Probing properties of the nuclear force in 'extreme' conditions

O. Sorlin (GANIL, Caen, France)

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

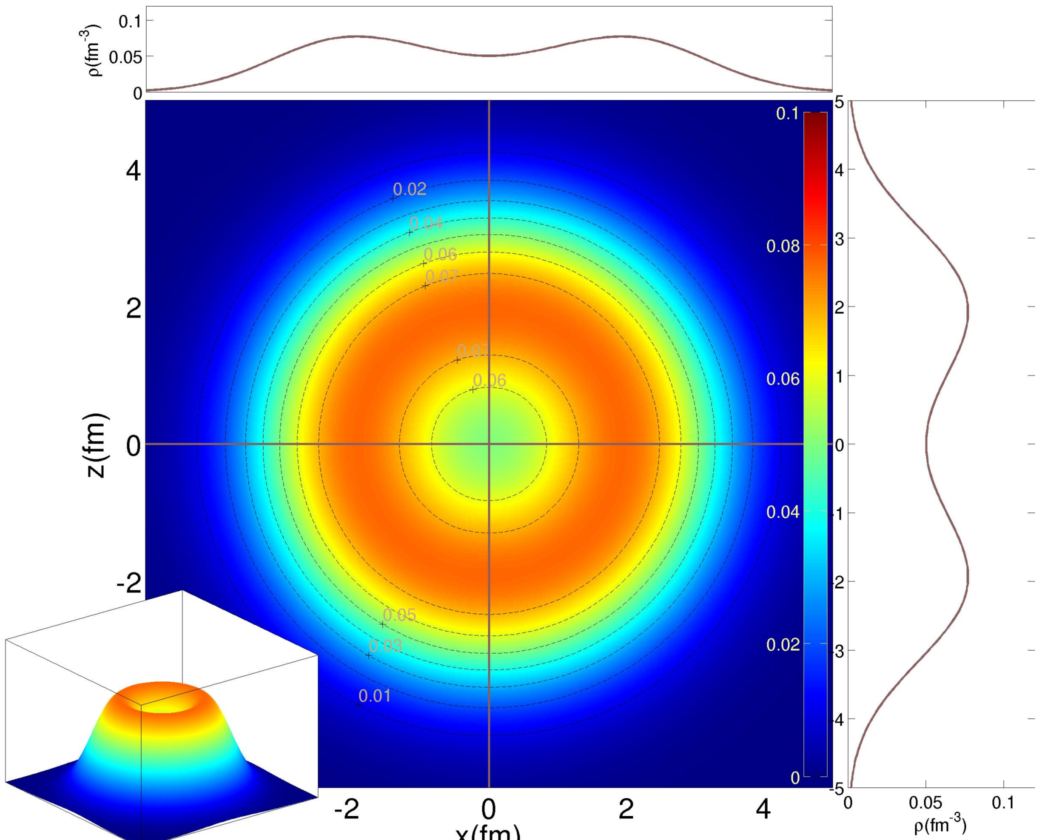
PART 1:

Testing the spin-orbit force with a 'bubble' nucleus

PART 2:

Proton-neutron forces at the drip-line

Part I:
Test of the spin-orbit interaction by using the doubly-magic ‘bubble’ nucleus ^{34}Si



^{34}Si doubly magic: High 2^+ energy, low B(E2), weak ρ(E0)…

Ibbotson et al. PRL 80 (1998) 2081, Rotaru et al. PRL 109 (2012) 092503

Enders et al. PRC 65 (2002) 034318 + talk S. Grévy

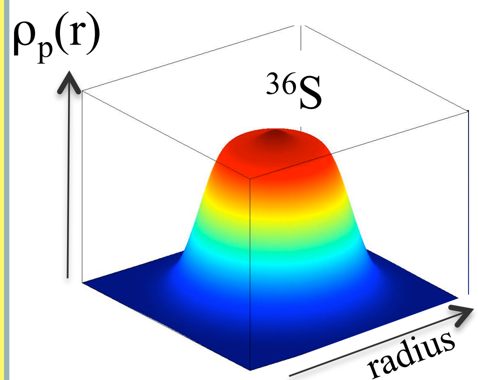
Proton density depletion in ^{34}Si ?

Proton orbits		C^2S
$1d_{3/2}$	——	0.2
$2s_{1/2}$	—●●—	1.8
$1d_{5/2}$	●●●●●●	6

$^{36}S_{20}$

$^{36}S(d,^3He)^{35}P$

Khan et al. PLB 156 (1985)

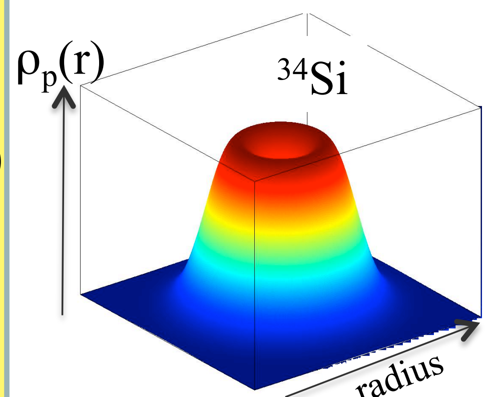


Proton orbits		C^2S
$1d_{3/2}$	——	
$2s_{1/2}$	——	0.17(3)
$1d_{5/2}$	●●●●●●	5.76(7)

$^{34}Si_{20}$

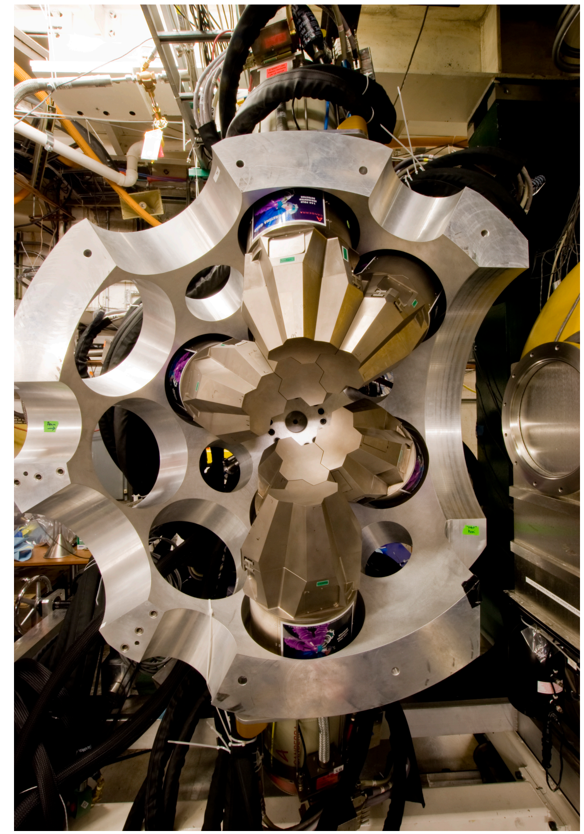
$^{34}Si(-1p)^{33}Al$

Mutschler et al. in prep.



