A Foreword : some open questions in nuclear physics …

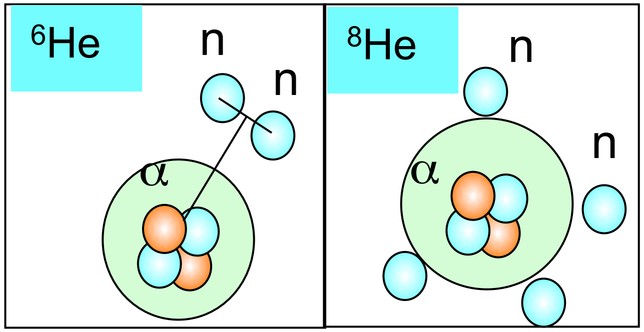
How to explain the existence of halo, clusters, quasi-molecular structures ?

Modeled from ab-initio approaches ?

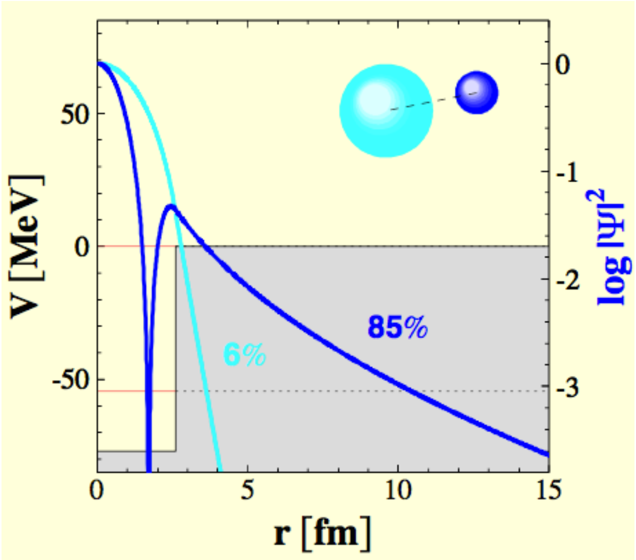
Role of nuclear force and symmetries ?

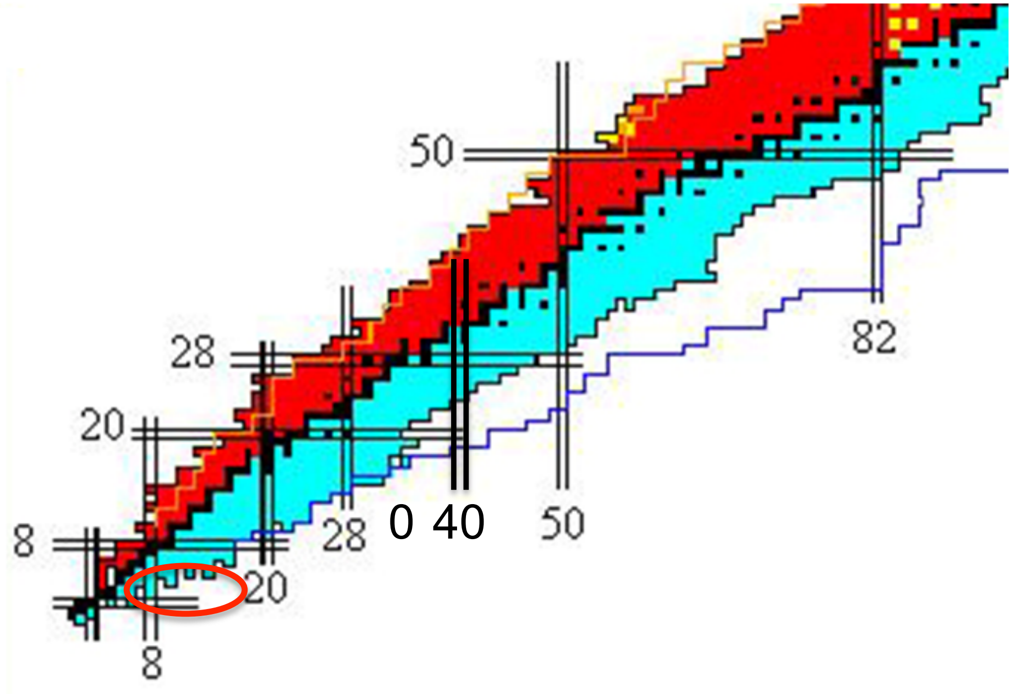
Role of coupling to continuum ?

