Shell evolution and nuclear forces relevant for the r process

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

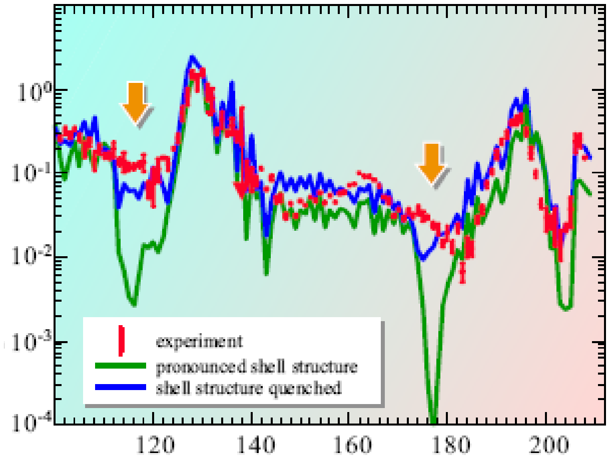
MOTIVATIONS

PART 1:
Proton-neutron forces close to the drip line
Study of the ^{26}F nucleus

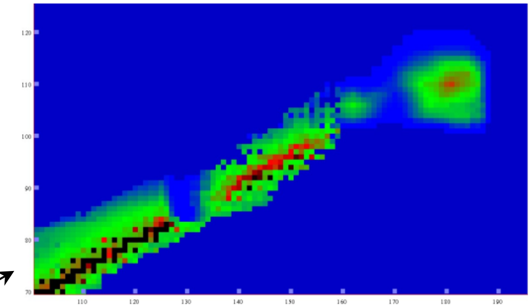
PART2:
Density dependance of the spin orbit interaction
Study of the bubble nucleus ^{34}Si

CONCLUSIONS - PERSPECTIVES

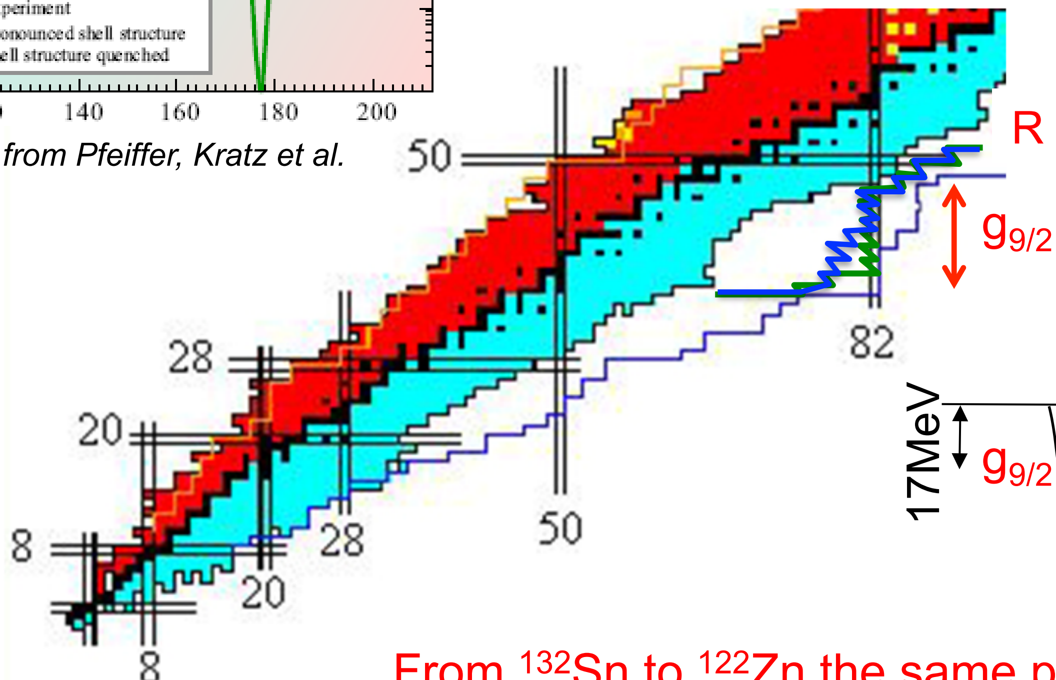
PART I : Nuclear forces at large proton-neutron asymmetry energy

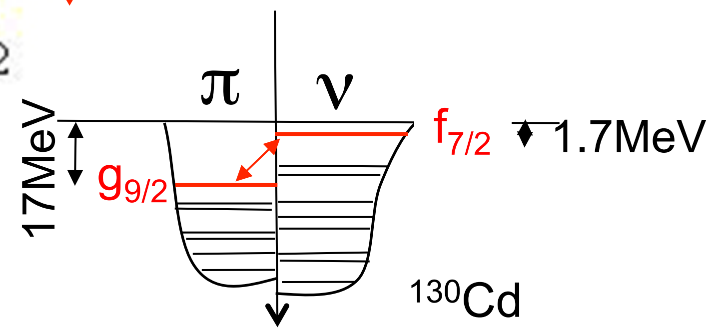


Adapted from Pfeiffer, Kratz et al.



Superheavy nuclei

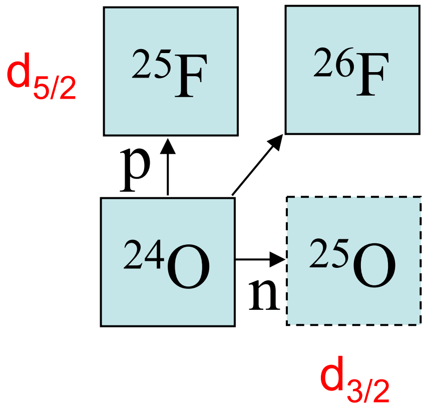




From ^{132}Sn to ^{122}Zn the same pn interactions are involved !
But change in binding energy asymmetry.

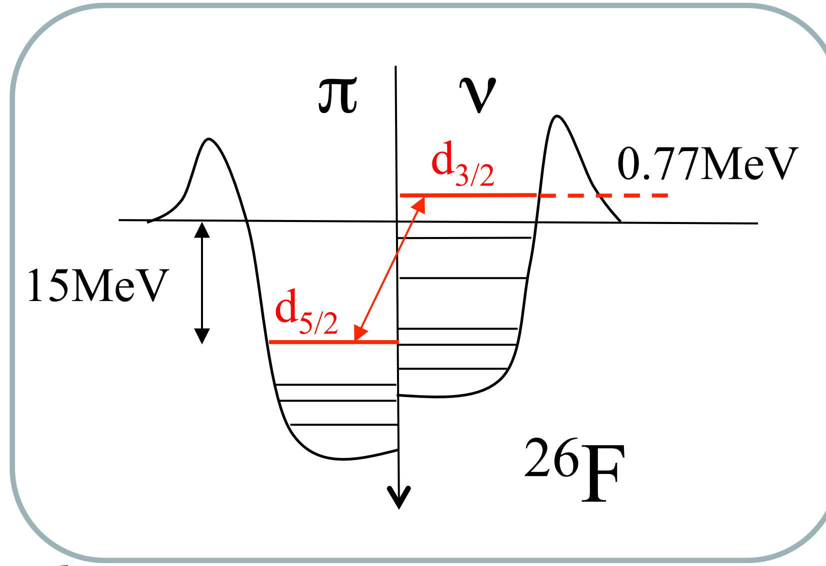
Do proton-neutron interactions change at large p-n binding energy asymmetry ?

Are proton-neutron interactions similar at drip line ?

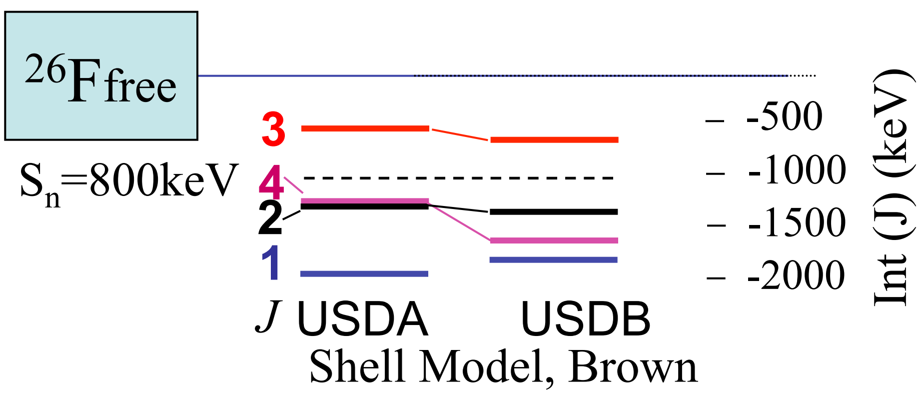


$V^{pn}(d_{3/2}d_{5/2})$

J=1,2,3,4



^{25}O unbound, Hoffman PRL 100 (2008)
^{26}F g.s. J=1 from β-decay, Reed et al. PRC
3^+ : Frank et al., PRC 84 (2011)
Masses: Jurado et al., PLB 649 (2007)