J.P. Ebran DDME2 interaction

$\Delta(2s_{1/2})$ between ^{36}S and ^{34}Si using (-1p) reaction

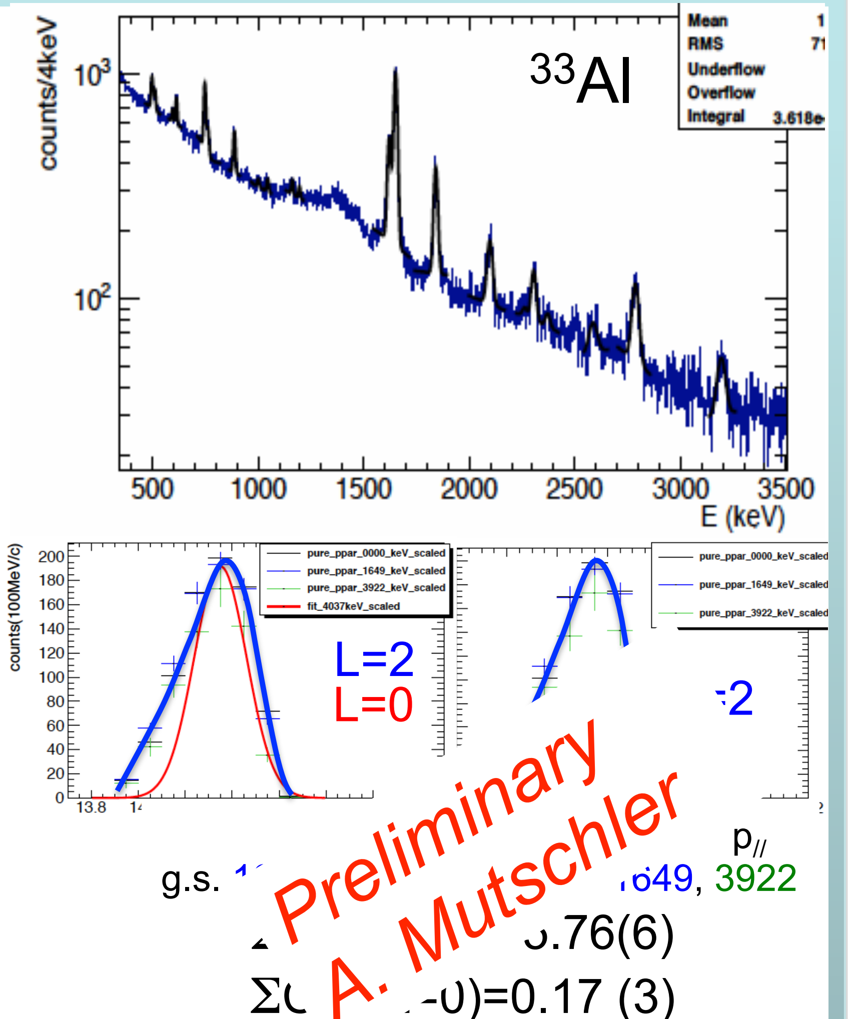


NSCL/S800 with Gretina

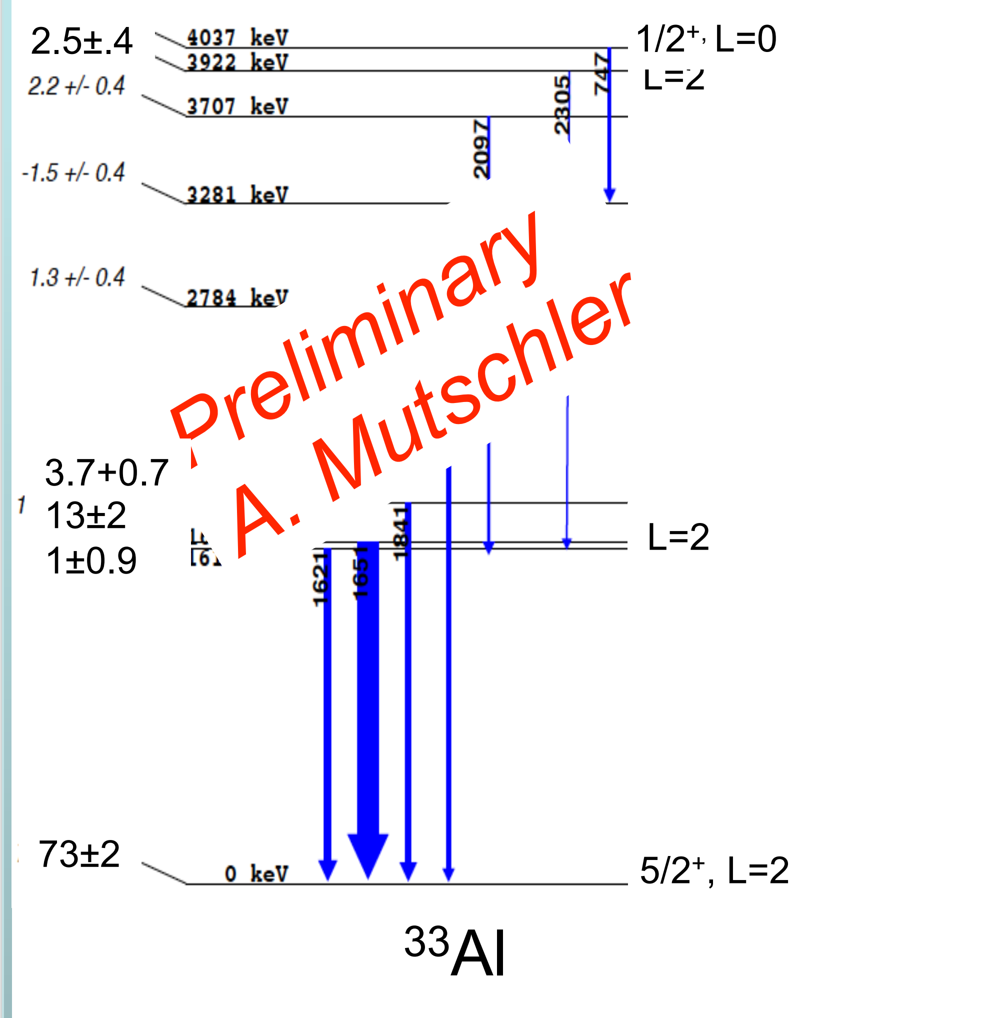
Gamma-gated $p_{//}$ of fragments

Proton occupancies in ^{34}Si using (-1p) reaction

Gamma-ray spectrum at 90°



^{34}Si (-1p) ^{33}Al

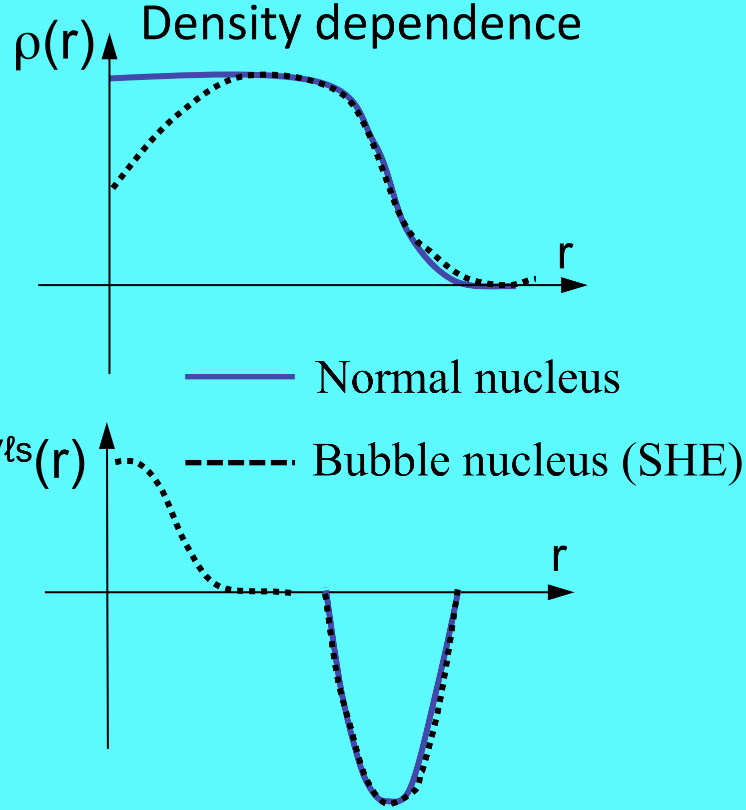


So far very small L_p=0 knock-out observed -> *in agreement with a 'bubble' nucleus*

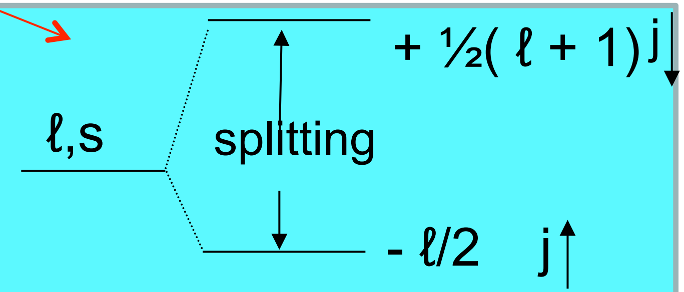
The spin-orbit (SO) interaction

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

Density dependence



Reduced SO splitting in bubble nucleus for orbits probing the interior of the nucleus such as L=1