clusters

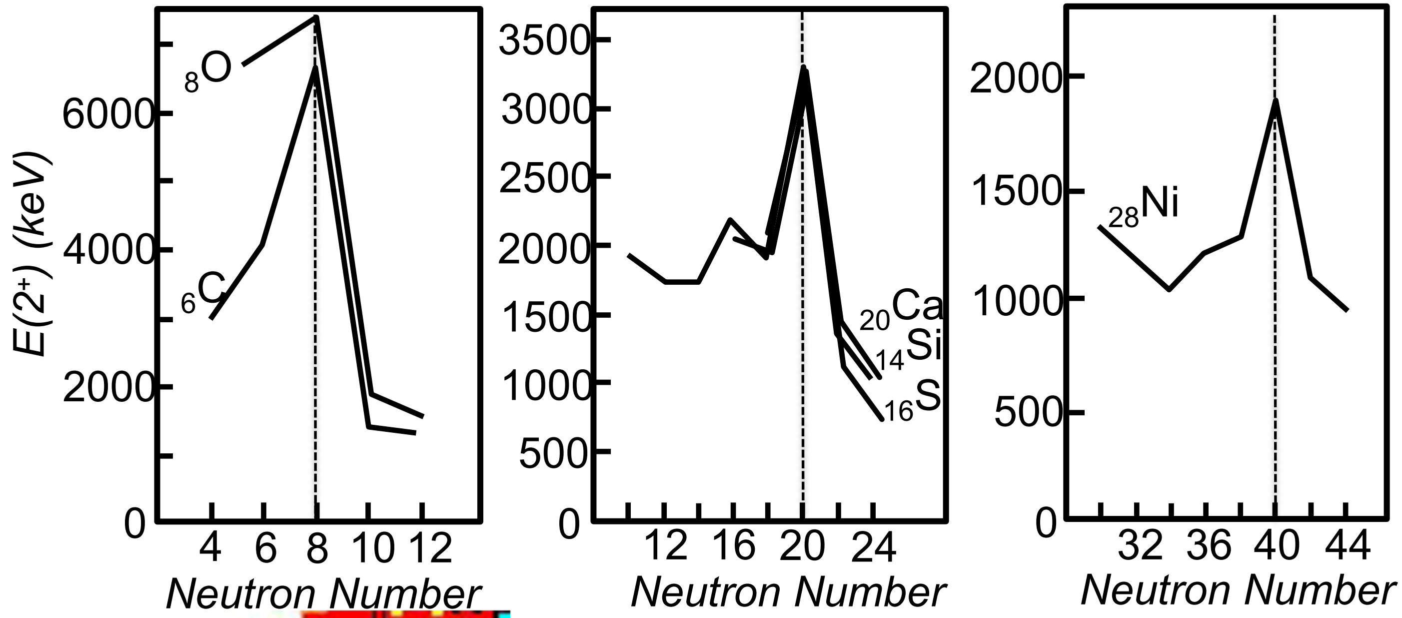


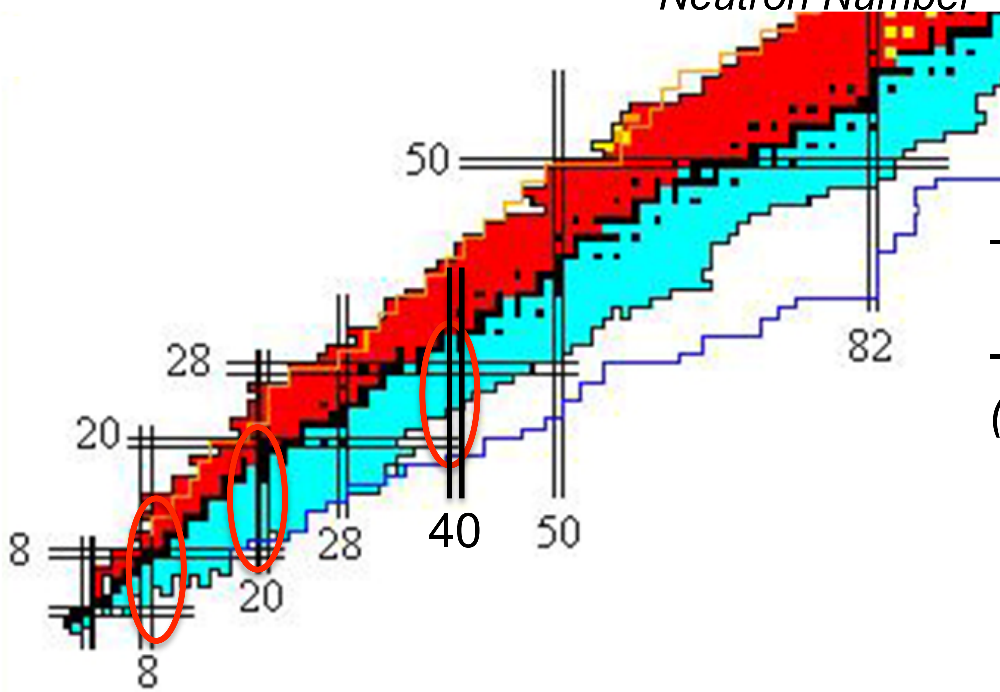
haloes





A Foreword : some open questions in nuclear physics …



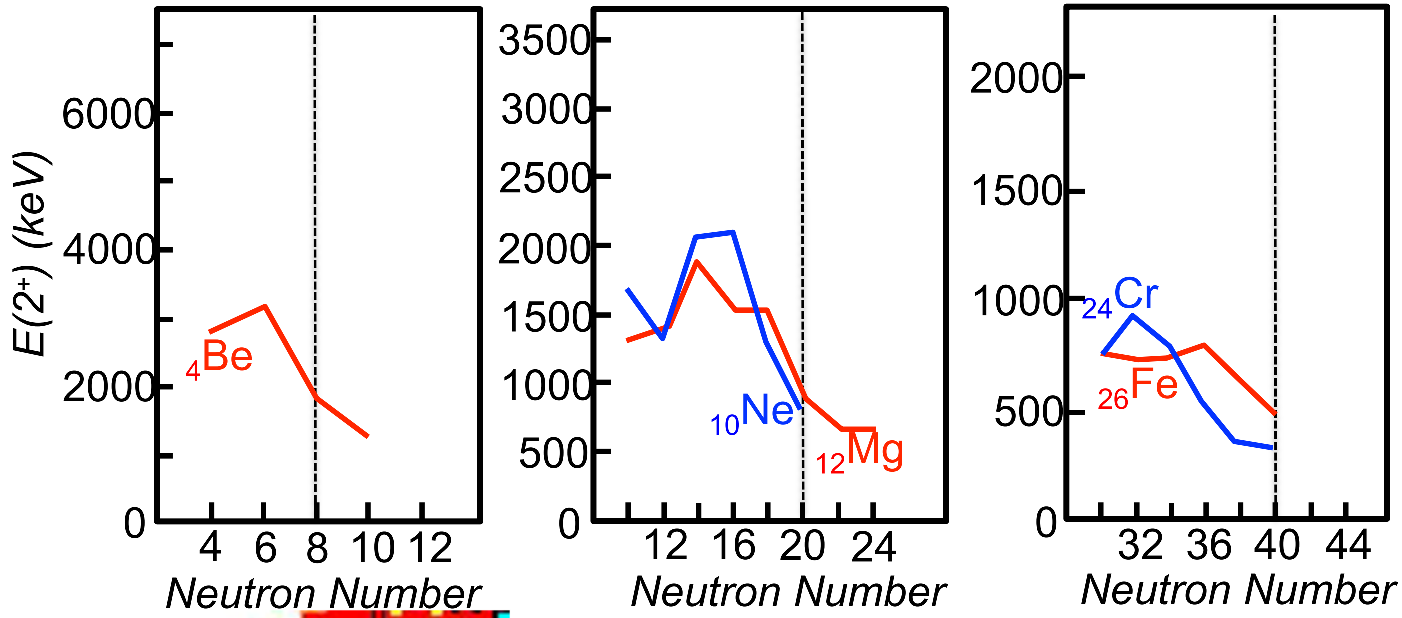


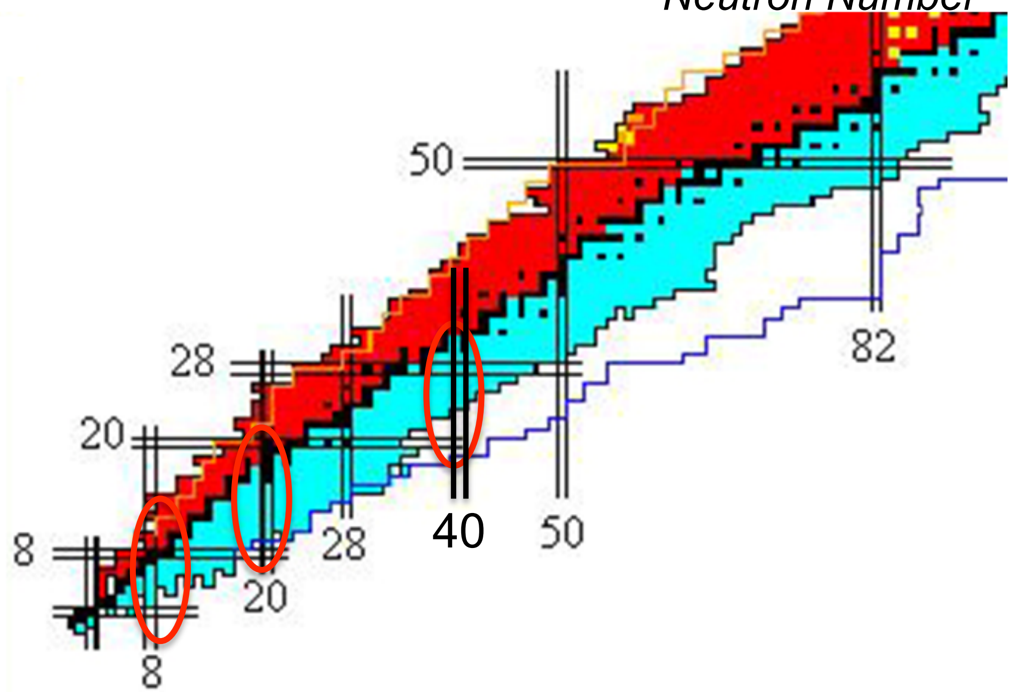
Do magic nuclei persist far off stab.?

-> pillars of nuclear structure

-> remarkable properties due to shell gaps
(i.e. large first excited state energy)

A Foreword : some open questions in nuclear physics …





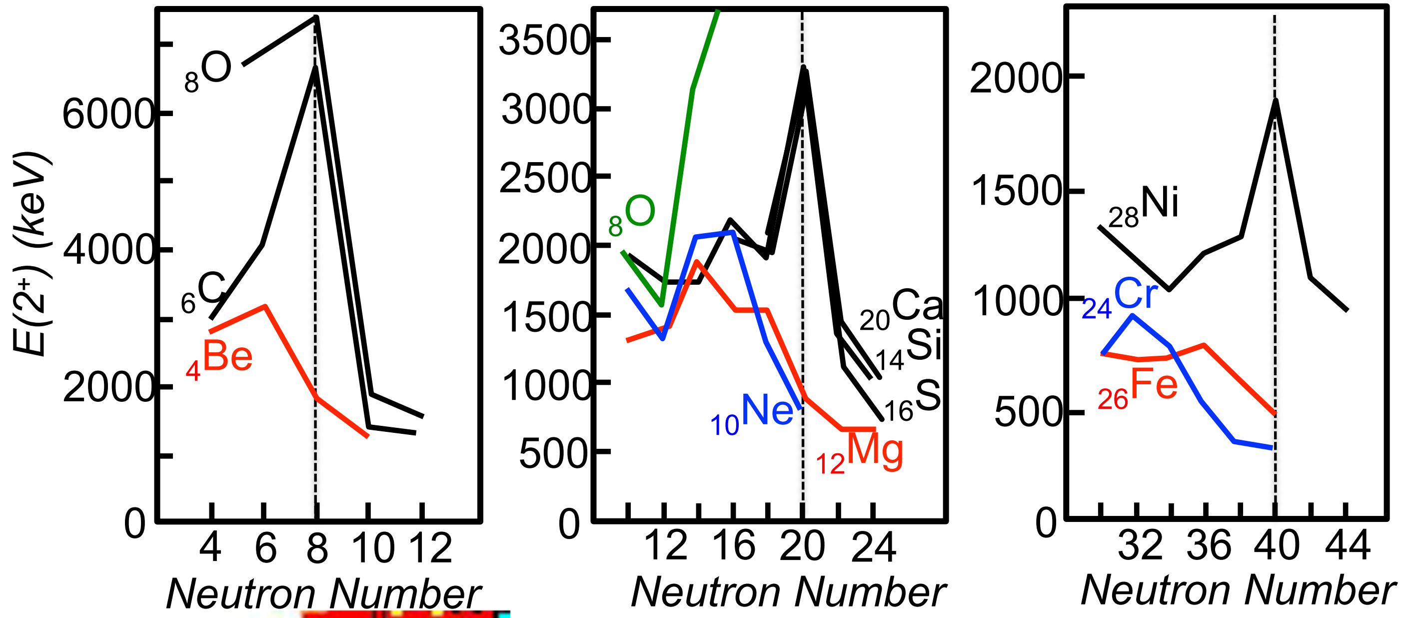
If our world were more neutron-rich ….

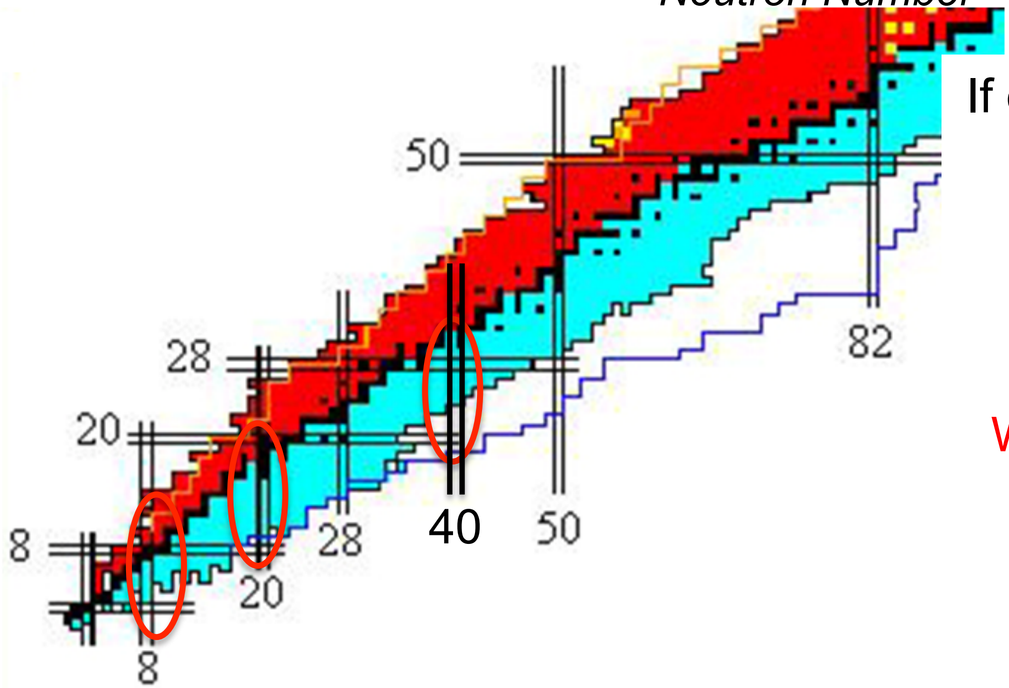
->No sign of energy increase

-> No magic number far from stability !