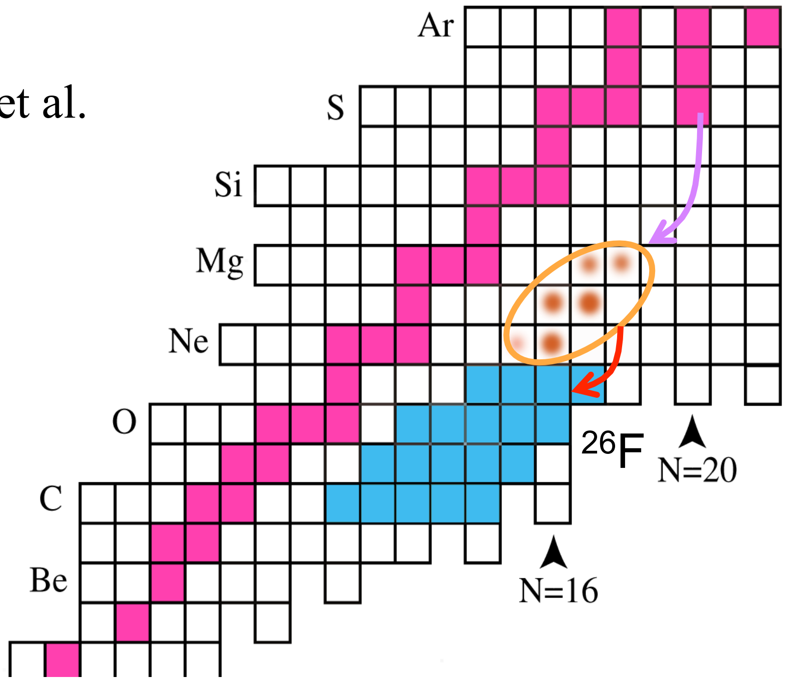
J=2 in-beam γ spectroscopy
J=4 isomer

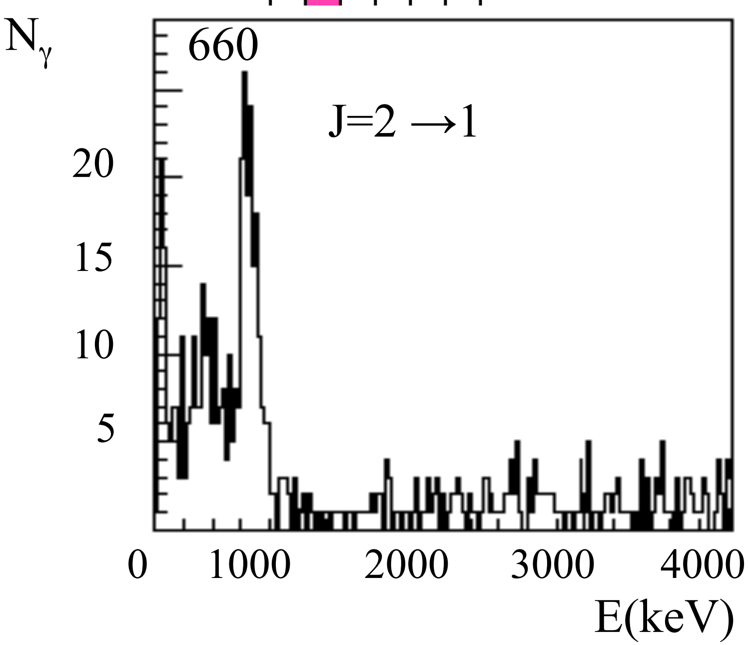
Compare experimental binding energies in ^{26}F to those predicted by Shell Model using effective forces constrained closer to stability

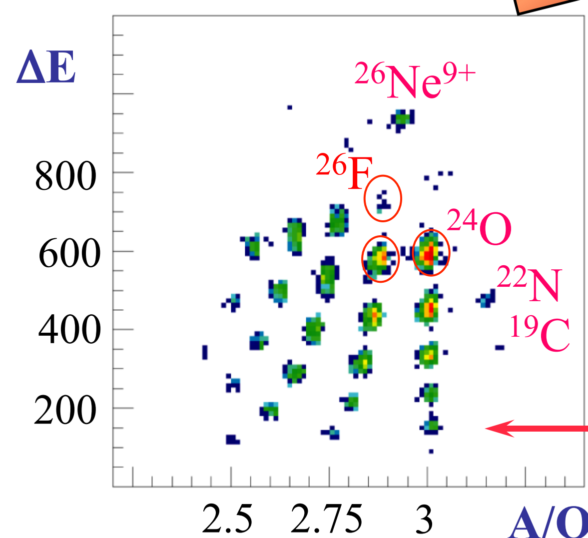
Search for J=2 excited state in ^{26}F

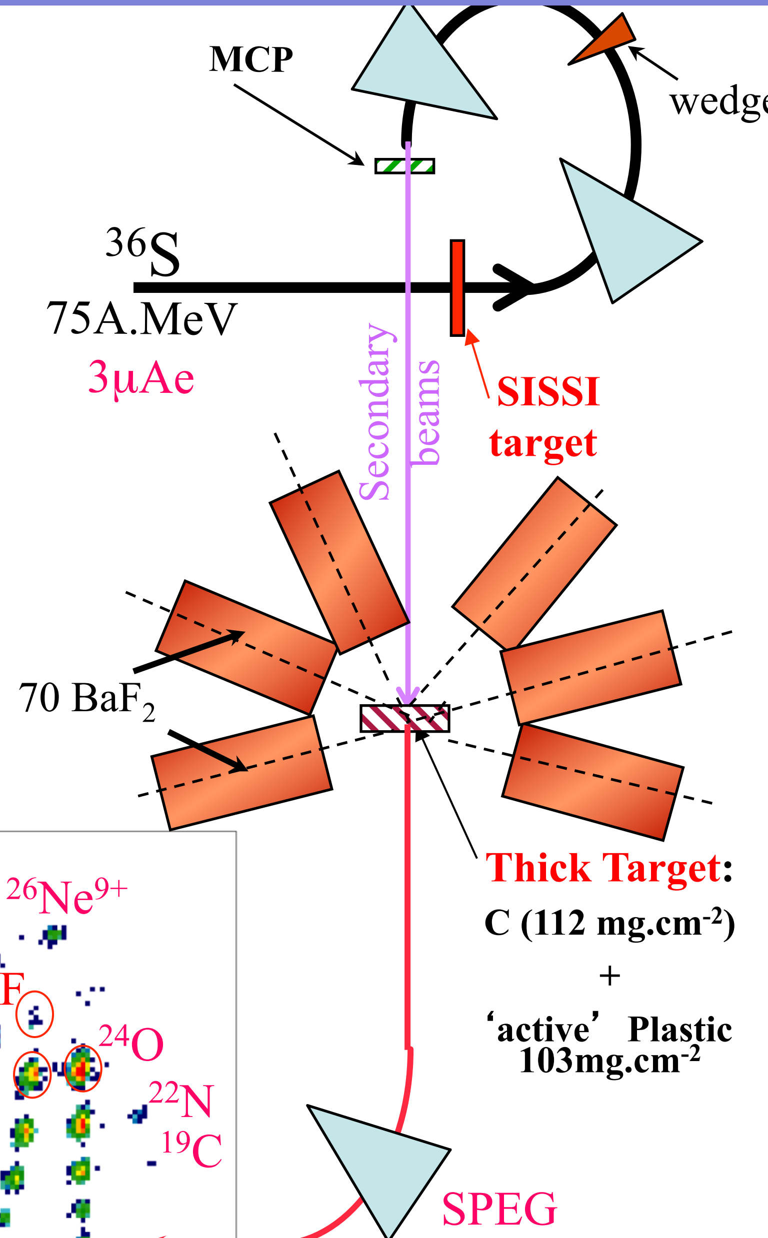
M. Stanoiu et al.
PRC (2012)