Asymmetric splitting of j orbits

Isospin dependence

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

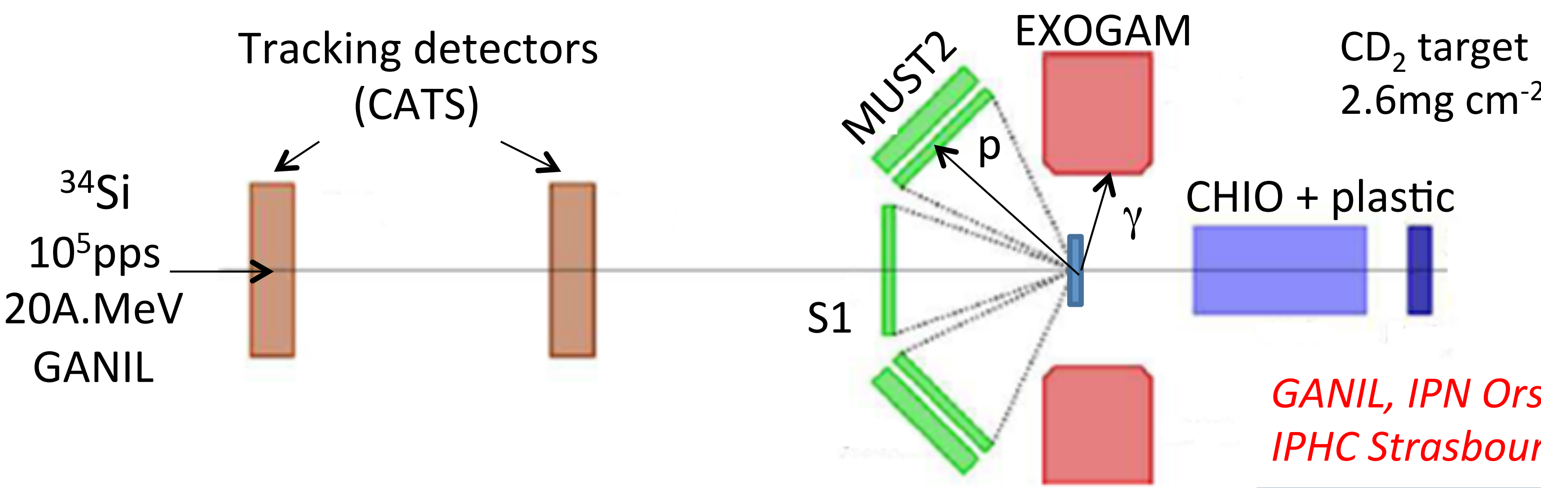
$$W_1 \approx W_2 \quad (RMF)$$

No isospin dependence in RMF

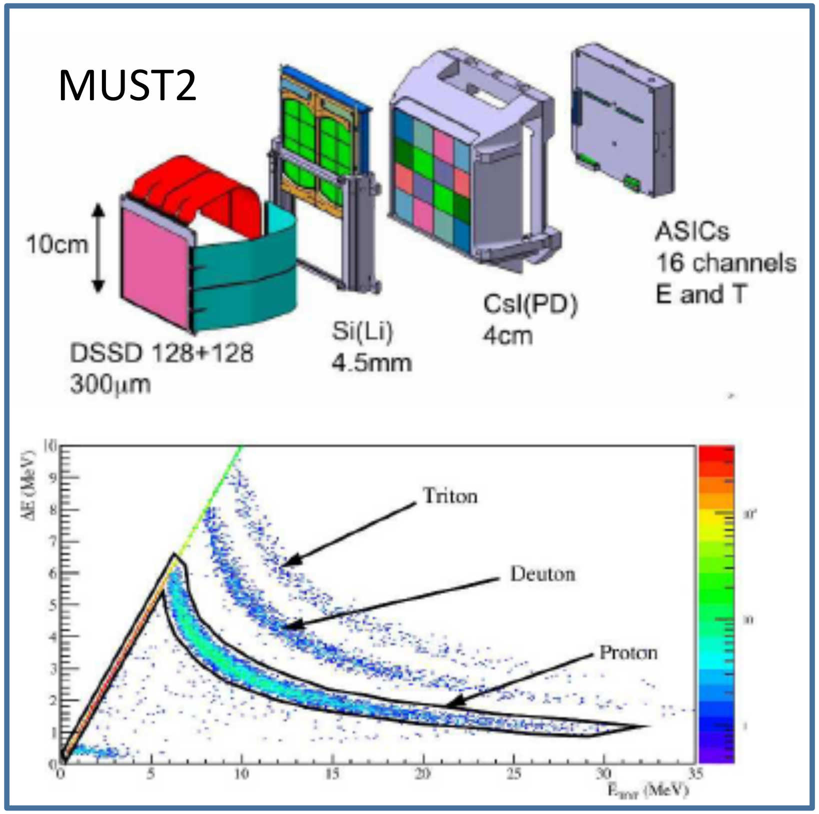
Looking at neutron $p_{3/2}$-$p_{1/2}$ SO evolution when depleting the proton central density

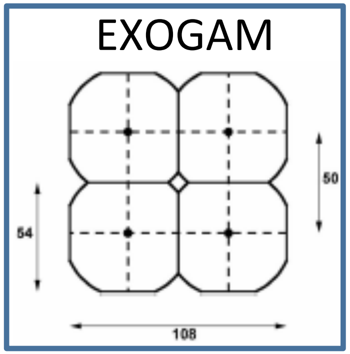
-> test density and isospin dep. of SO

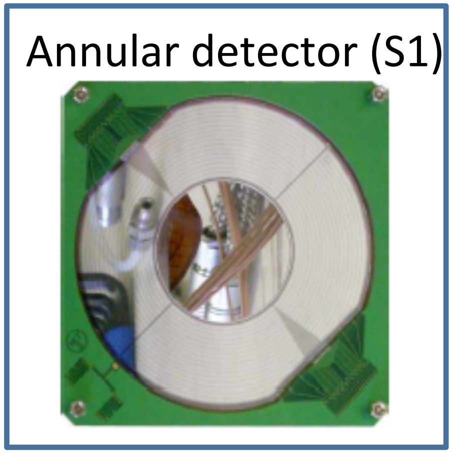
$^{34}Si(d,p)$ reaction in inverse kinematics at GANIL