-> Change of paradigm ….

A Foreword : some open questions in nuclear physics …





If our world would be more neutron-rich ….

->No sign of energy increase
-> No magic number far from stability !
-> Change of paradigm ….

Why ? Which part(s) of nuclear force ?

Are there new magic nuclei ?

What happens to heavier nuclei ?

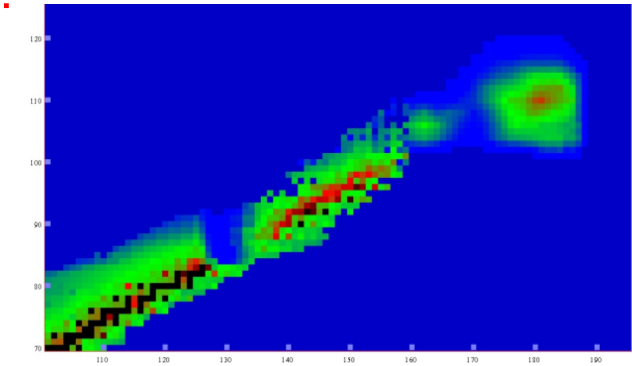
A Foreword : some open questions in nuclear physics …

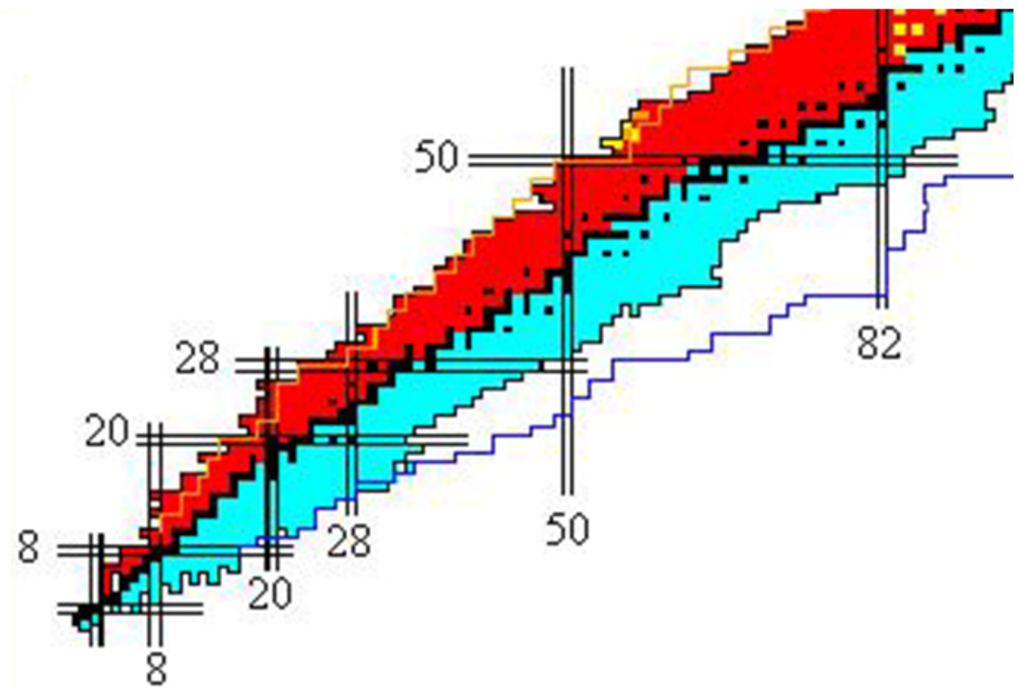
Does an island of extra-stability exist for superheavy nuclei ?

Could we predict its location ?

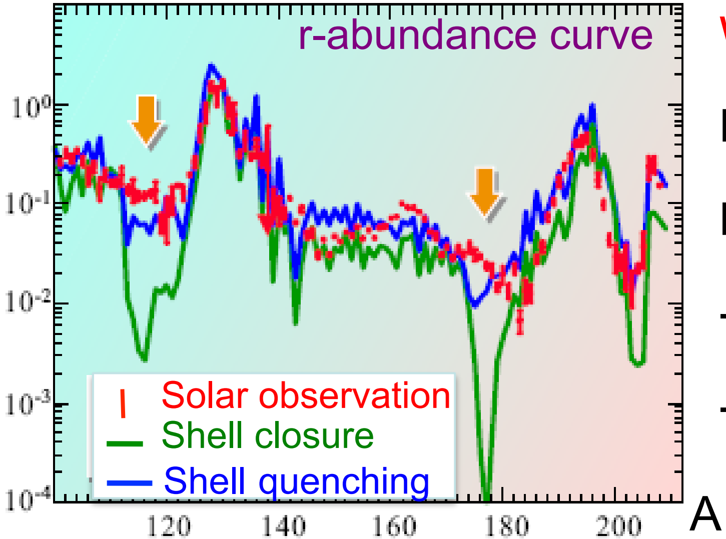
Could we synthesize new elements on earth ?

Which chemical properties ?





A Foreword : some open questions in nuclear physics …



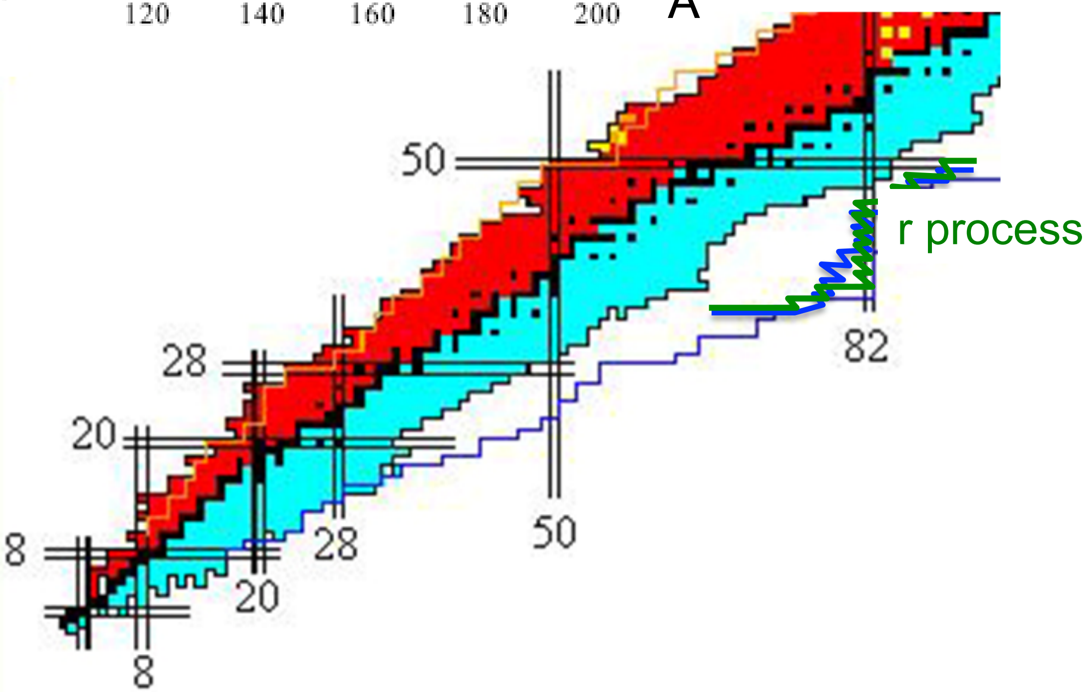
Which stellar environment(s) produce elements Z>26?

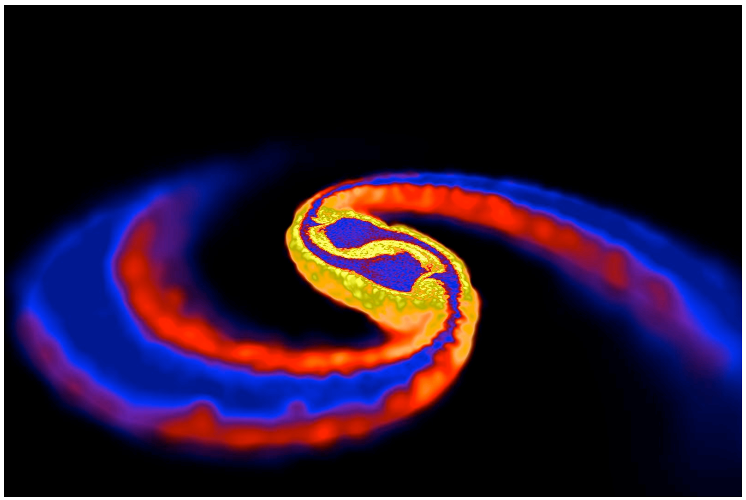
Neutron star mergers ? Likely but ….

