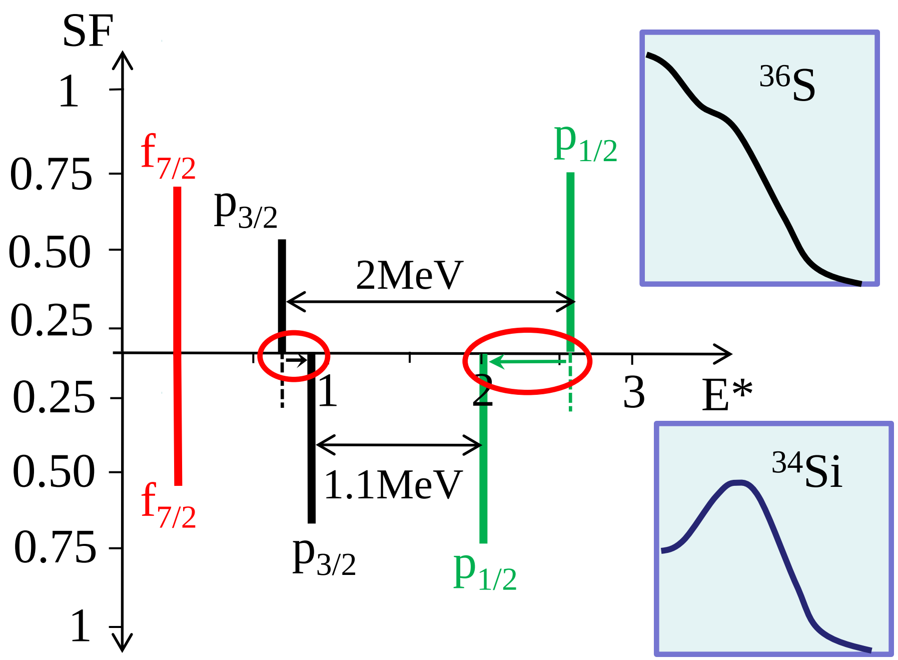
→ Determine experimentally the amplitude of the bubble (scheduled in 2012 at NSCL/MSU)

EXPERIMENTAL RESULTS (2)



Taking the major fragment of the s.p. strength the p3-p1 SO splitting is 2MeV in ^{41}Ca

It is 1.7MeV taking the whole strength.
Uozumi et al. PRC (1993).

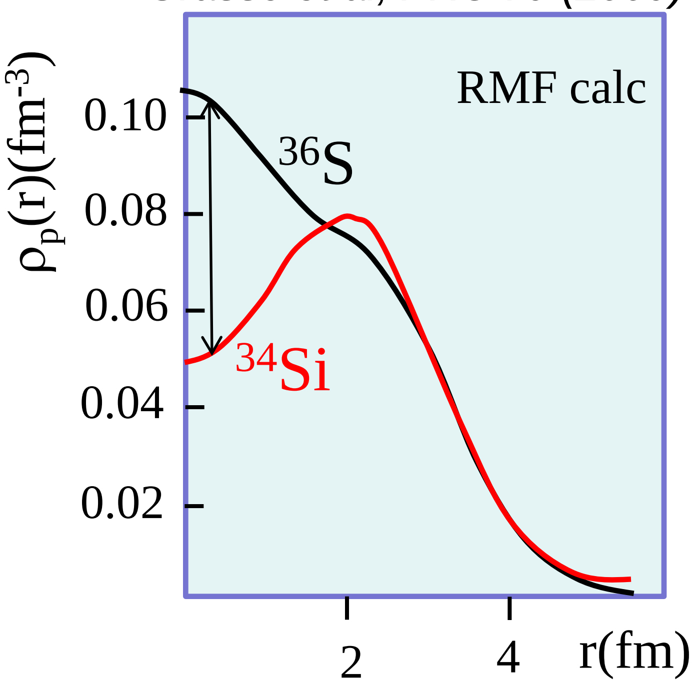


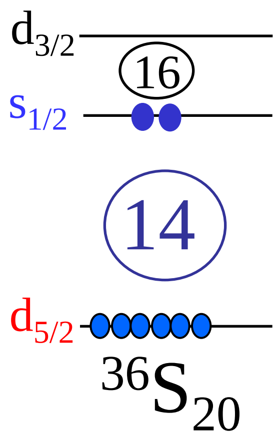
Taking the major fragment of the s.p. strength
-> Reduction of the SO splitting by 55%
-> Asymmetric shift of $p_{1/2}$ and $p_{3/2}$ states

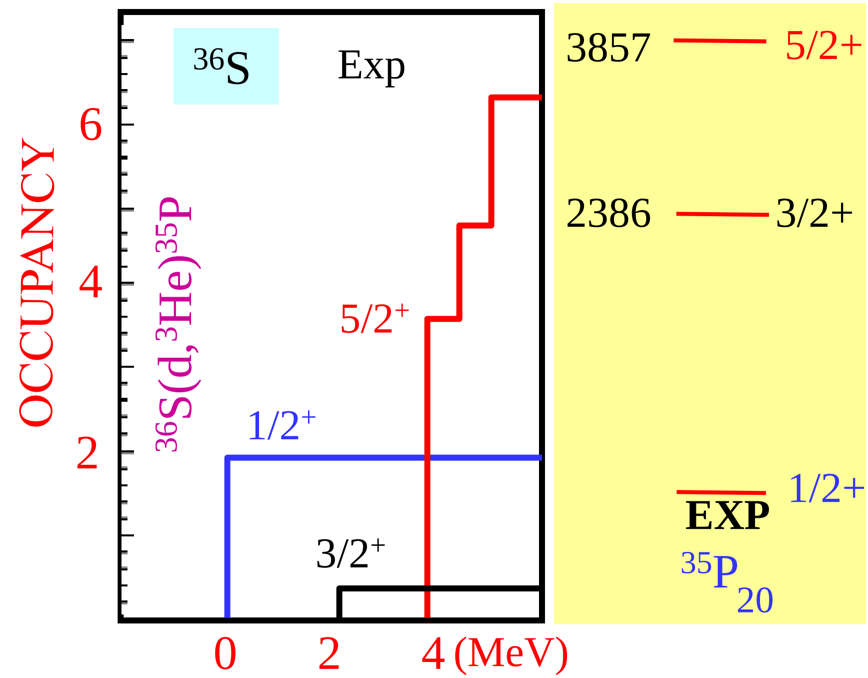
Role of correlations is being investigated…
F. Nowacki and A. Poves

The use of a 'bubble nucleus' to probe the SO interaction

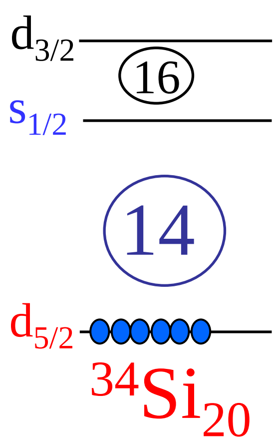
Grasso et al, PRC 79 (2009)







Khan et al. PLB 156 (1985)



IDEAL CANDIDATE

- -Large central proton depletion F~40%
- -Magic nucleus $E(2^+) > 3.3$MeV
- -Weak mixing between states

The neutron p orbits probes the interior of the nucleus, while the f probes the surface

The neutron $p_{3/2}$-$p_{1/2}$ splitting should change between ^{36}S and ^{34}Si