GANIL

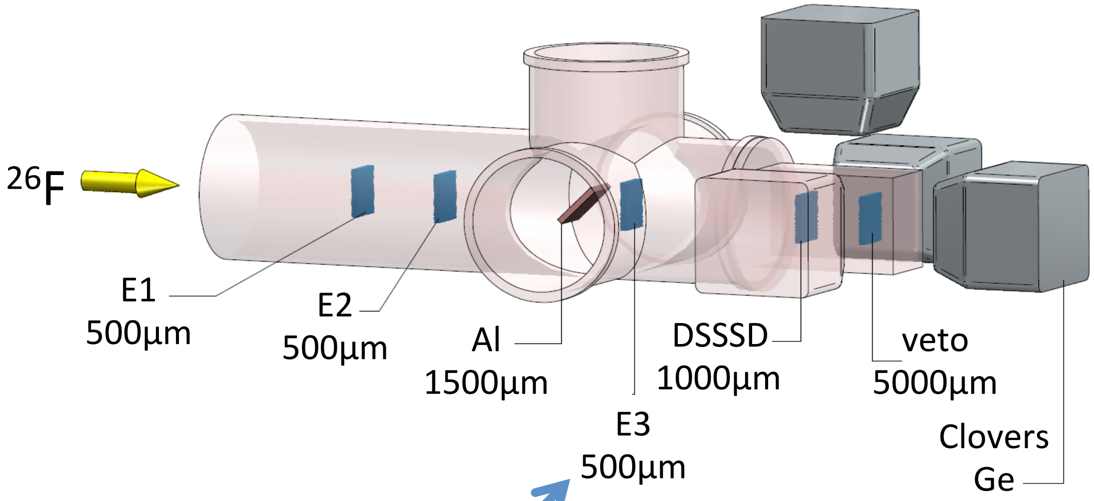


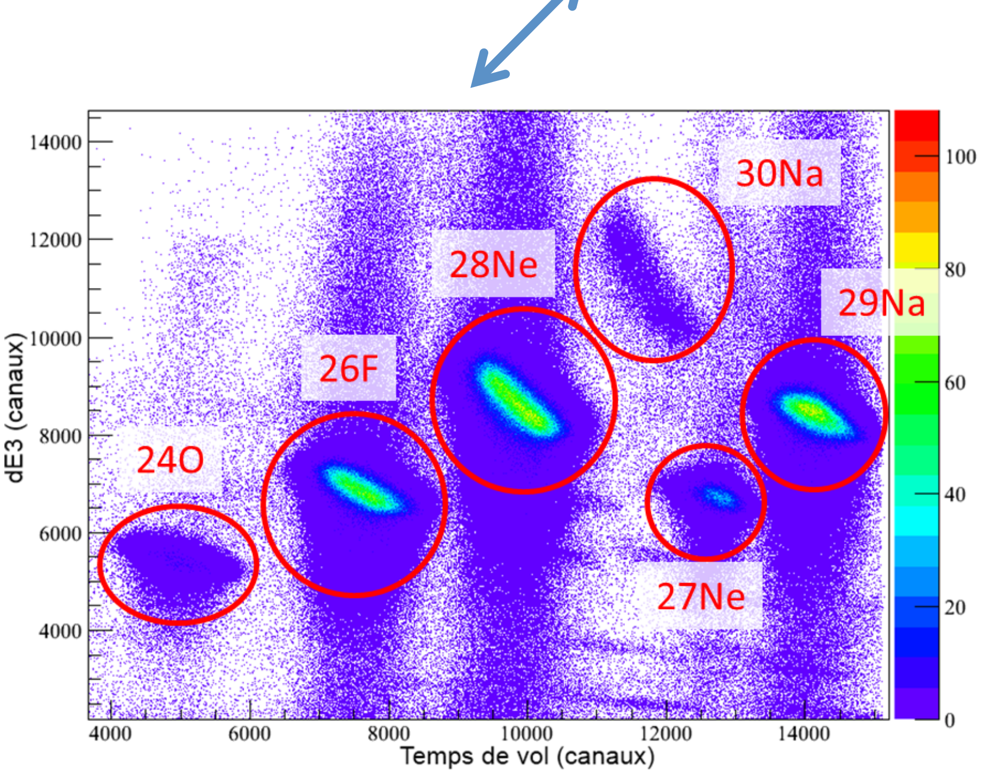






Search for the isomeric 4^+ state in ^{26}F



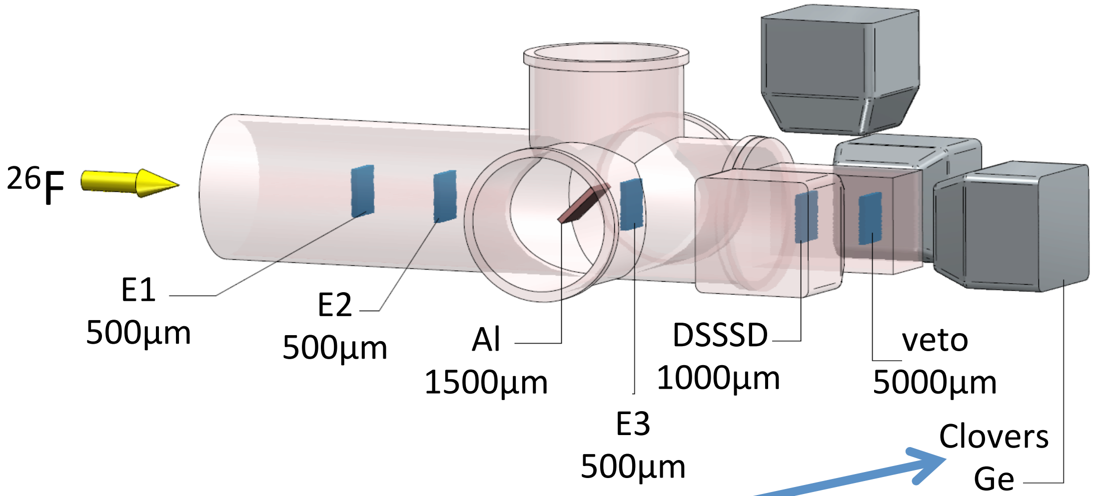


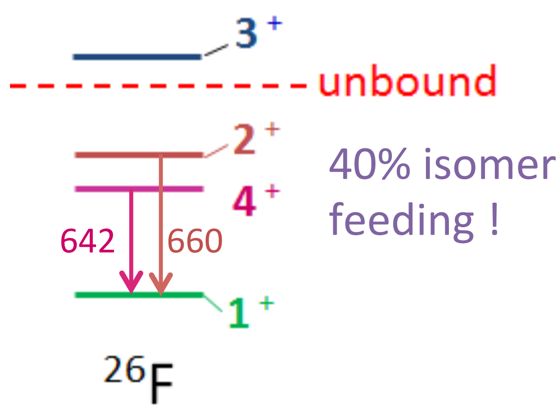
^{28}Ne : 10.4/s

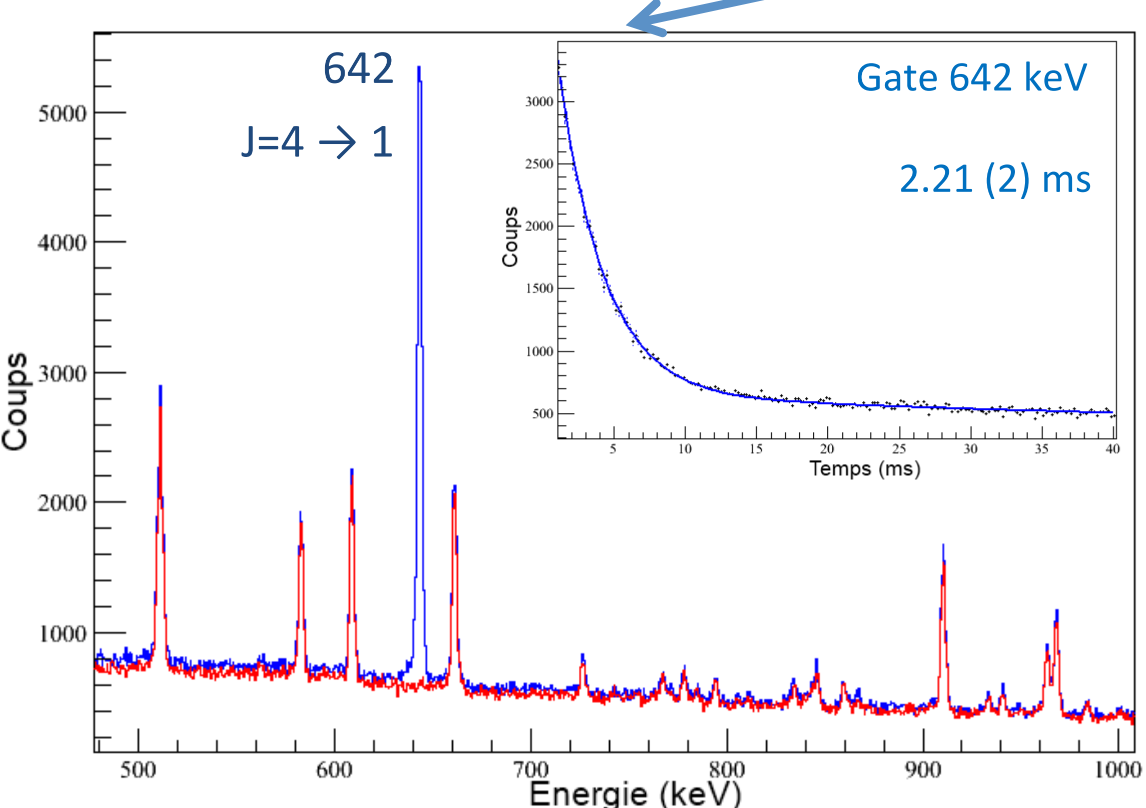
^{26}F : 5.5/s

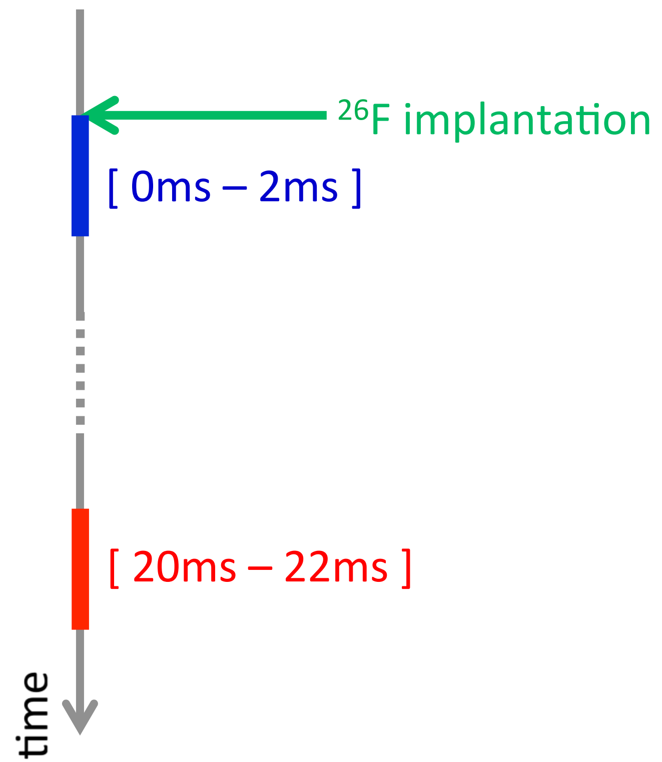
^{24}O : 0.058/s

Discovery of an isomeric 4^+ state in ^{26}F



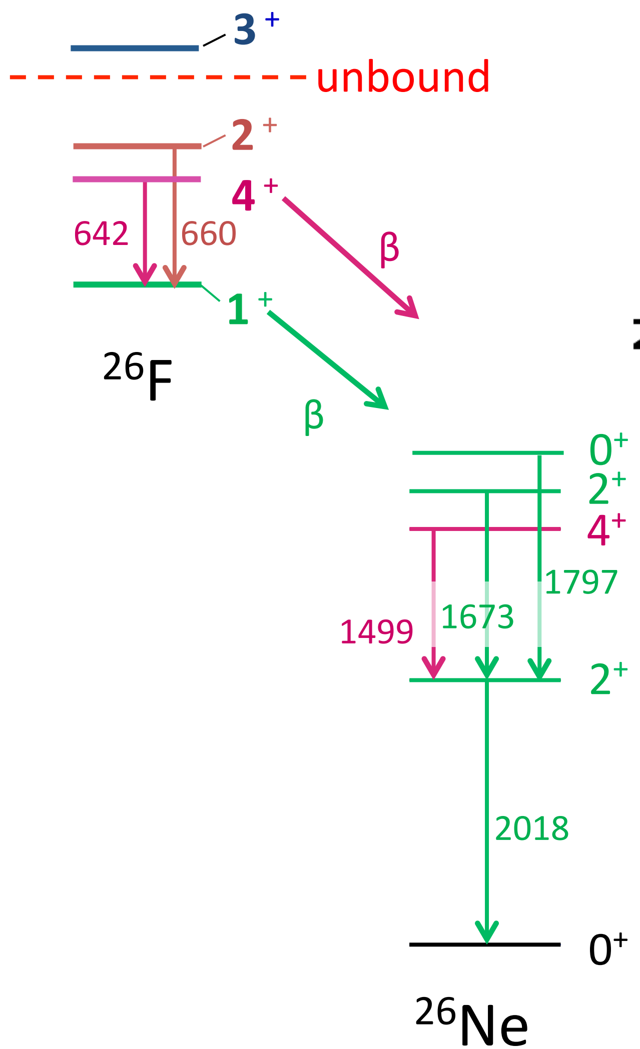


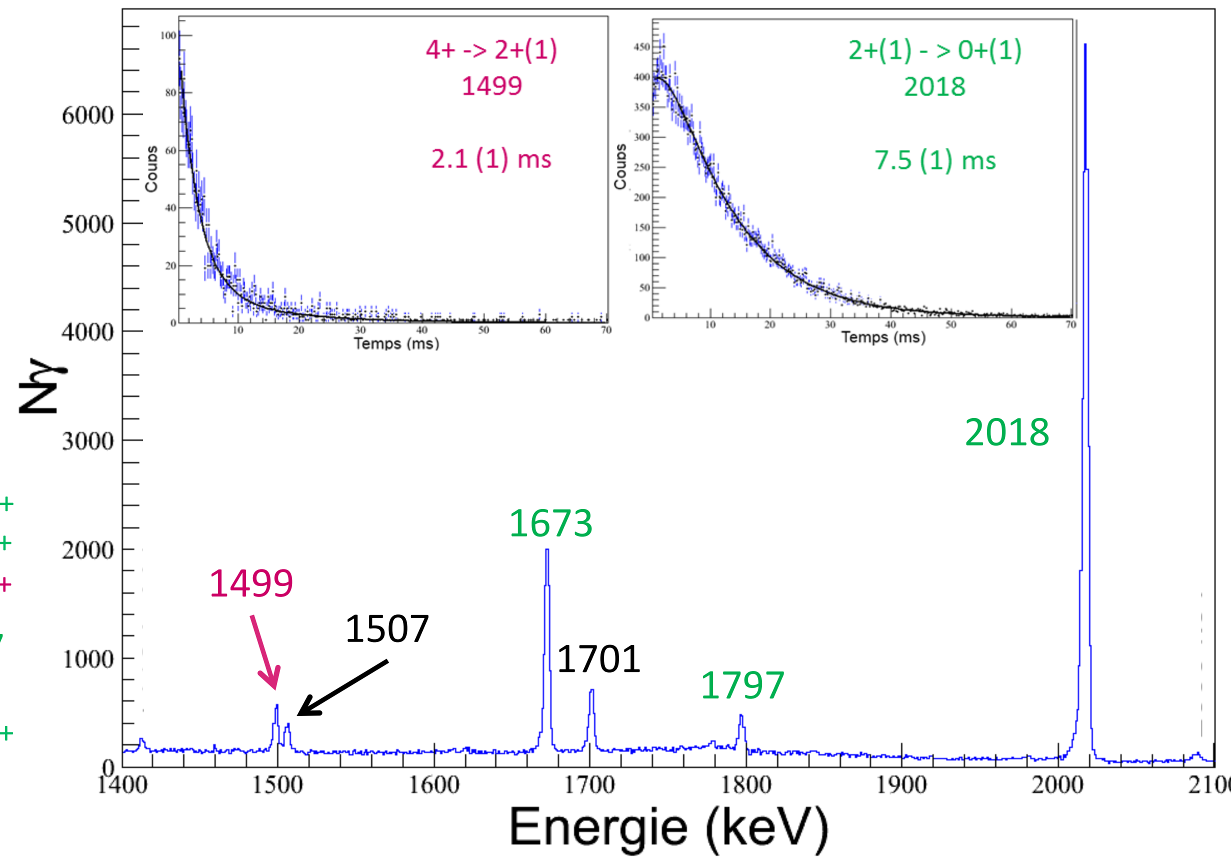