Link between closed shells and abundance peaks

-> A real impact of shell structure far from stability

-> Determine mass, lifetime, n-capture rates of nuclei





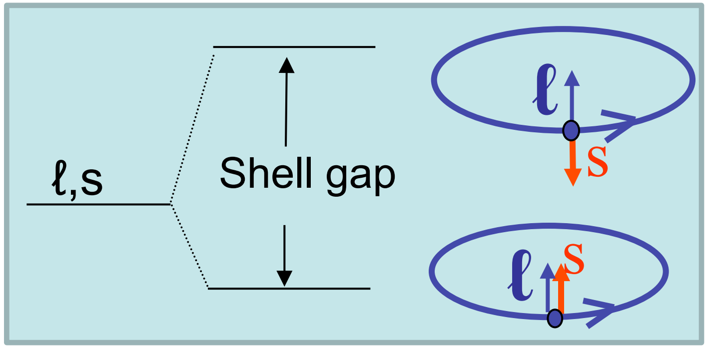
D. Price & S. Rosswog Science 2006

Study of the spin orbit force using a bubble nucleus

O. Sorlin (GANIL, presently at CERN)

THE PITCH

The spin orbit (SO) force plays major role in nuclear structure to create shell gaps that give rise to magic nuclei.

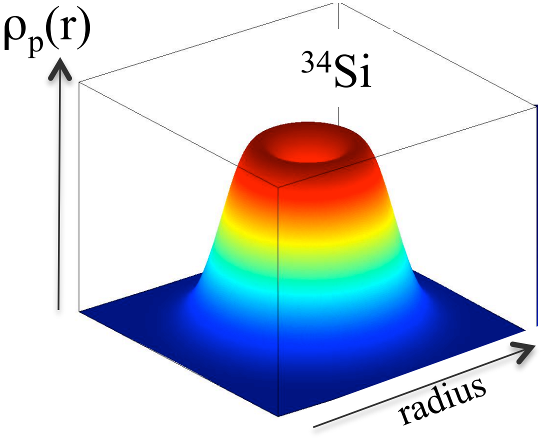


SO force: postulated more than 60 years ago.

Theoretical descriptions now exist but predictions differ for ab-normal nuclei

No experiment was yet able to test the SO force in 'extreme' conditions (superheavy elements, nuclear drip-line -> astrophysics)

We propose to use a 'bubble' nucleus to test the properties of this SO force



Layout of the talk

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

Introduction on the atomic nucleus
-> Charge density, orbital occupancies

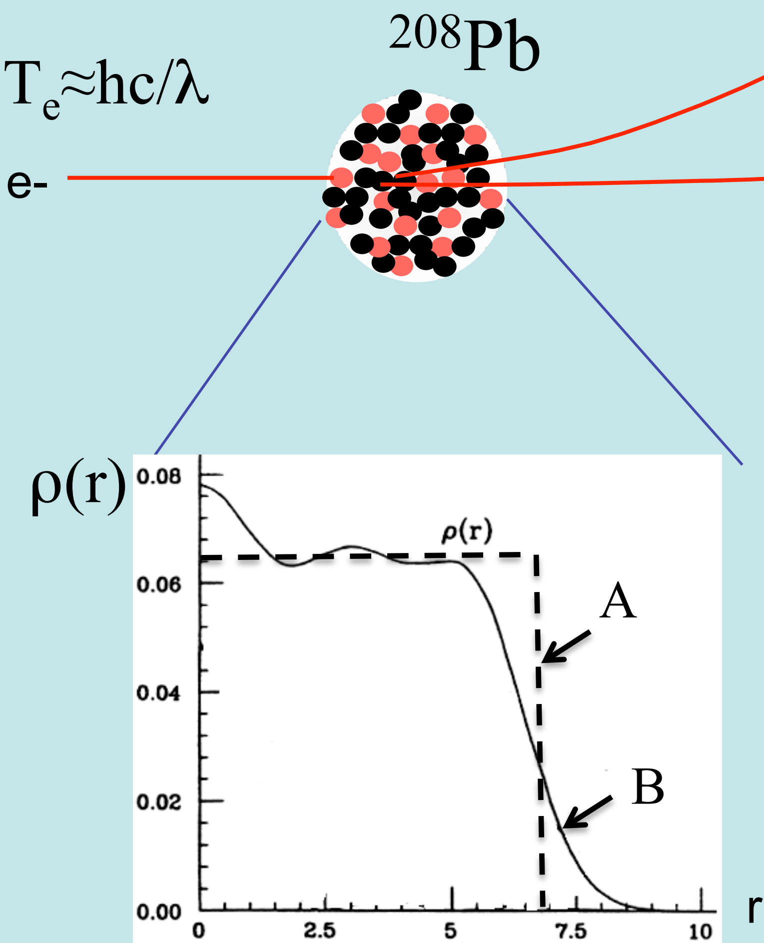
Probe charge density in ^{36}S and ^{34}Si:knockout reactions at NSCL
-> Central proton density depletion in ^{34}Si (i.e. bubble)

Introduction to the spin orbit (SO) force
-> Properties and expectations
-> Use a bubble nucleus to constrain unknown properties

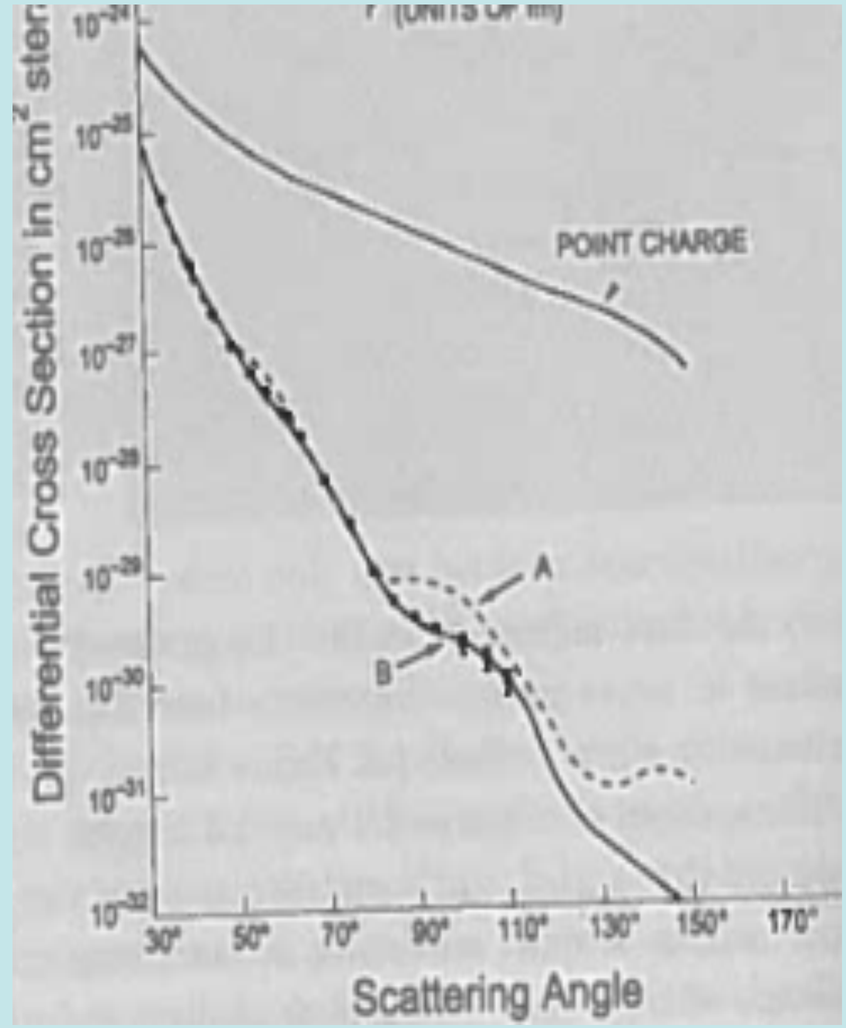
Reduced SO interaction between ^{36}S & ^{34}Si: (d,p) reaction at GANIL

Conclusions / consequences

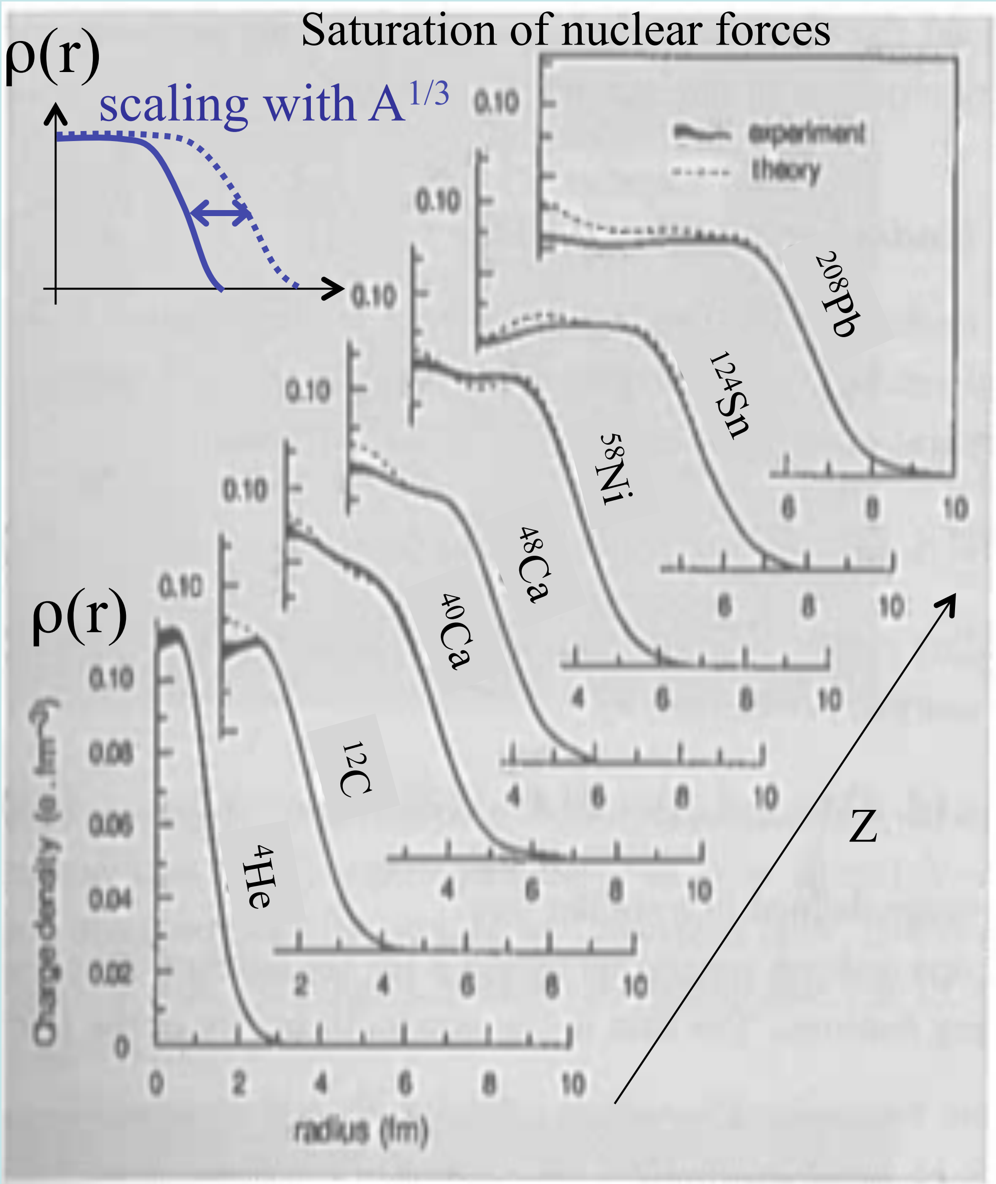
Charge density of the nucleus : ρ(r)