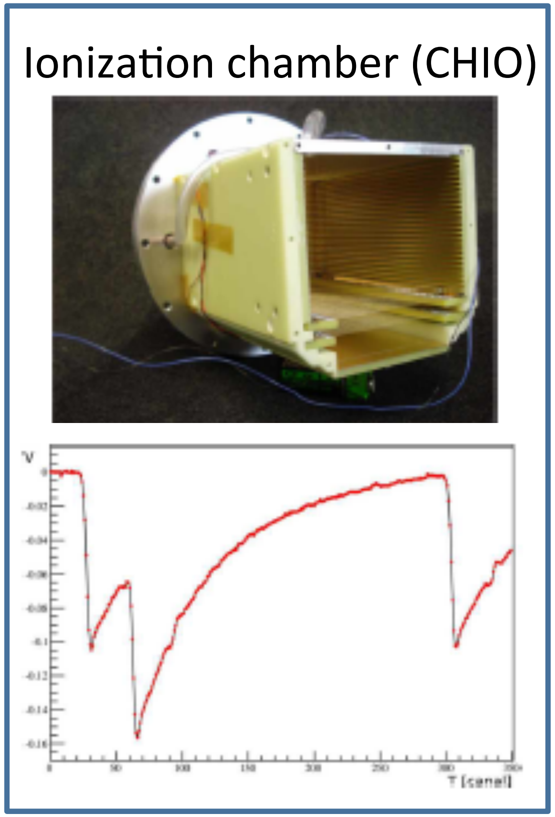


GANIL, IPN Orsay, CEA Saclay
IPHC Strasbourg

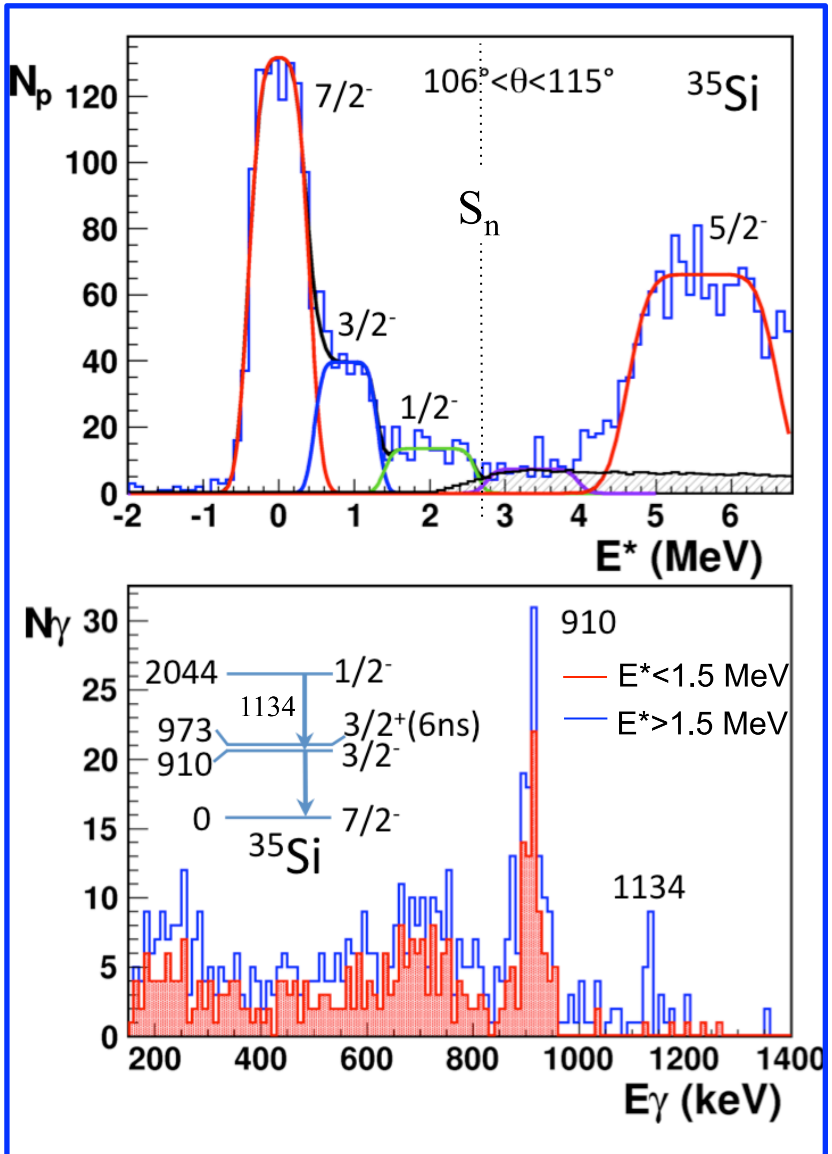


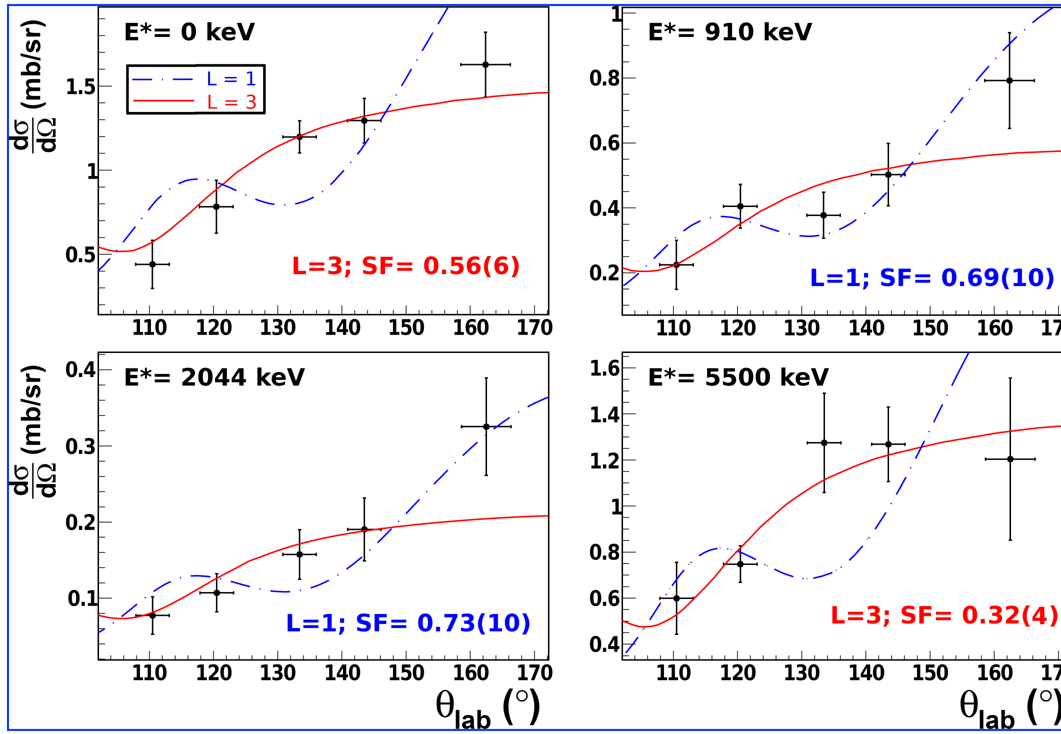






Spin-orbit splittings in ^{35}Si using ^{34}Si(d,p)^{35}Si



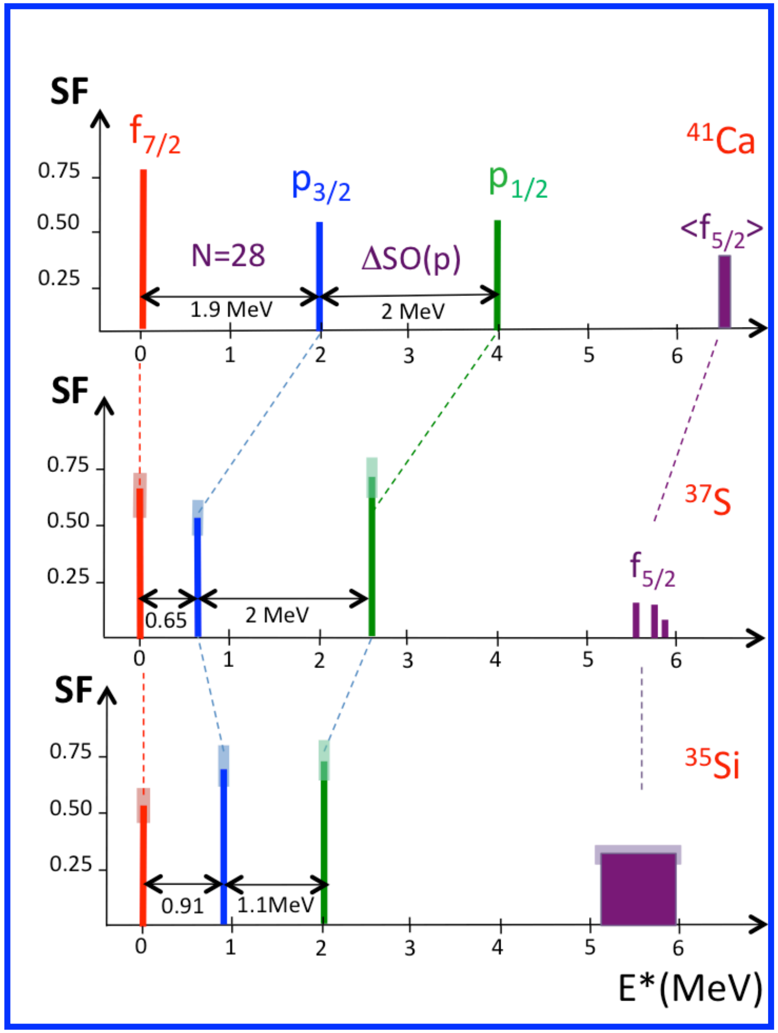


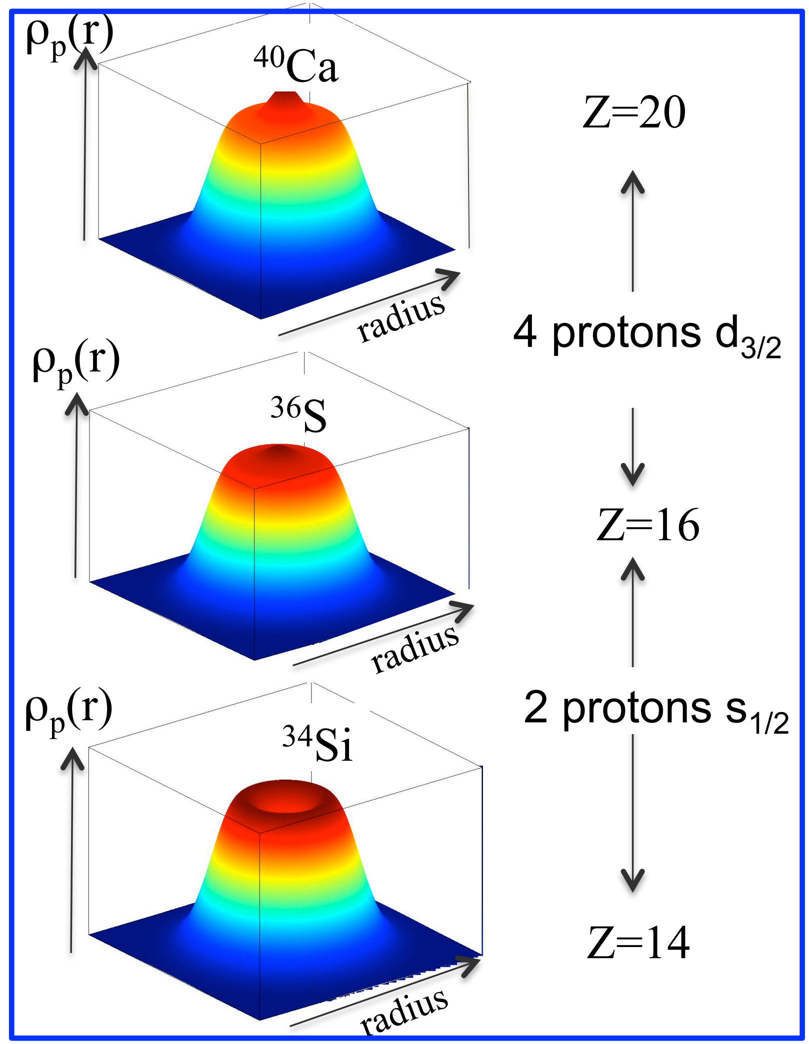
L assignments from proton angular distributions

Accurate energy of states with γ-ray detection

G. Burgunder et al., Phys. Rev. Letters 112 (2014)

Evolution of the $p_{3/2}$-$p_{1/2}$ SO splitting



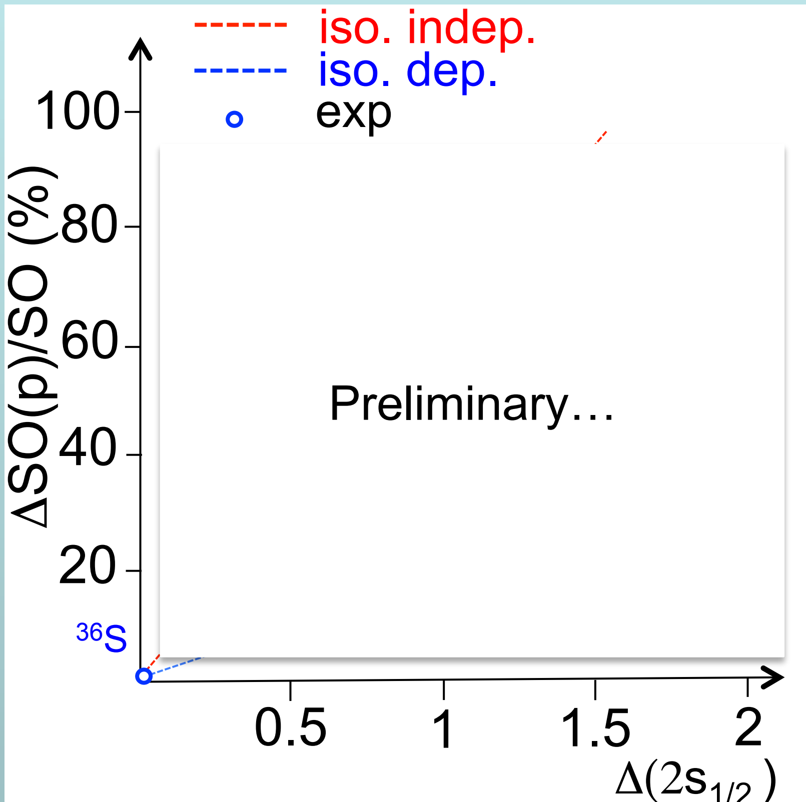


No change in $p_{3/2}$-$p_{1/2}$ splitting between ^{41}Ca and ^{37}S