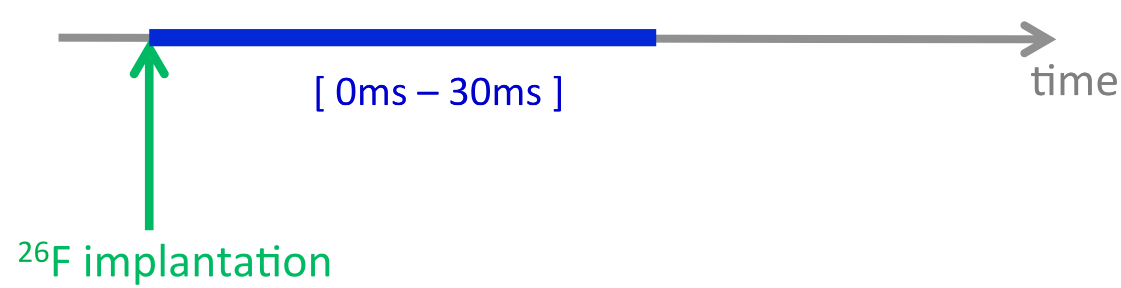


Study of the beta decay of ^{26}F

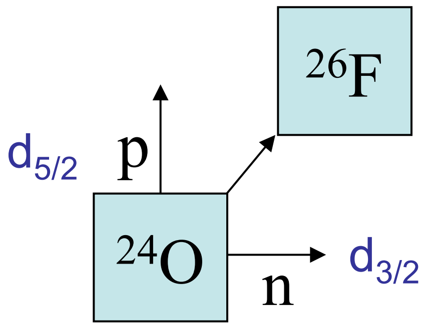
β-decay selection rules :
$\Delta J = 0 , \pm 1$







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

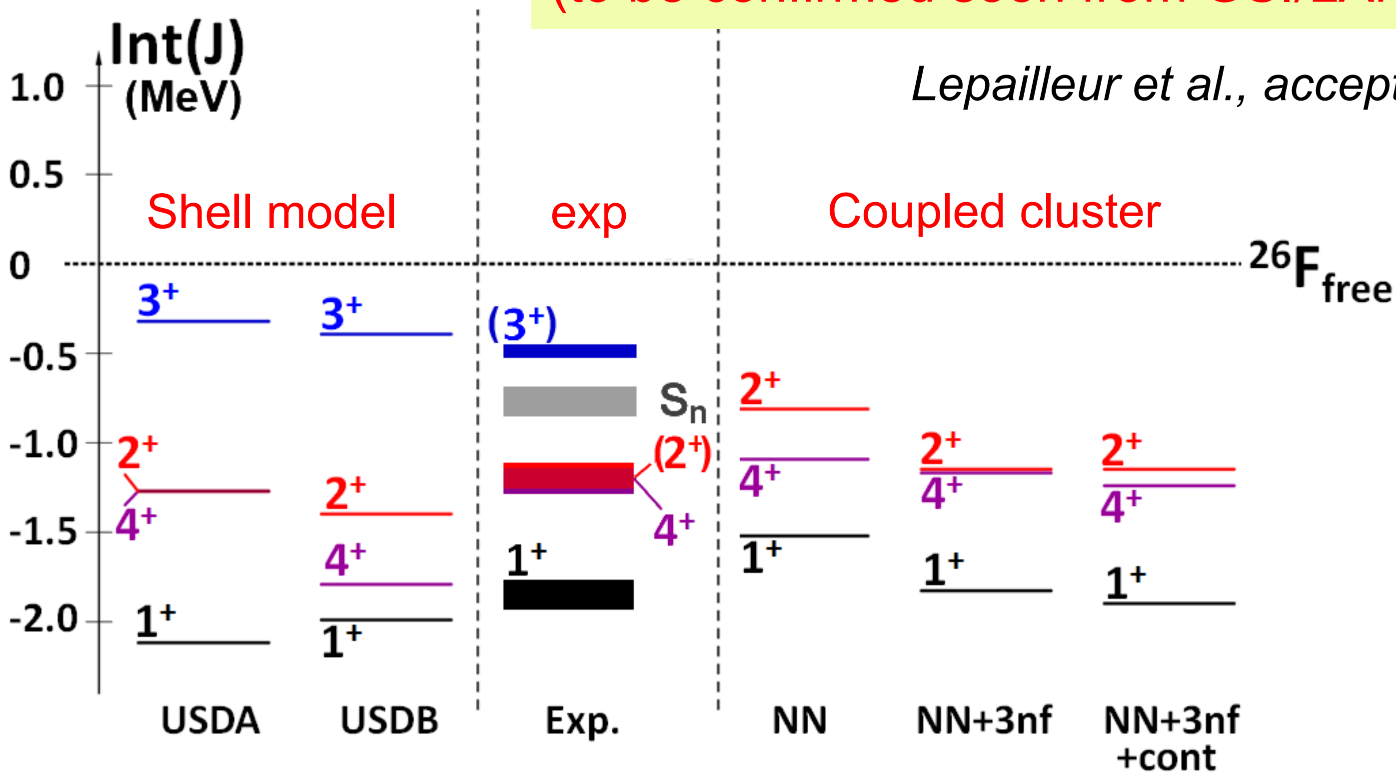


Reduced interaction as compared to Shell Model
Compression in energy -> reduced residual interaction

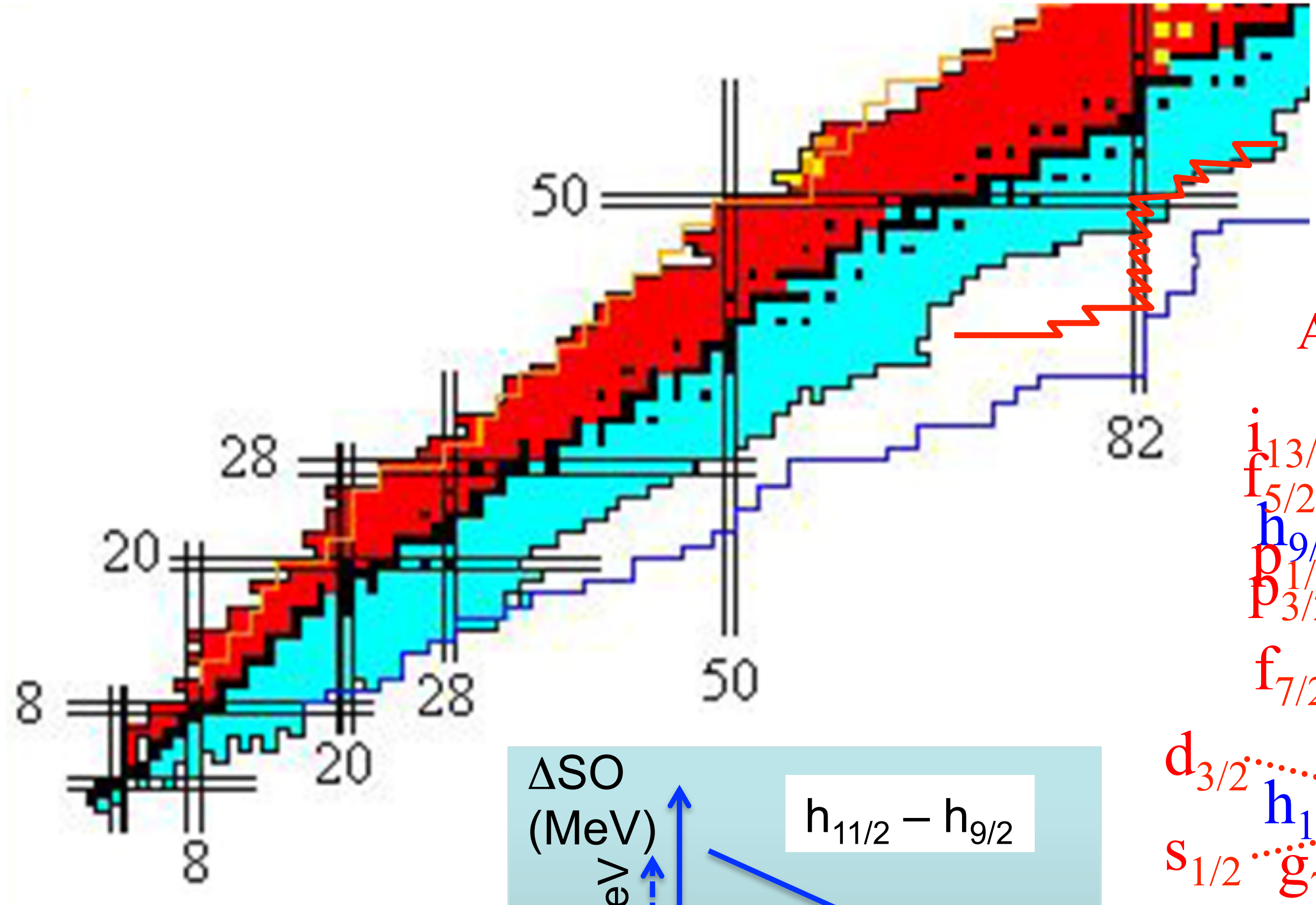
Excellent agreement with coupled cluster calculations