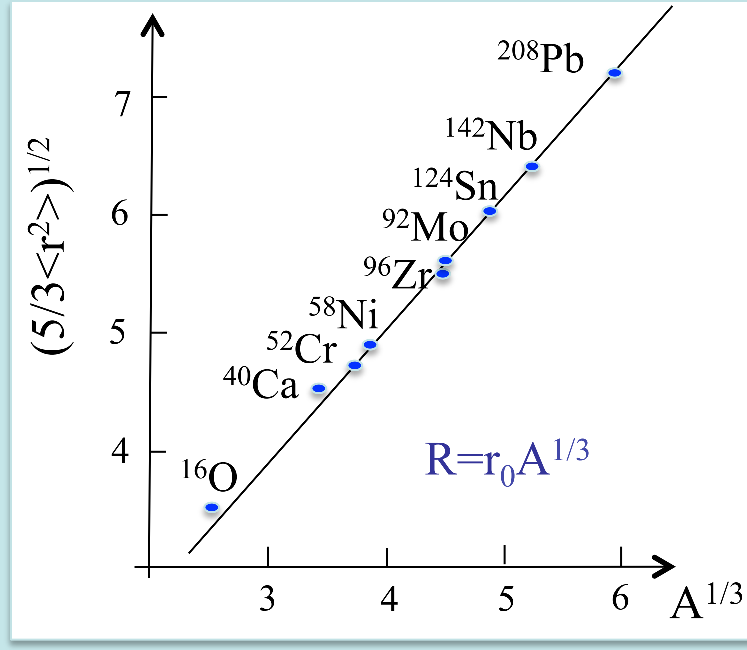
Large transferred momentum
-> details of the density distribution

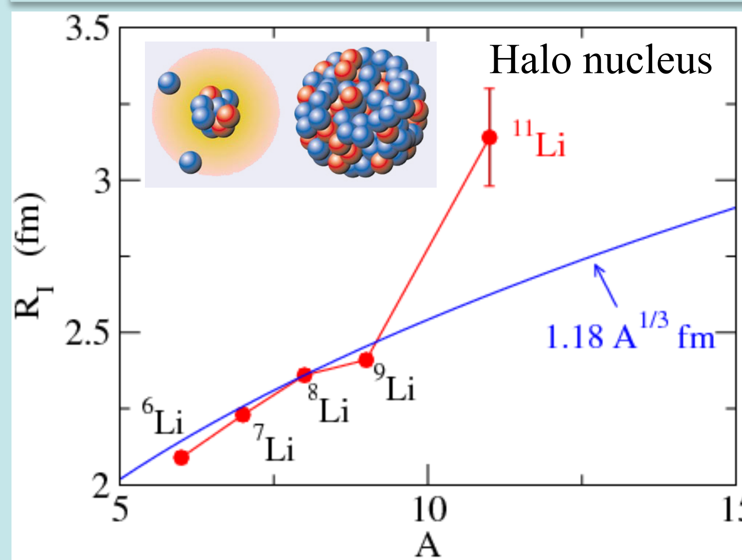


Charge density of the nucleus : ρ(r)

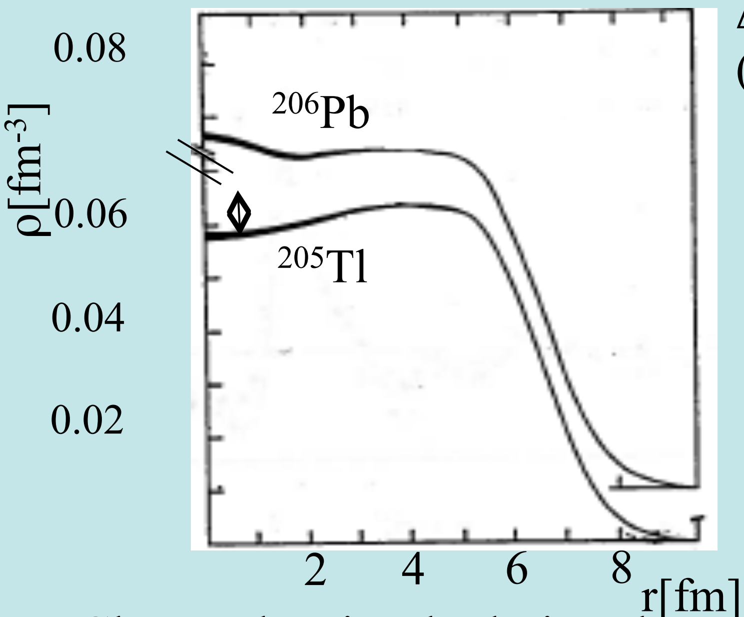


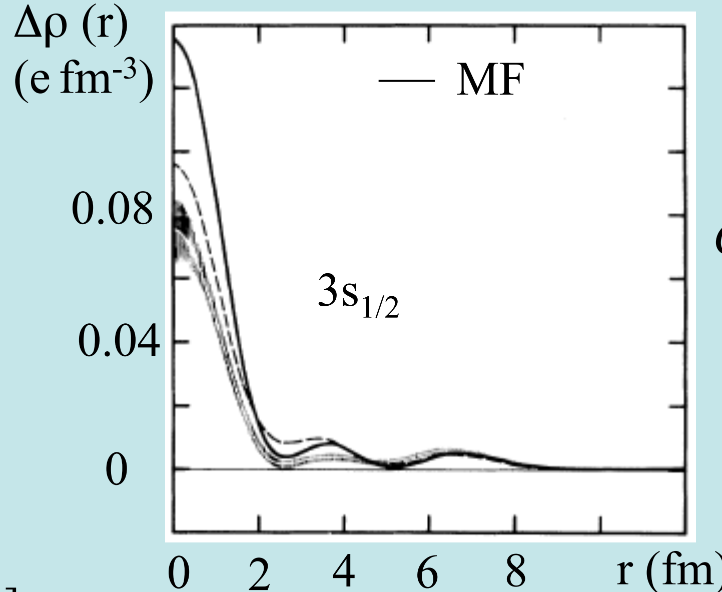
Hofstader Rev. Mod. Phys. 28 (1956)





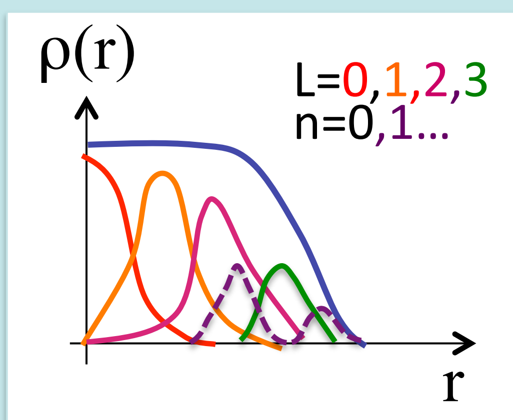
Charge density depletion in the center of the ^{205}Tl nucleus





Cavedon PRL (1982)

Charge density depletion due to the change in $3s_{1/2}$ occupancy by 0.7 proton
Independent particle model works rather well also in the interior of nucleus