Large reduction of $p_{3/2}$-$p_{1/2}$ splitting between ^{37}S and ^{35}Si, no change of $f_{7/2}$-$f_{5/2}$

Density and Isospin dependence of the SO interaction

Evolution of the p SO splitting as a function of central depletion

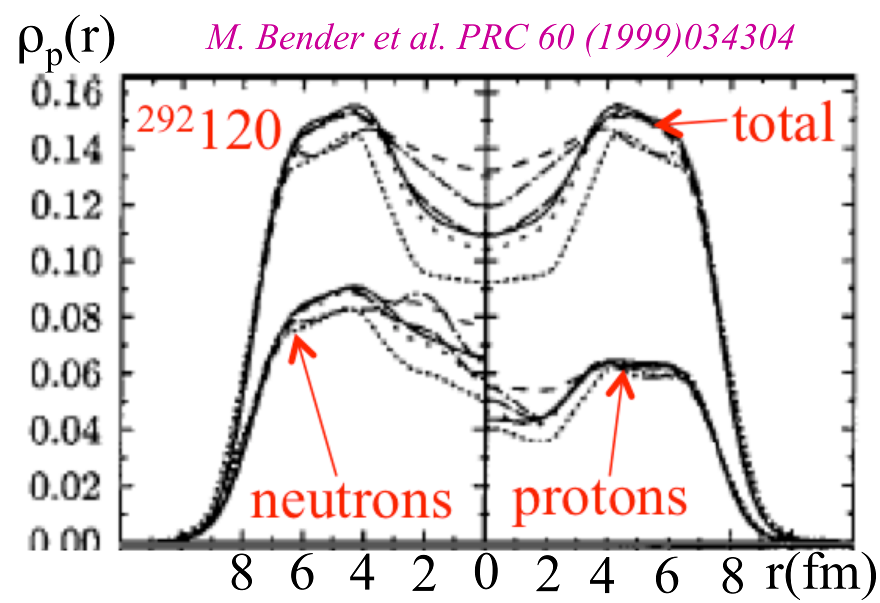


^{46}Ar: Gaudefroy et al. PRL 99 (2007)
^{34}Si: Burgunder et al. PRL 112 (2014)

Density dependence
Isospin dependence
} of the SO inter.

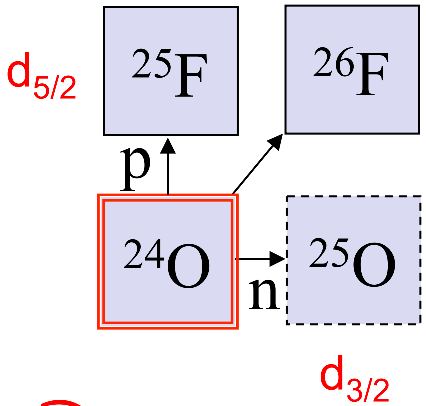
RMF does not have the proper isospin dependence of the SO interaction

Consequences for predicting shell gaps formed by the SO interaction in SHE



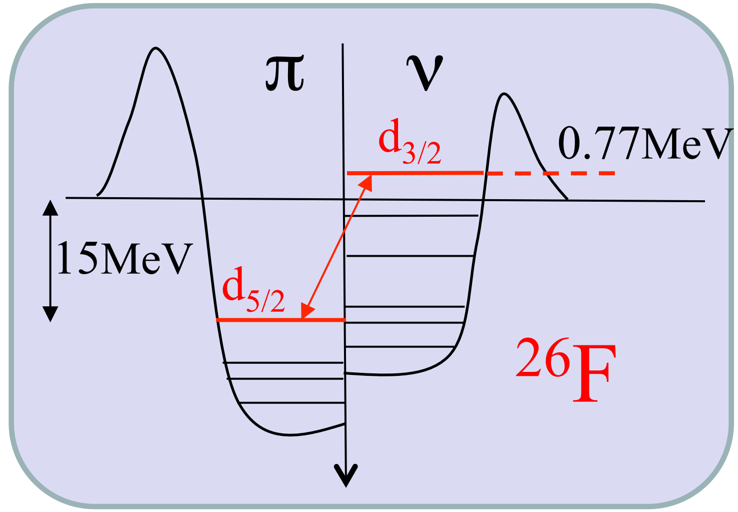
Part II:
Proton-neutron interactions at the drip-line