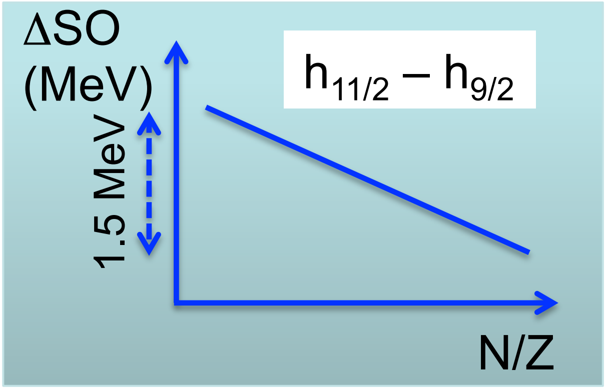
'Strange behaviour' of the J=3 state
(to be confirmed soon from GSI/LAND data)

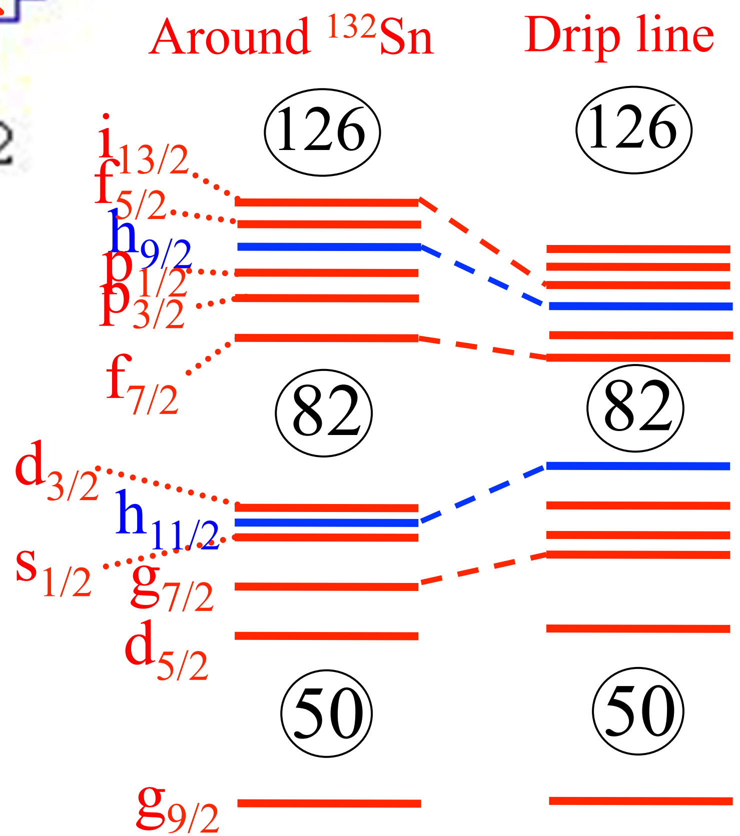
Lepailleur et al., accepted in PRL (2013)



PART II: Spin orbit interaction far from stability





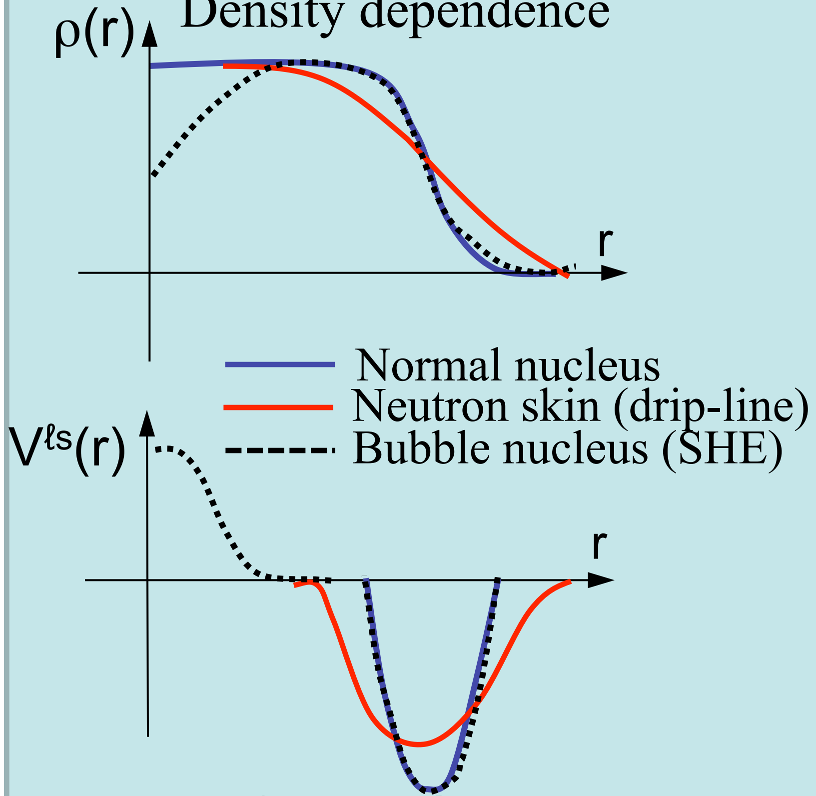


How does the spin-orbit interaction changes far from stability when the surface diffuseness is increased ?

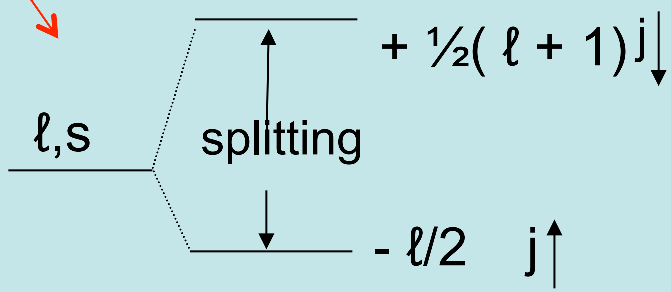
The spin orbit (SO) interaction in Mean Field models