Nuclear density
= superposition of radial vave funtions with n,L values

Probing nuclear orbits with (e,e’ p) reaction

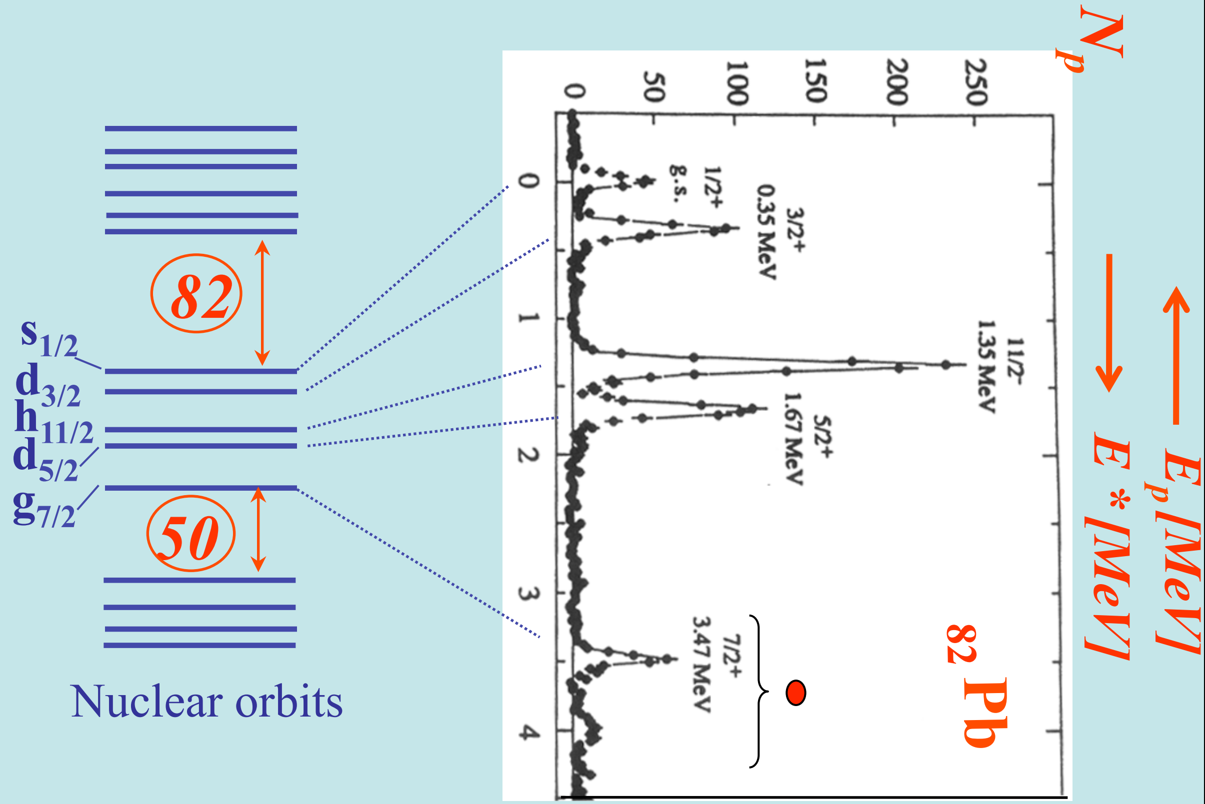
Orbital labelling

n,L,J

n nodes (n=0,1,2)
L angular momentum
(s,p,d,f,g,h…)
$(-1)^L$ parity

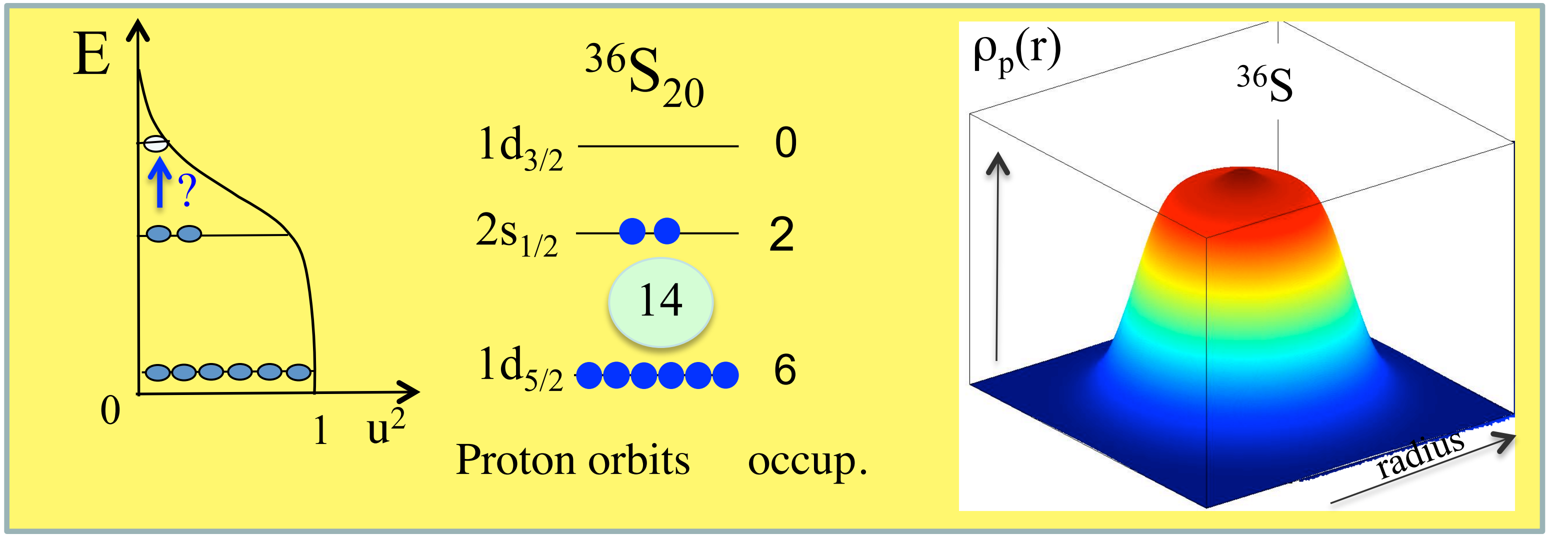
|L-s|<J<|L+s|
(2J+1) per shell

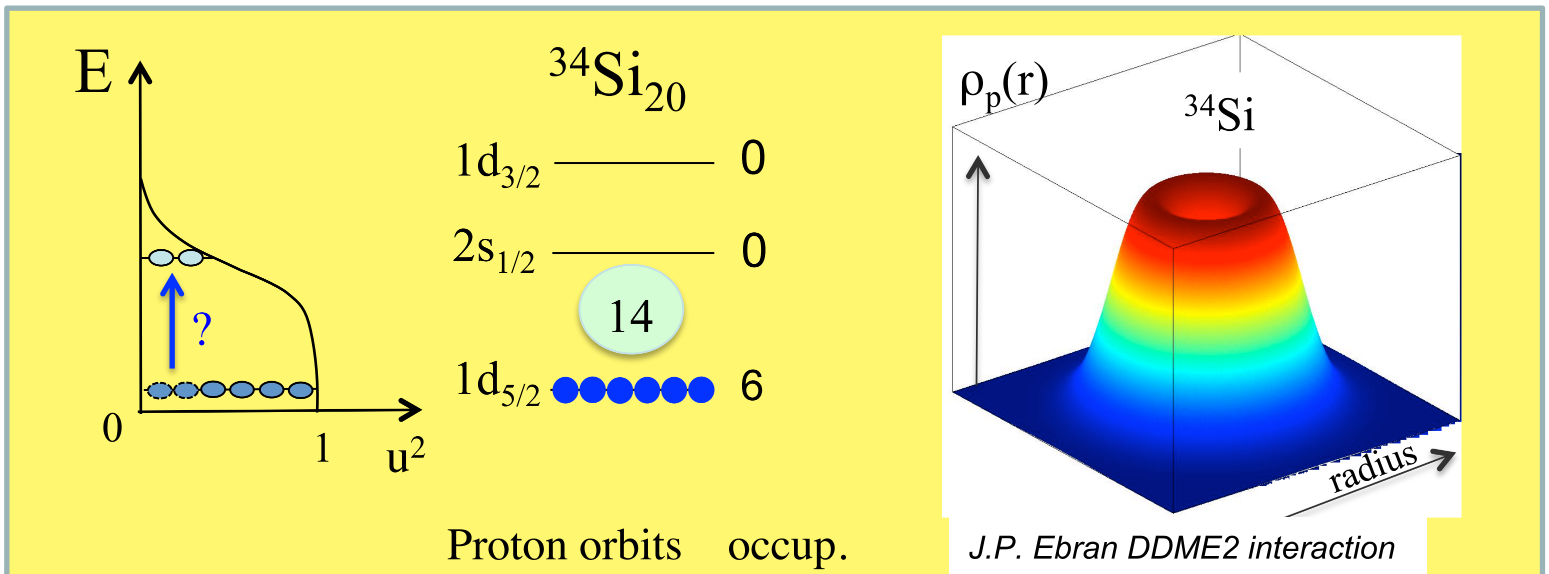
example :
$h_{11/2}$: L=5, J=11/2,
L and s aligned
contains 12 nucleons



->Nucleons are arranged on shells
-> Gaps are present for certain nucleon numbers
-> N_p detected follows orbit occupancy
-> Quenching factor of occupancy by about 70%
-> Mixing with collective states at high E*
-> Study limited (so far) to STABLE nuclei

Proton density depletion in ^{34}Si as compared to ^{36}S?