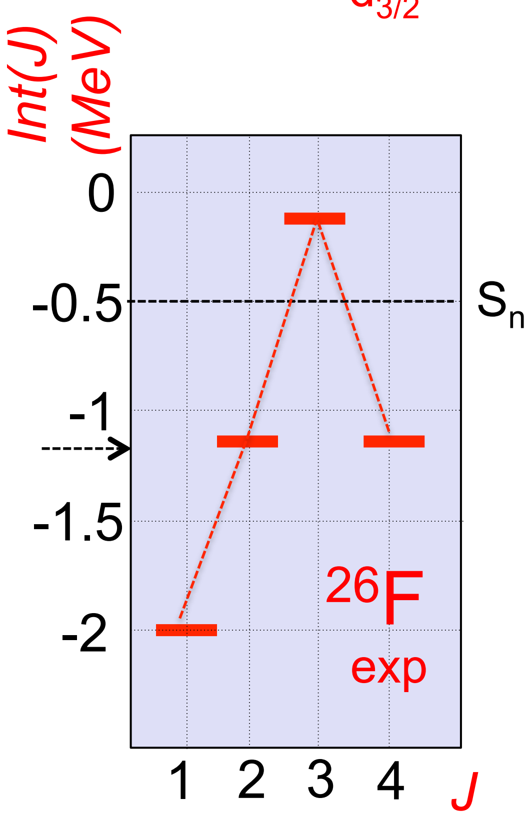
Proton-neutron interactions at the drip-line



$$V^{pn} \approx \frac{\sum (2J+1)\, int(J)}{(2J+1)}$$

J=1,2,3,4





Determine the $d_{5/2}$- $d_{3/2}$ proton-neutron force in ^{26}F

Compare to Shell Model calculations constrained closer to stability

Compare to models using realistic interactions

4 experiments to determine the energy of the J=1-4 states !

J=1, Mass g.s.: Jurado et al., PLB 649 (2007)

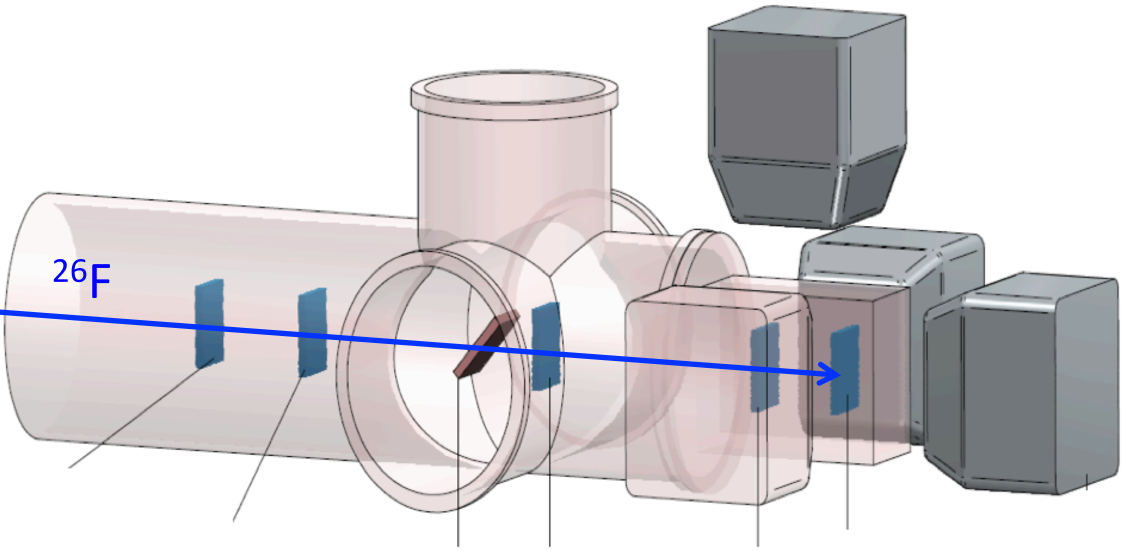
J=2, excited state 'in beam' Stanoiu et al. PRC 85 (2012)

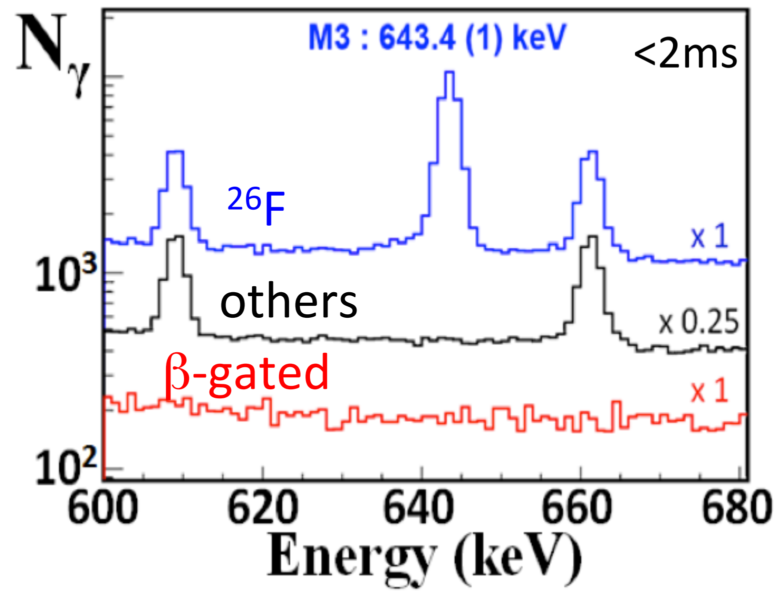
J=3, unbound state Frank et al., PRC 84 (2011) + a new one

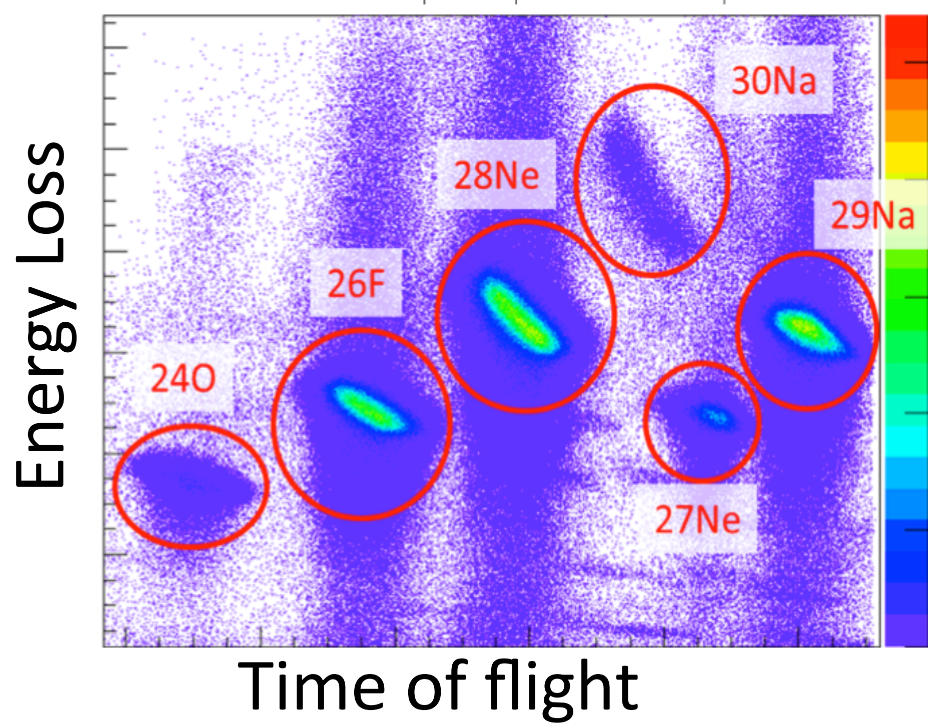
J=4, M3 isomer Lepailleur et al. PRL 110 (2013)