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

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

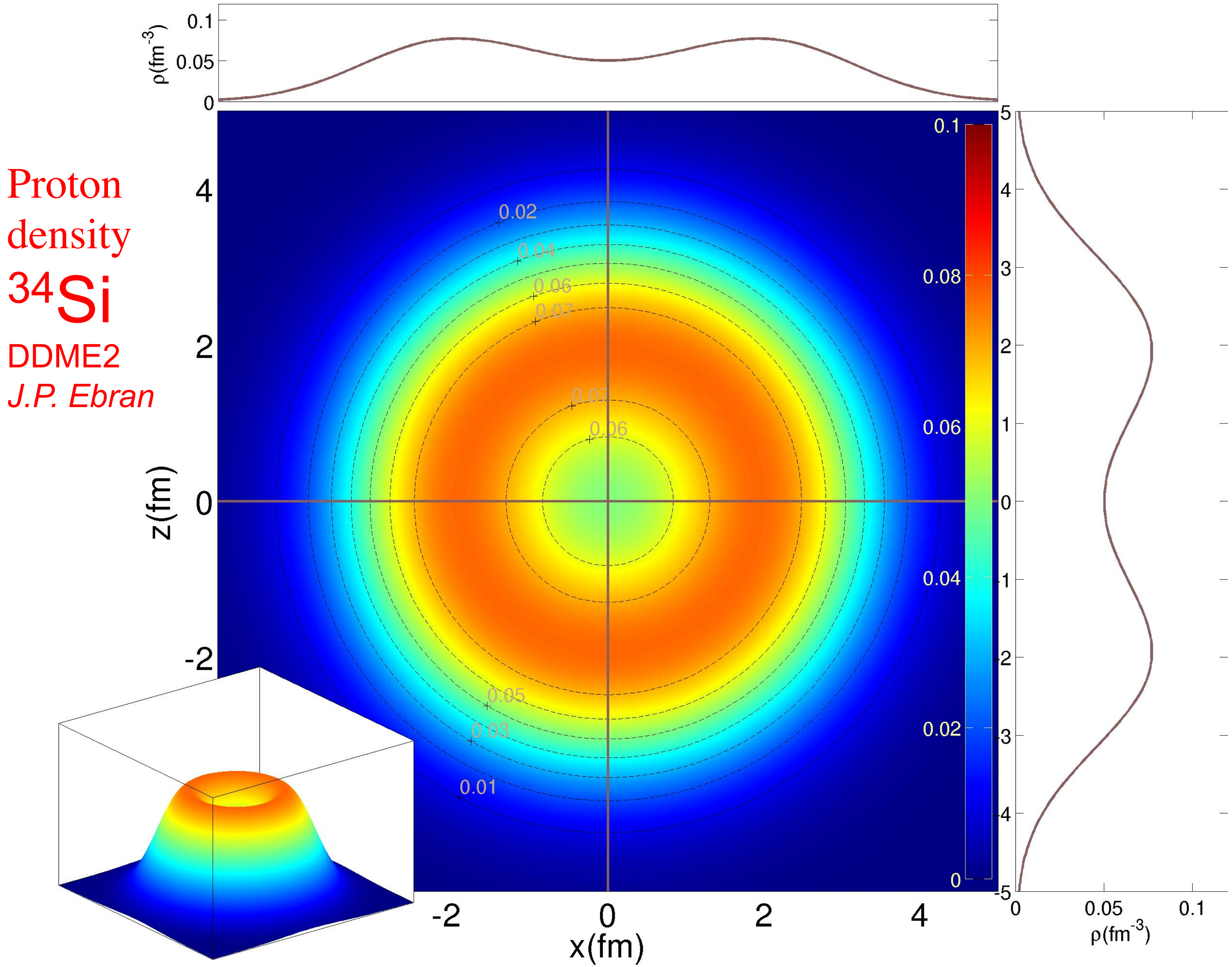
$$W_1 \approx 2W_2 \quad (MF)$$

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

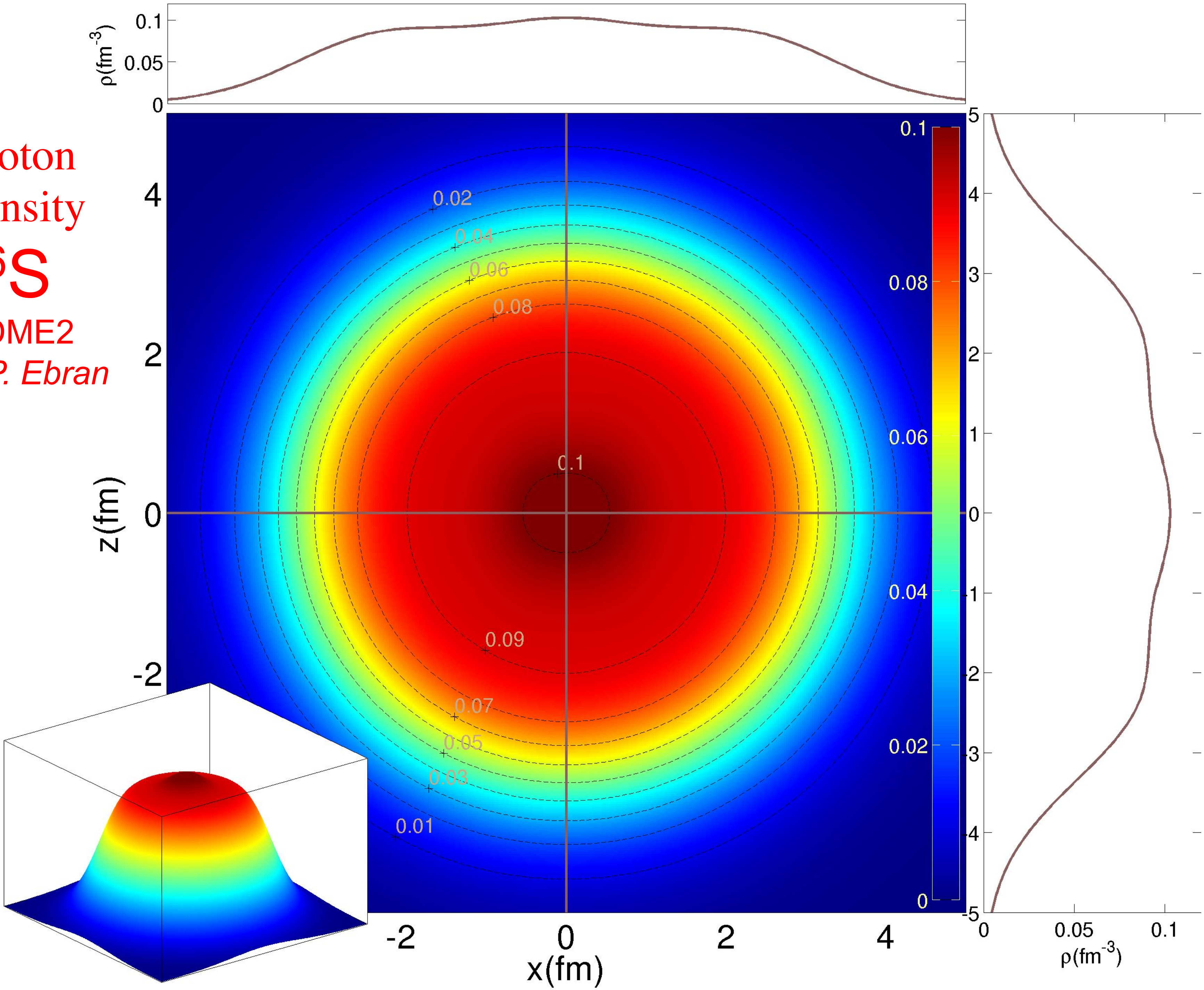
No isospin dependence in RMF

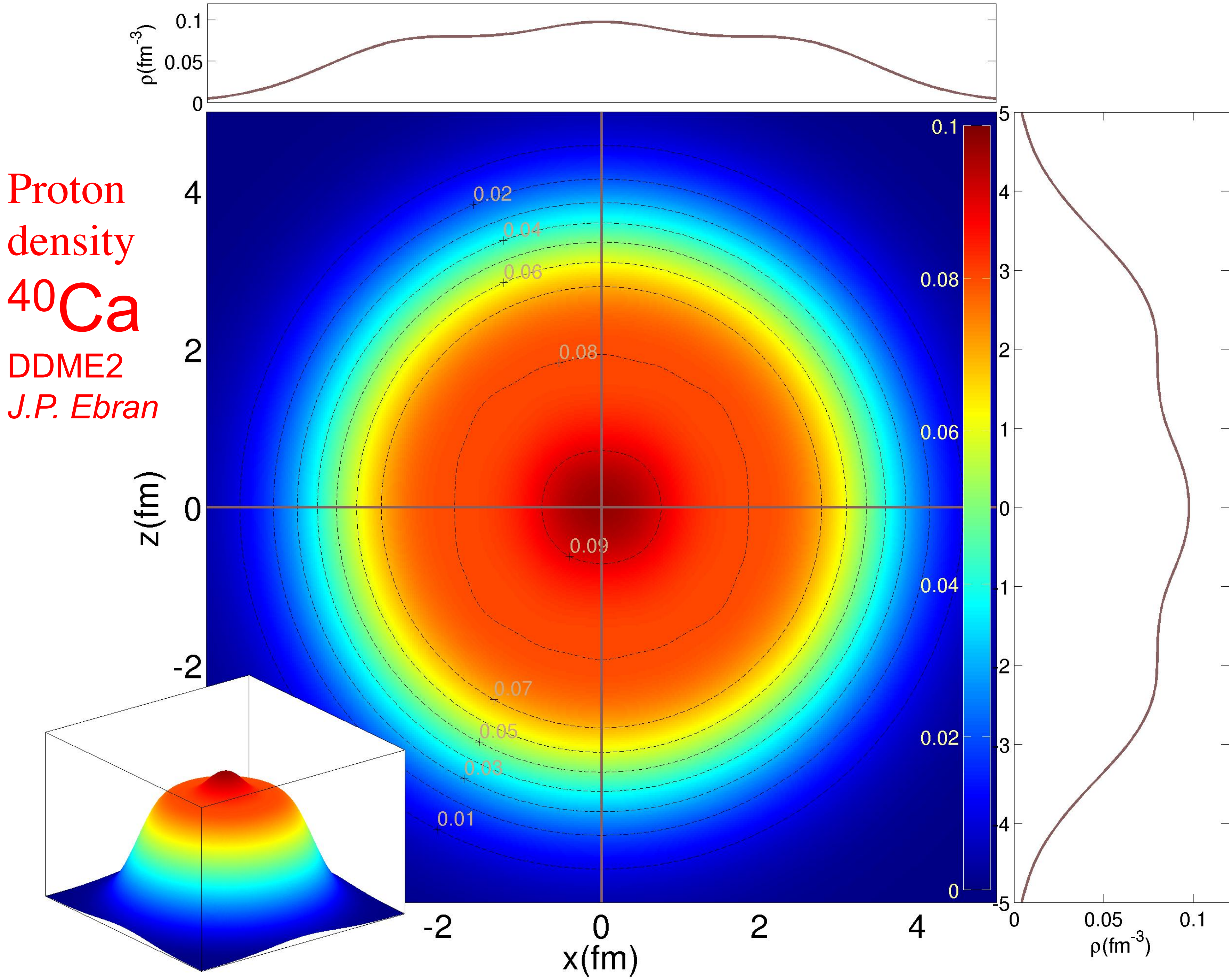
Reduced SO splitting in bubble nucleus for orbits probing the interior of the nucleus !

Reduction magnified in RMF approaches

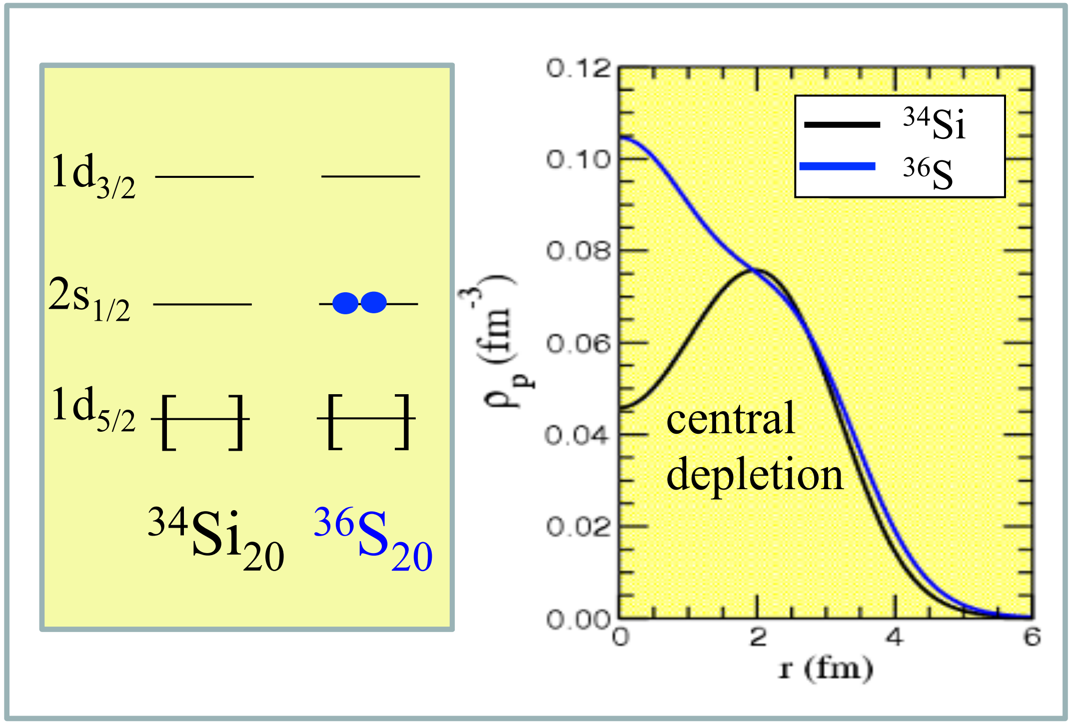

Proton
density
34Si
DDME2
J.P. Ebran
ρ(fm-3)
z(fm)
x(fm)
0.01
0.02
0.03
0.04
0.05
0.06
0.07

Proton density ^{36}S
DDME2
J.P. Ebran




Proton density
^{40}Ca
DDME2
J.P. Ebran
ρ(fm^{-3})
0.1
0.05
0
z(fm)
x(fm)
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
-2
0
2
4
5
3
1
-1
-3
-4
-5