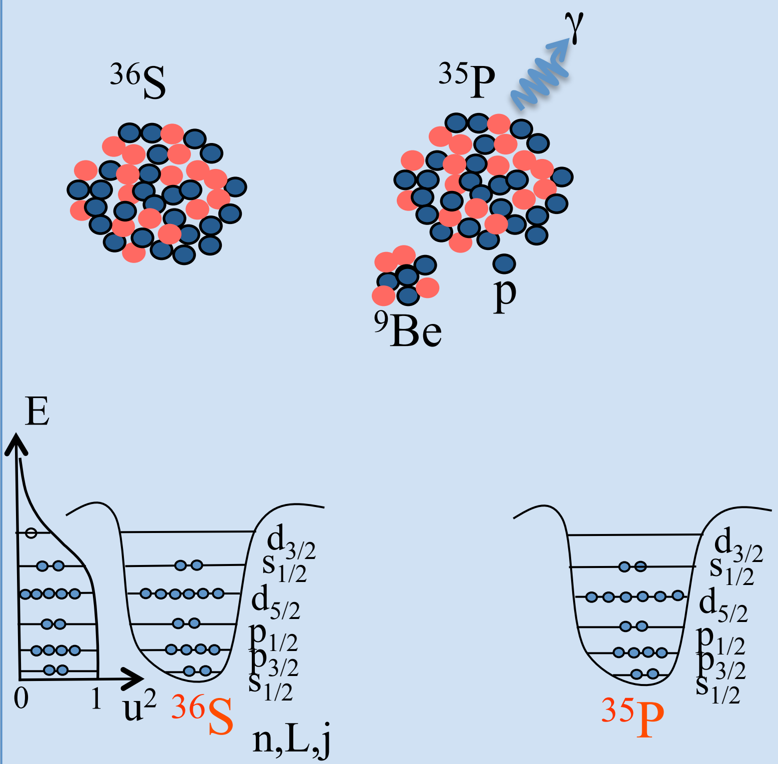
Amplitude of the central depletion depends on the change in $2s_{1/2}$ occupancy

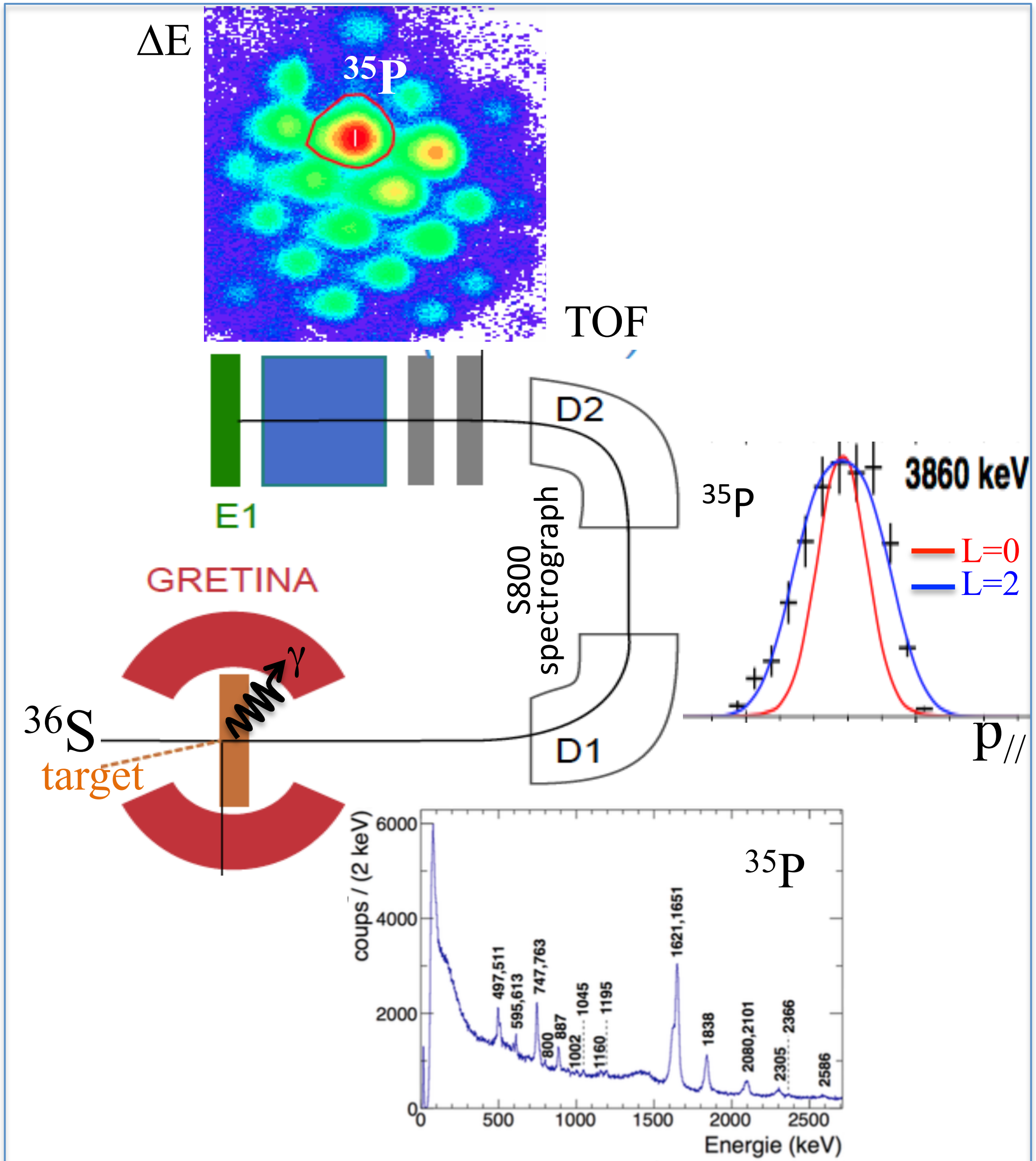
But correlations can reduce the amplitude of this depletion

Probing proton density in ^{36}S

Knock-out reactions at $\beta \approx 0.4$

$$\sigma(n,L) = \underbrace{C^2 S\,(j,n,L)}_{\textit{occupancy}} \quad \underbrace{\sigma_{sp}(j,S_p)\, R_S}_{\textit{reaction theory}}$$



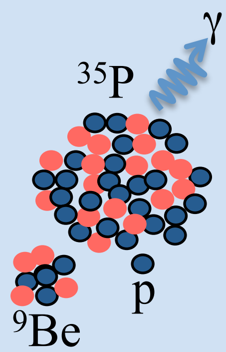


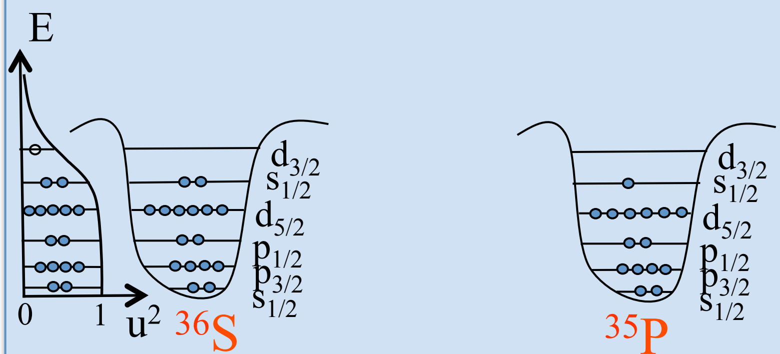
Probing proton densities in ^{36}S

Knock-out reactions at $\beta \approx 0.4$

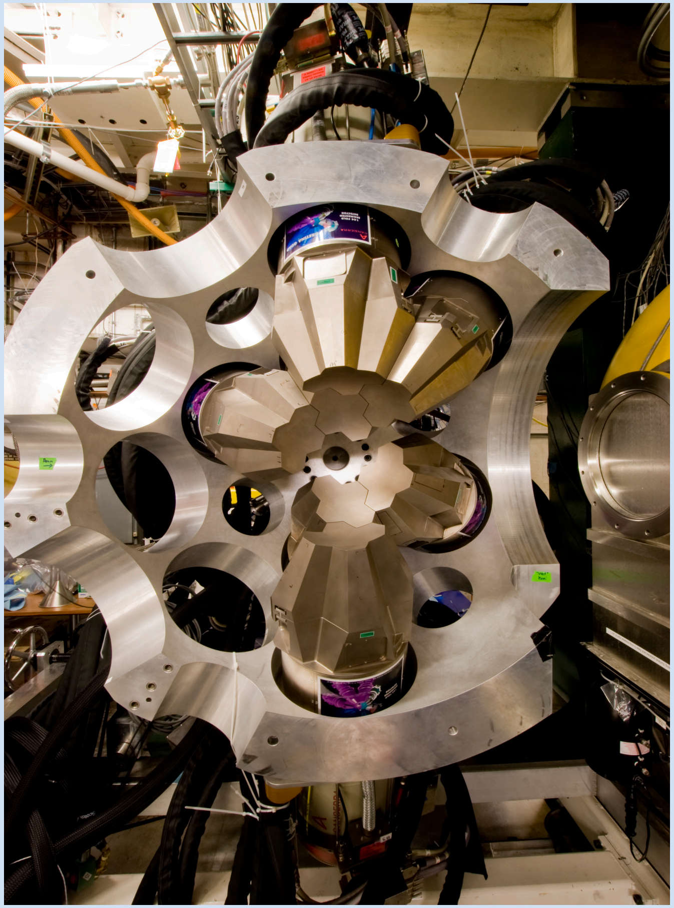
$$\sigma(n,L) = C^2 S(j,n,L) \quad \sigma_{sp}(j,S_p)\, R_S$$

occupancy *reaction theory*





Gretina array: segmented Ge detectors



In-flight γ-ray detection-> Doppler corrections

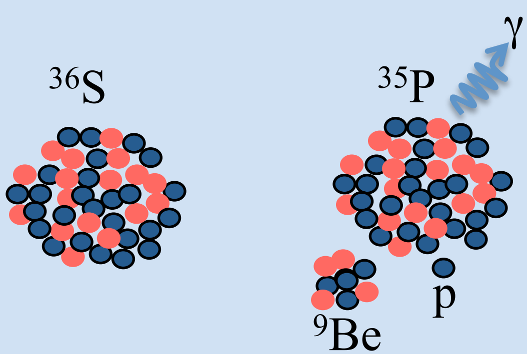
Segmented Ge cristals -> Interaction position