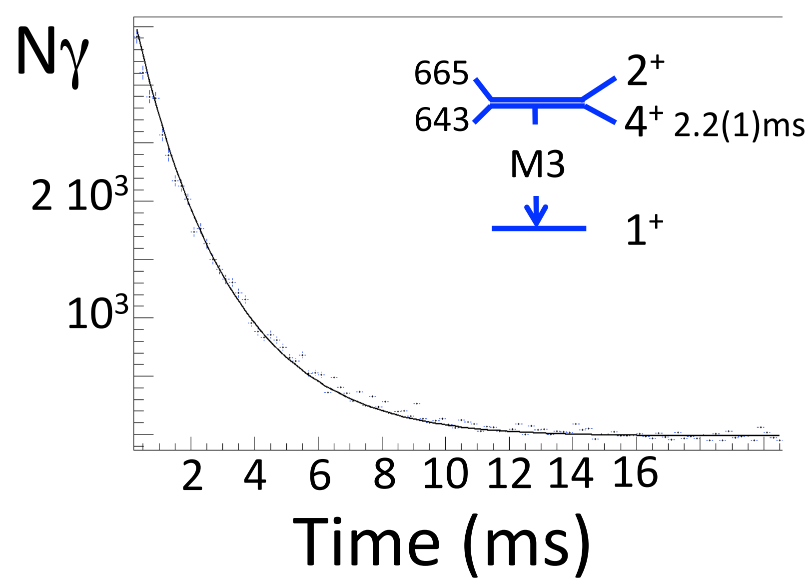
$^{24,25}O$ Hoffman et al. PLB 672(2009), PRL 100(2008)