Probing the SO interaction using a bubble nucleus

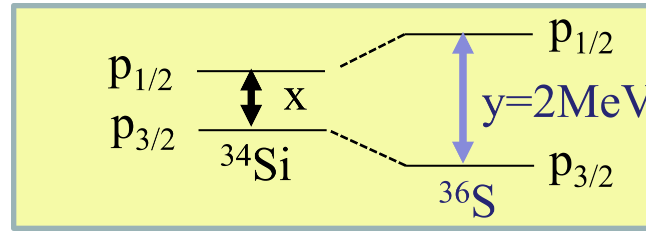


Central hole due to proton $s_{1/2}$ depletion

Test of density/isospin dependence of the SO force

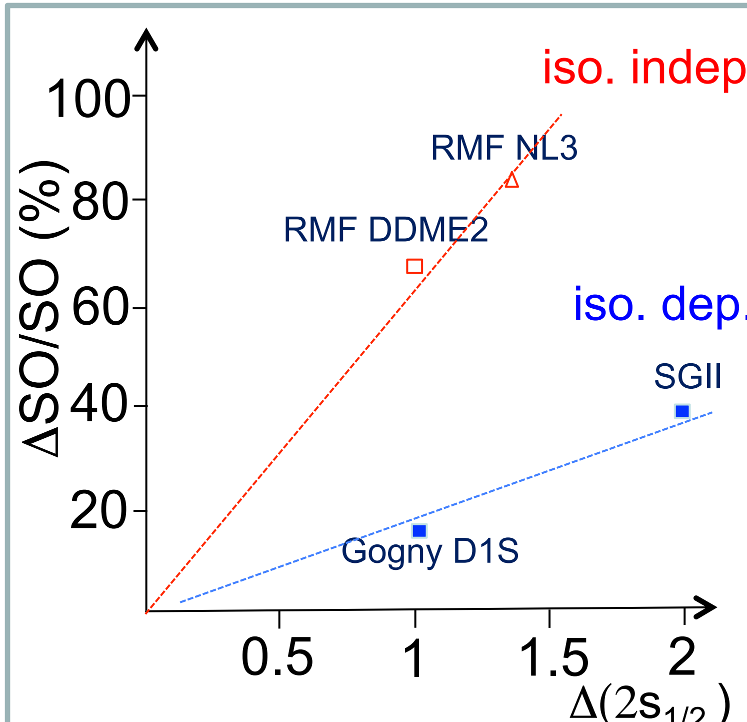
Change of neutron $p_{3/2}$-$p_{1/2}$ splitting between ^{34}Si and ^{36}S

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



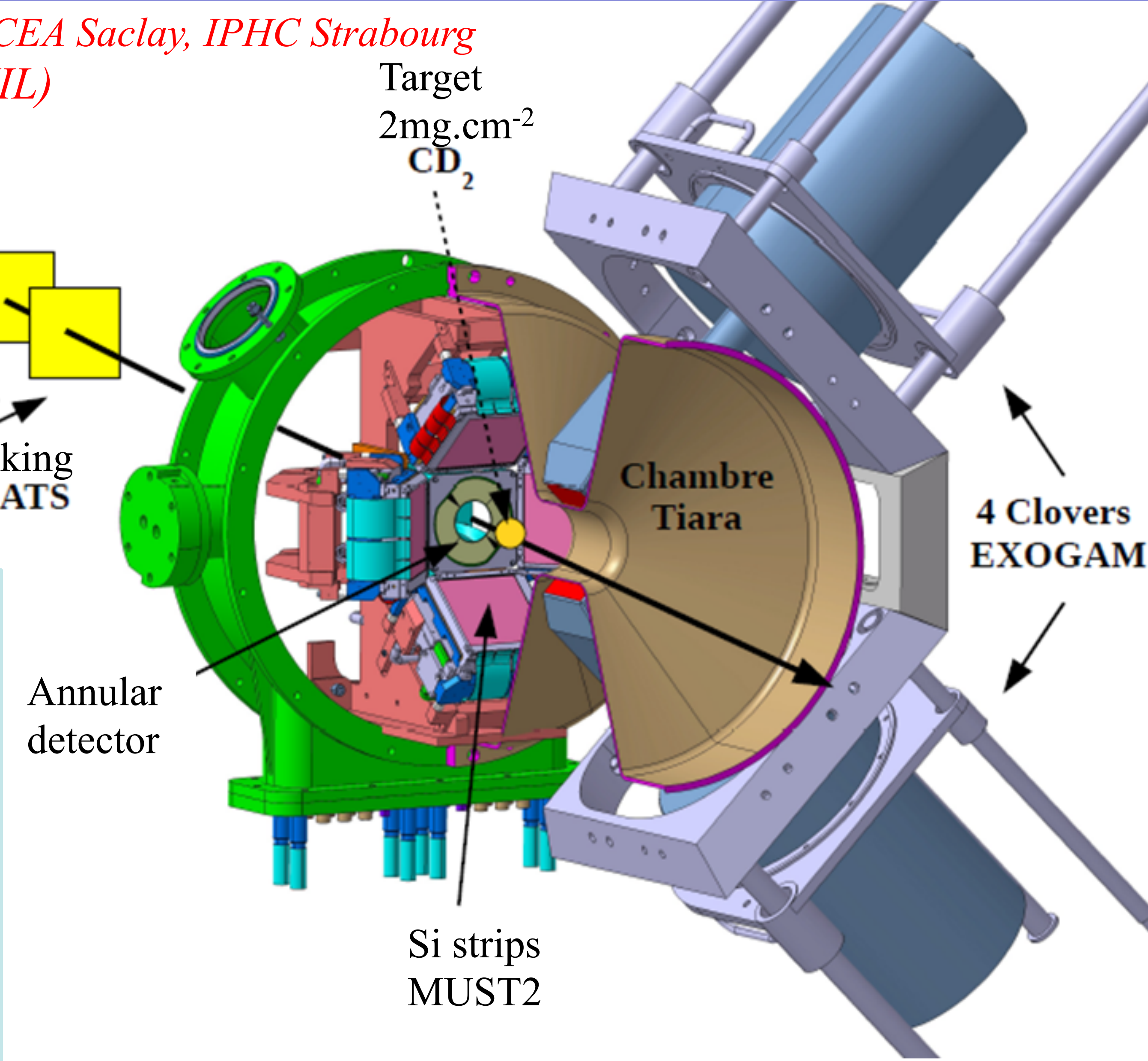
$$\Delta_n(SO) = y-x$$

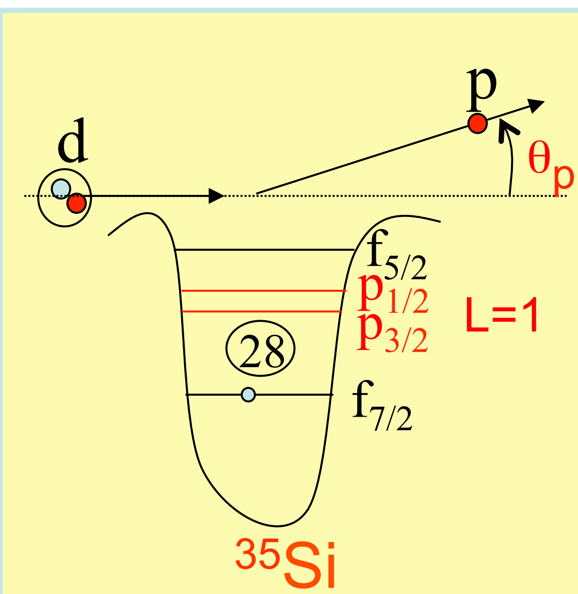
$$\Delta_n SO/SO\ (\%) = \frac{\text{Diff}}{\text{Mean}} = \frac{y-x}{(x+y)/2}$$



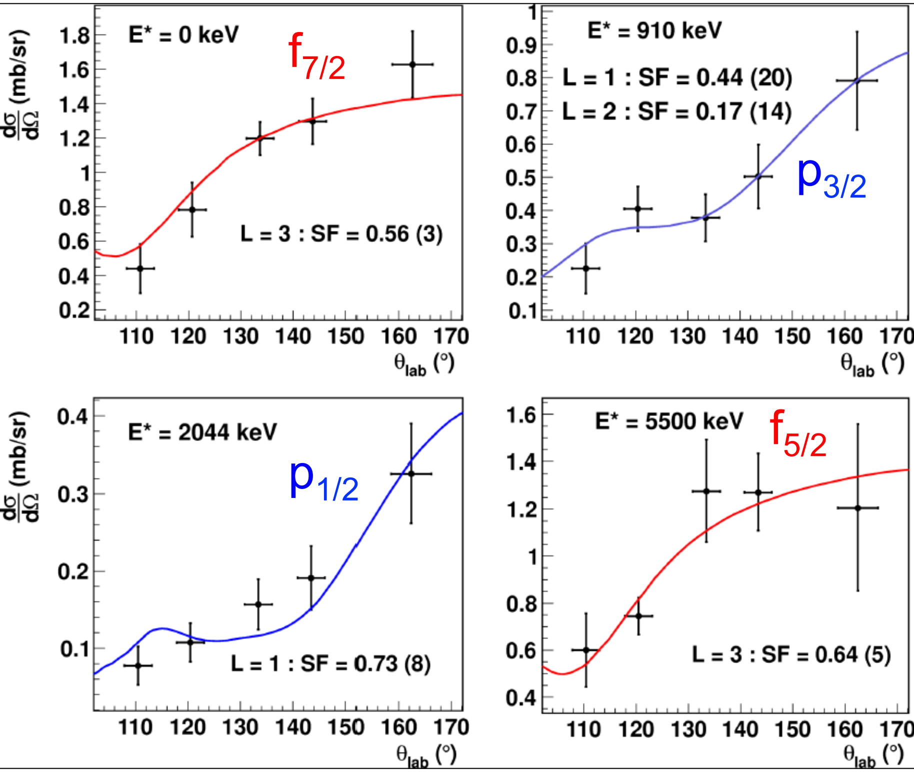
Experimental set up to study the $^{34}Si(d,p)^{35}Si$ reaction

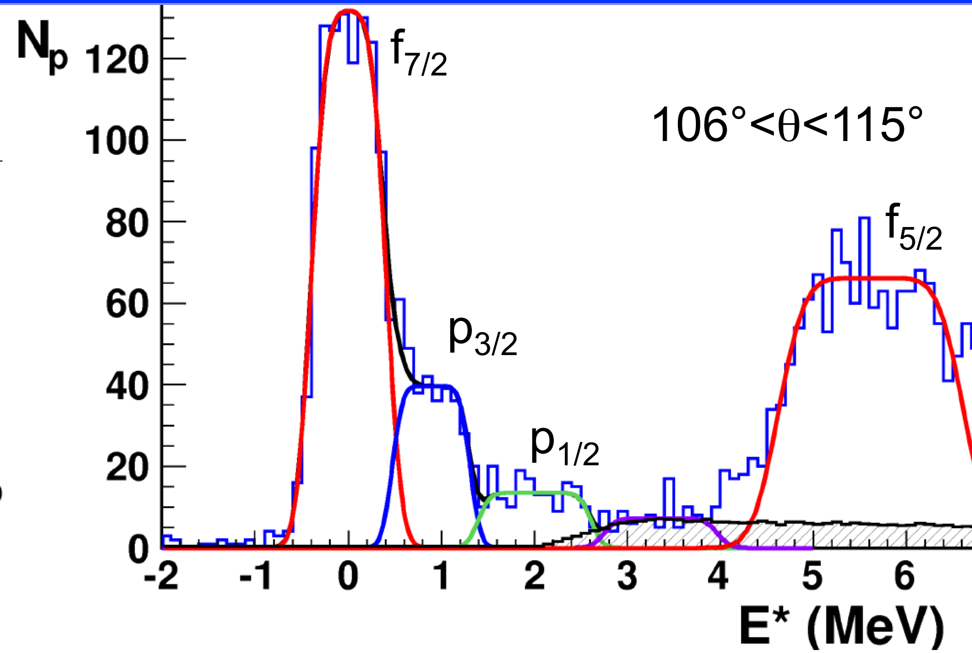
Collab. GANIL, IPN Orsay, CEA Saclay, IPHC Strabourg
PHD G. Burgunder (GANIL)