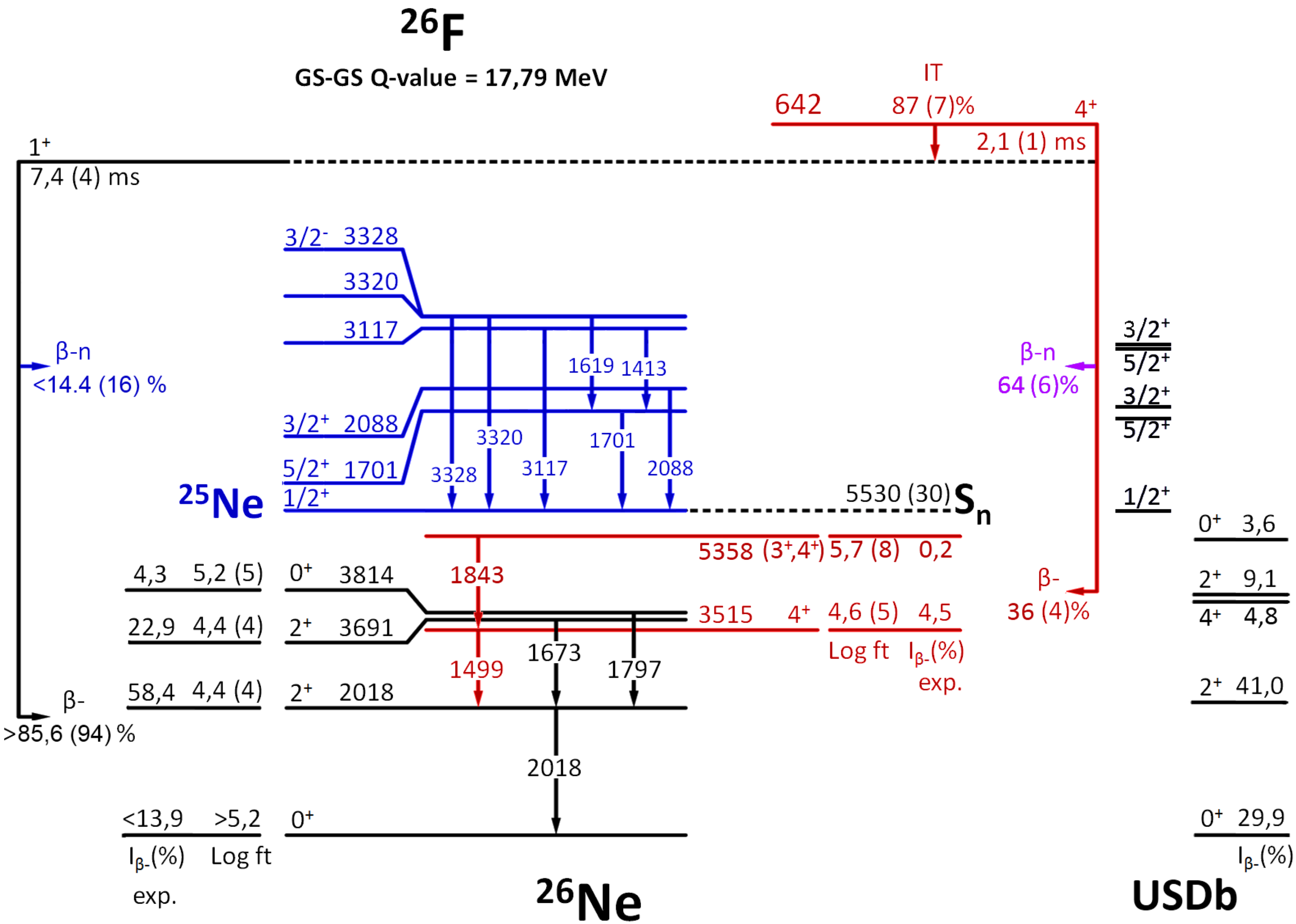
Discovery of a 4^+ isomer in ^{26}F





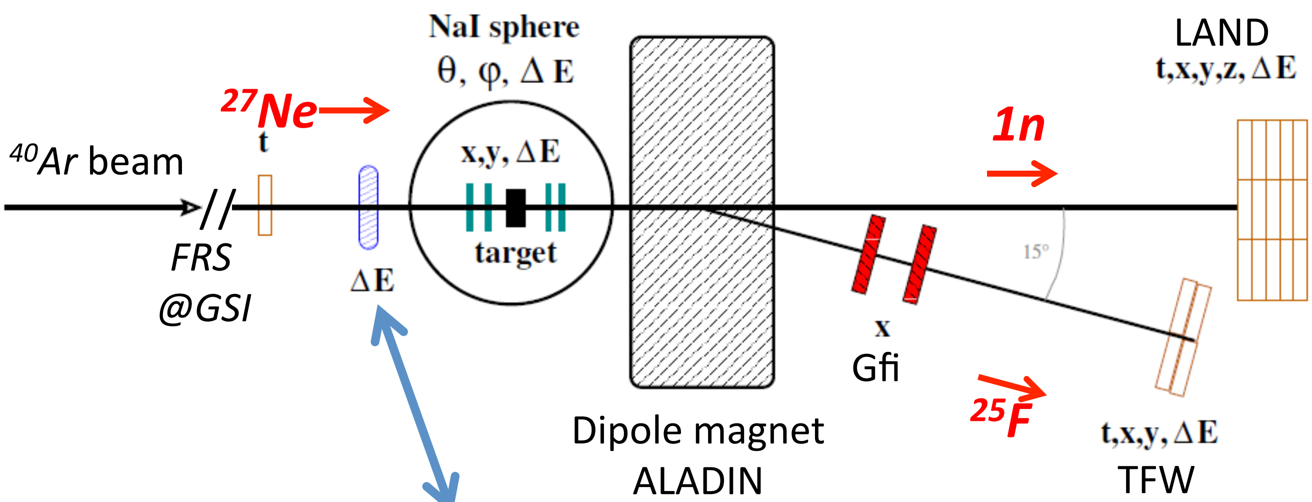


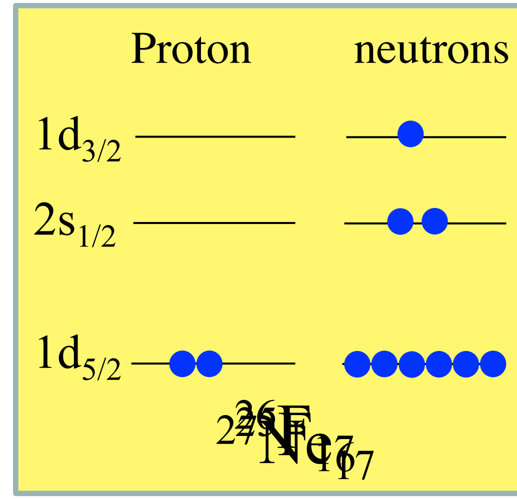


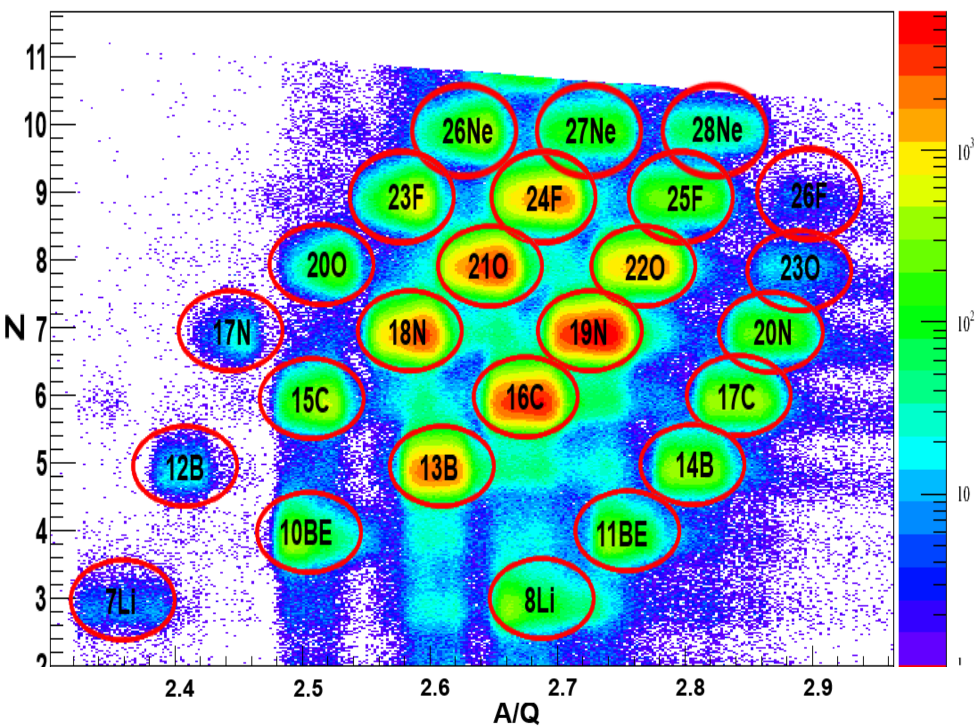


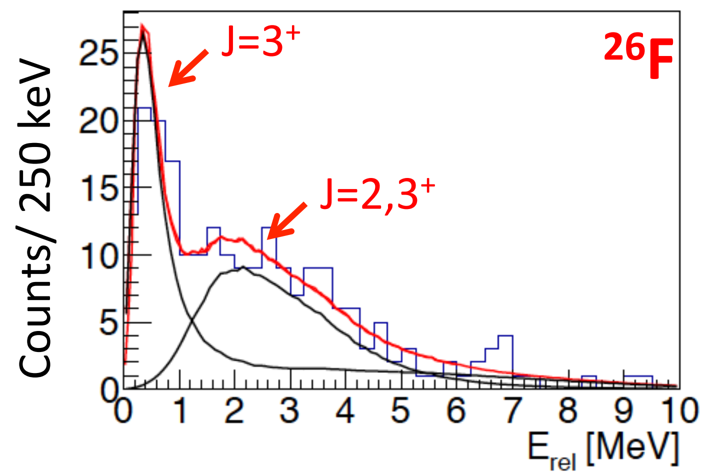
Lepailleur et al. Phys. Rev. Lett. 110 (2013)

Unbound states in ^{26}F studied at GSI/LAND





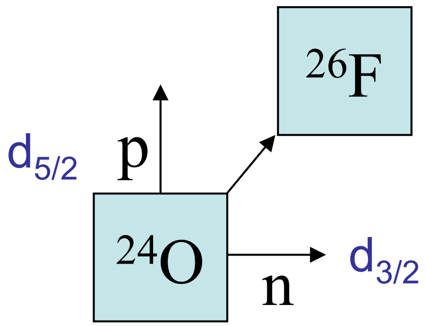




From the widths of $p_{//}$ and neutron peak
-> Excellent candidate for J=3$^+$ state at 550 keV

M. Vandebrouck, preliminary

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

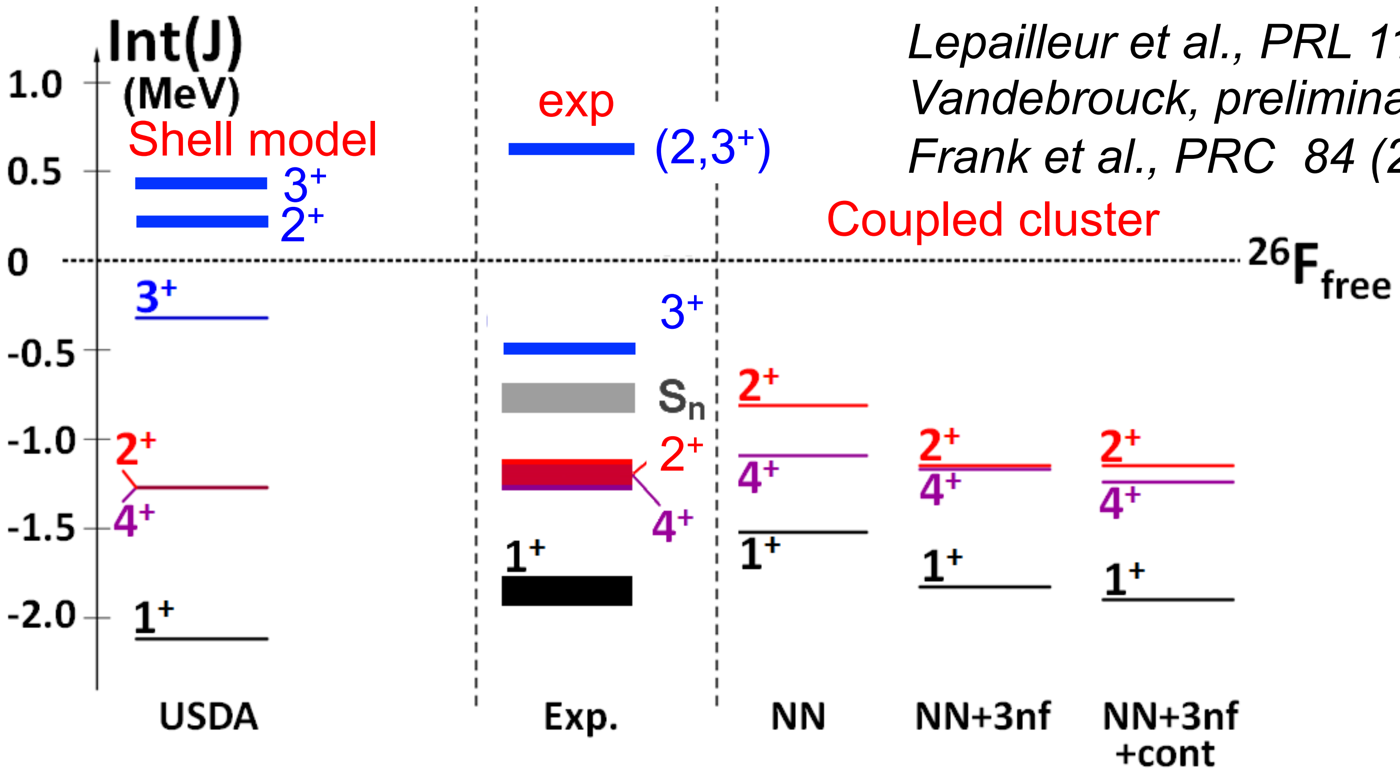


Excellent agreement with coupled cluster calculations (continuum not yet implemented)

pn interaction slightly reduced as compared to Shell Model

Weak change energies of states in continuum
Centrifugal barrier ? Fit with data into continuum ?

Lepailleur et al., PRL 110 (2013)
Vandebrouck, preliminary
Frank et al., PRC 84 (2011) – previous



Conclusions/ Outlooks

PART I:

^{34}Si good candidate for proton 'bubble', normal neutron density
Reduction of neutron $p_{3/2}$-$p_{1/2}$ splitting with proton $s_{1/2}$ depletion
Points to density and isospin dependence of SO interaction

PART II:
Spectroscopy of bound and unbound states in ^{26}F
No drastic change with SM calculations
Benchmark for testing realistic forces up to continuum
But …Atomic mass of ^{26}F to be confirmed….

Special thank's to:
GANIL/IPNO: G. Burgunder, A. Lepailleur, A. Mutschler, M. Vandebrouck, A. Lemasson …
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The NSCL/S800/Gretina teams: D. Weisshar, F. Recchia, D. Bazin, A. Gade, K Wimmer…
Theory: F. Nowacki, T. Otsuka, J. P. Ebran, G. Hagen, G. Jansen, A. Brown