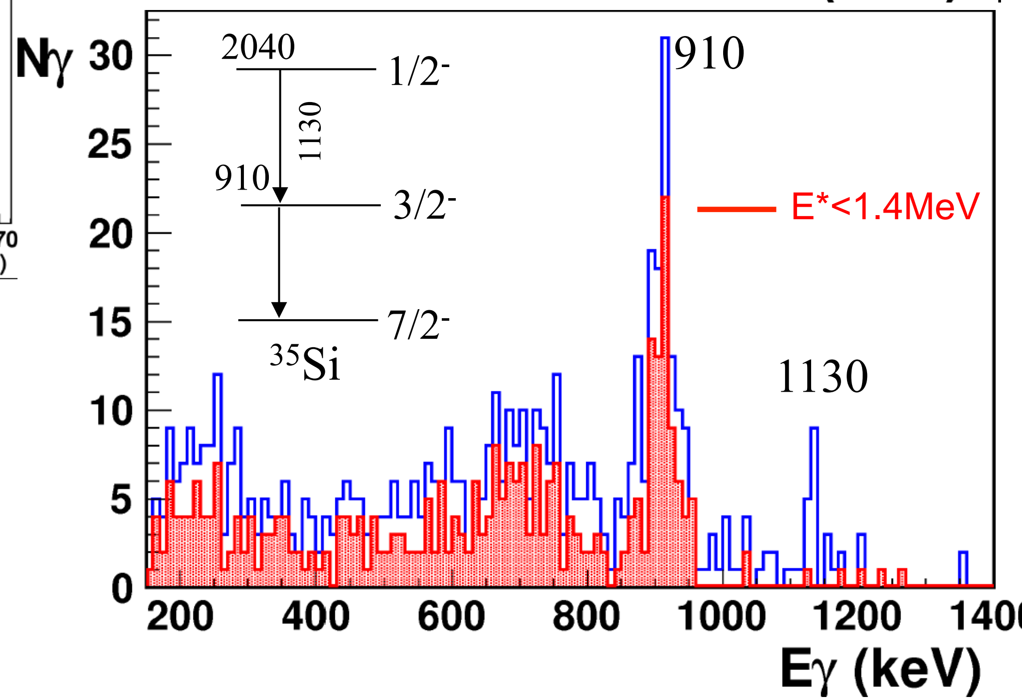




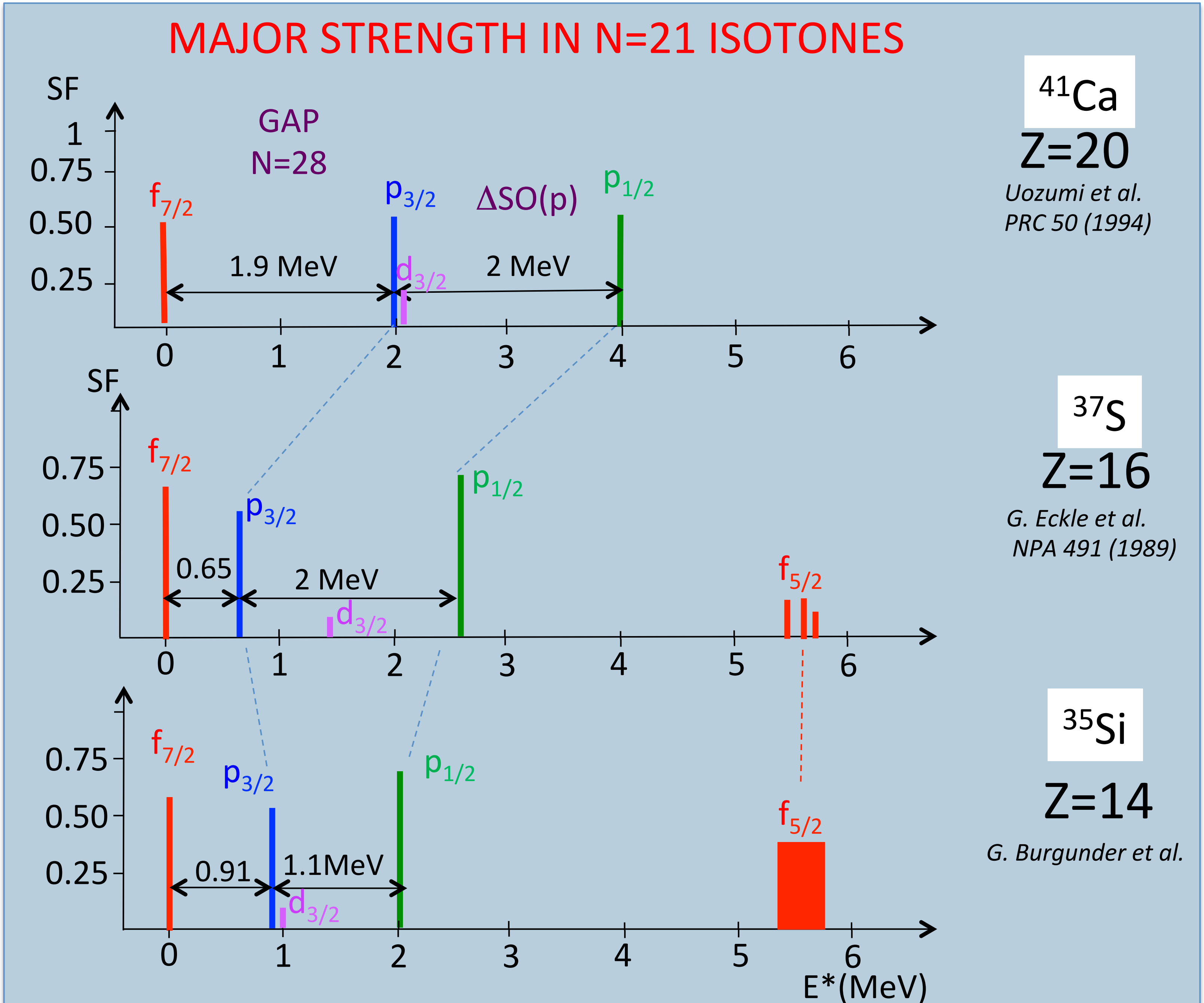
EXPERIMENTAL RESULTS $^{34}Si(d,p)^{35}Si$



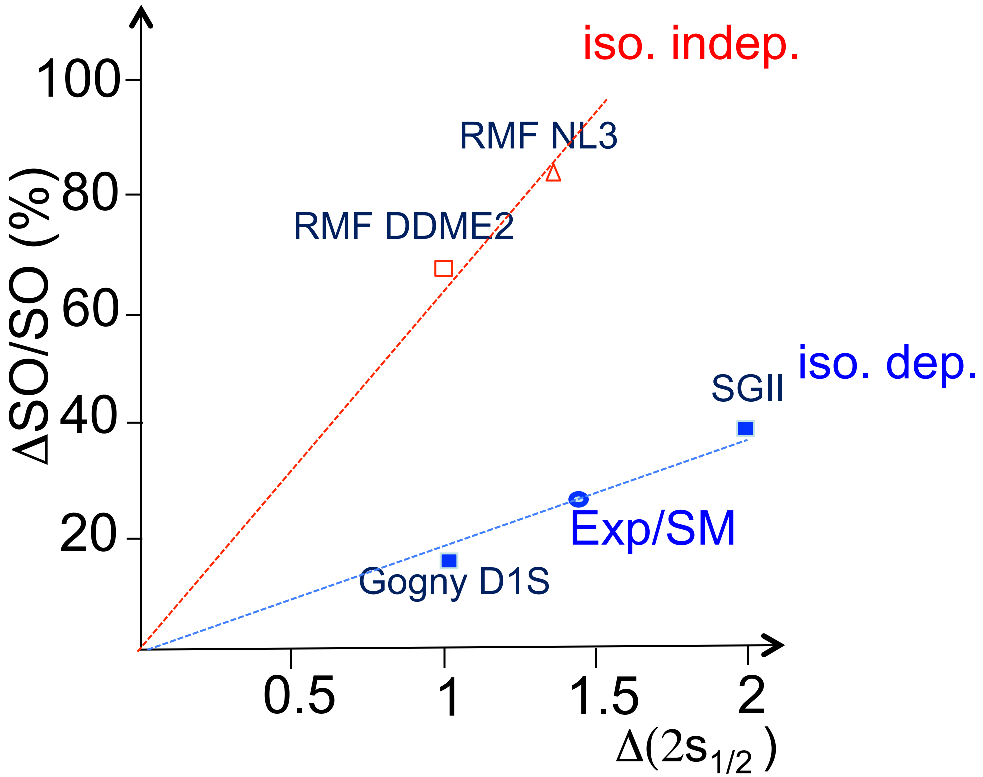




Identification of the major part of the $p_{3/2}$ and $p_{1/2}$ strengths in ^{35}Si


MAJOR STRENGTH IN N=21 ISOTONES
SF
1
0.75
0.50
0.25
GAP
N=28
f7/2
p3/2
ΔSO(p)
p1/2
1.9 MeV
d3/2
2 MeV
0
1
2
3
4
5
6
41Ca
Z=20
Uozumi et al.
PRC 50 (1994)
SF
0.75
0.50
0.25
f7/2
p3/2
p1/2
0.65
2 MeV
d3/2
f5/2
37S
Z=16
G. Eckle et al.
NPA 491 (1989)
0.75
0.50
0.25
f7/2
p3/2
p1/2
0.91
1.1MeV
d3/2
f5/2
35Si
Z=14
G. Burgunder et al.
E*(MeV)

Isospin dependence of the SO interaction



Experiment favors density AND isospin dep. of SO interaction

$\Delta s_{1/2}$ to be confirmed soon (experimental work in progress)

Anticipate consequences for drip line and SHE nuclei …

Conclusions & Perspectives

PART 1 :

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

→Modest reduction of the mean interaction and residual interaction compared to SM

→Excellent agreement with coupled cluster calculations

Confirm energy/spin assignment of the 3^+ unbound state

Calculate its energy (collab. G. Hagen)

PART 2:

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

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

(collab F. Nowacki)

Exp value confirm density dependence of the SO interaction

favor isospin dependence of the SO interaction

Confirm the amplitude of the bubble (under analysis)

Consequences for r process, SHE, to be done