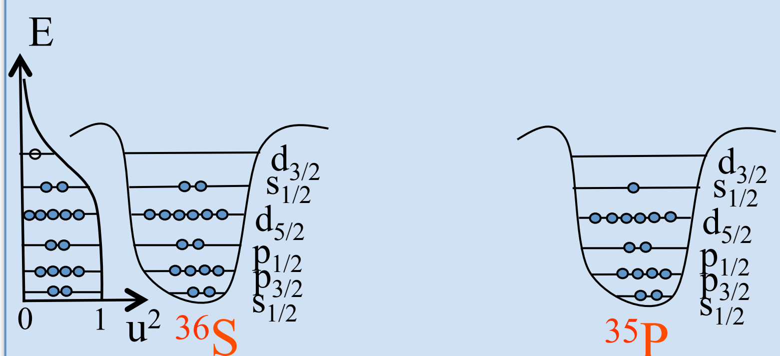
Probing proton densities in ^{36}S

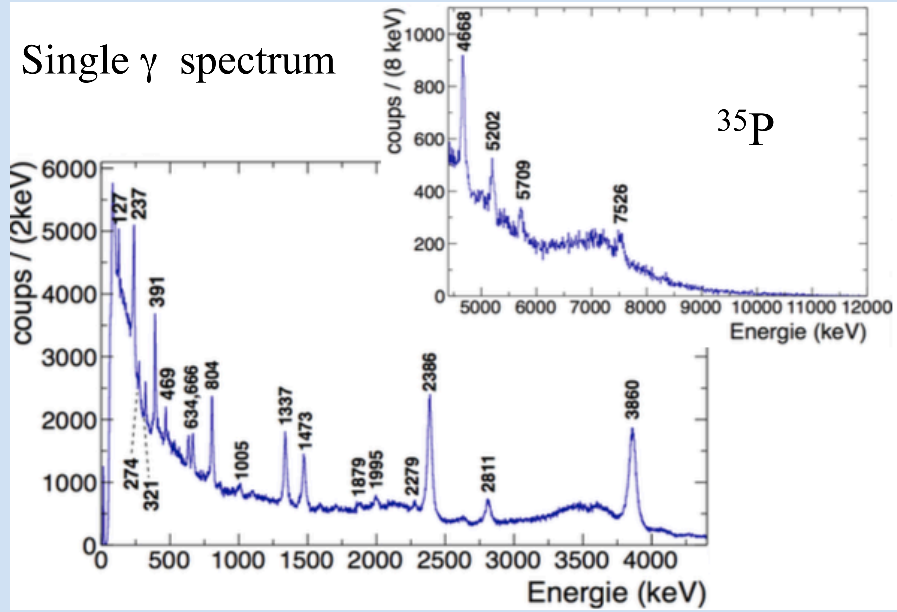
Knock-out reactions at $\beta \approx 0.4$

$$\sigma(n,L) = C^2 S(j,n,L) \quad \sigma_{sp}(j,S_p)\, R_S$$

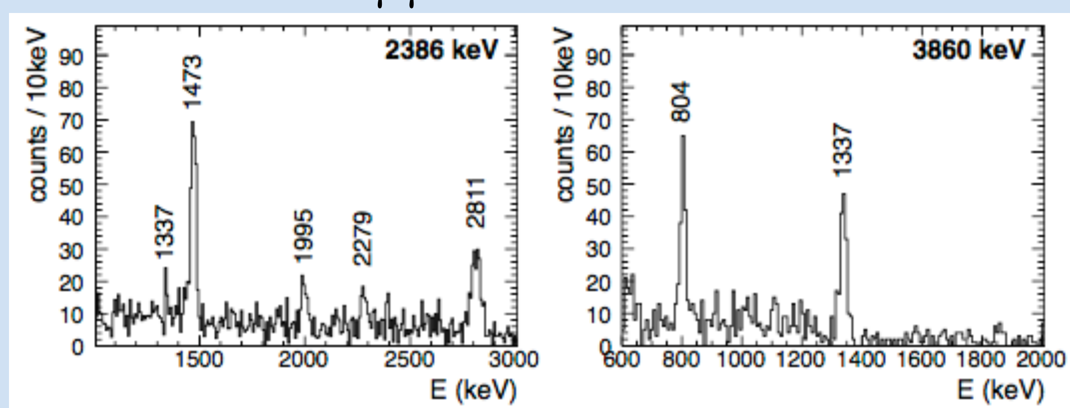
occupancy *reaction theory*







γ γ coincidences

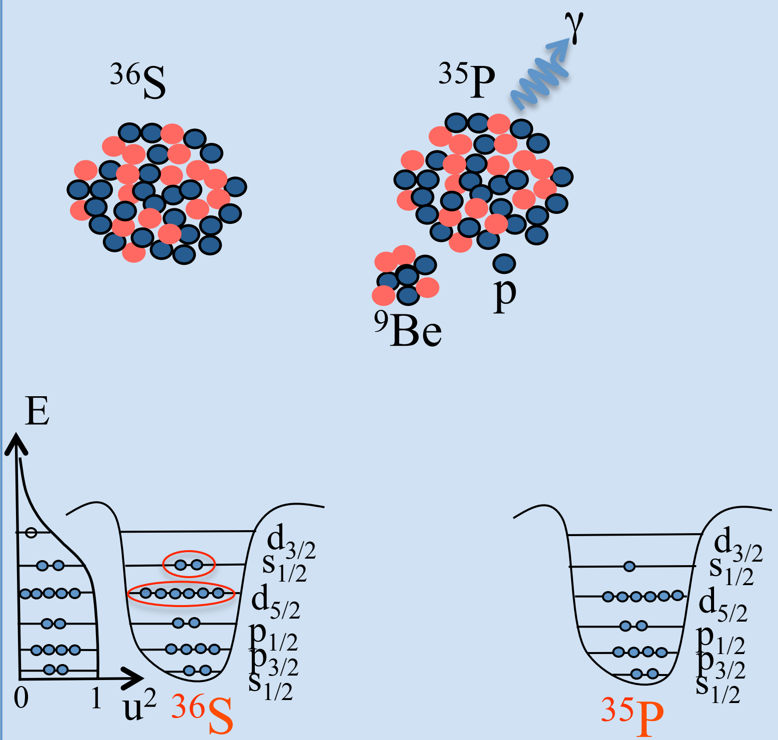


Probing proton densities in ^{36}S

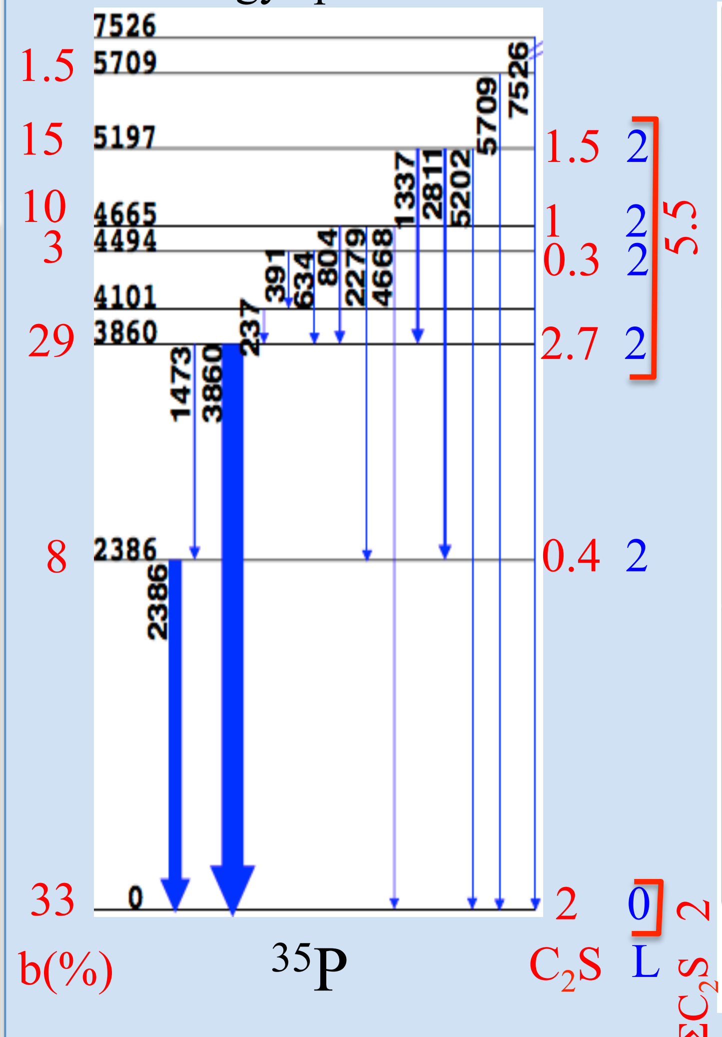
Knock-out reactions at $\beta \approx 0.4$

$$\sigma(n,L) = C^2S(j,n,L) \quad \sigma_{sp}(j,S_p)\, R_S$$

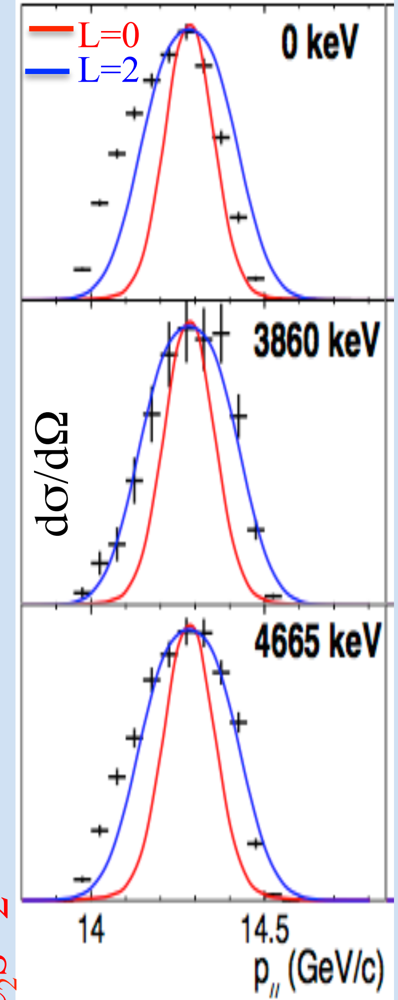
occupancy *reaction theory*



Energy spectrum



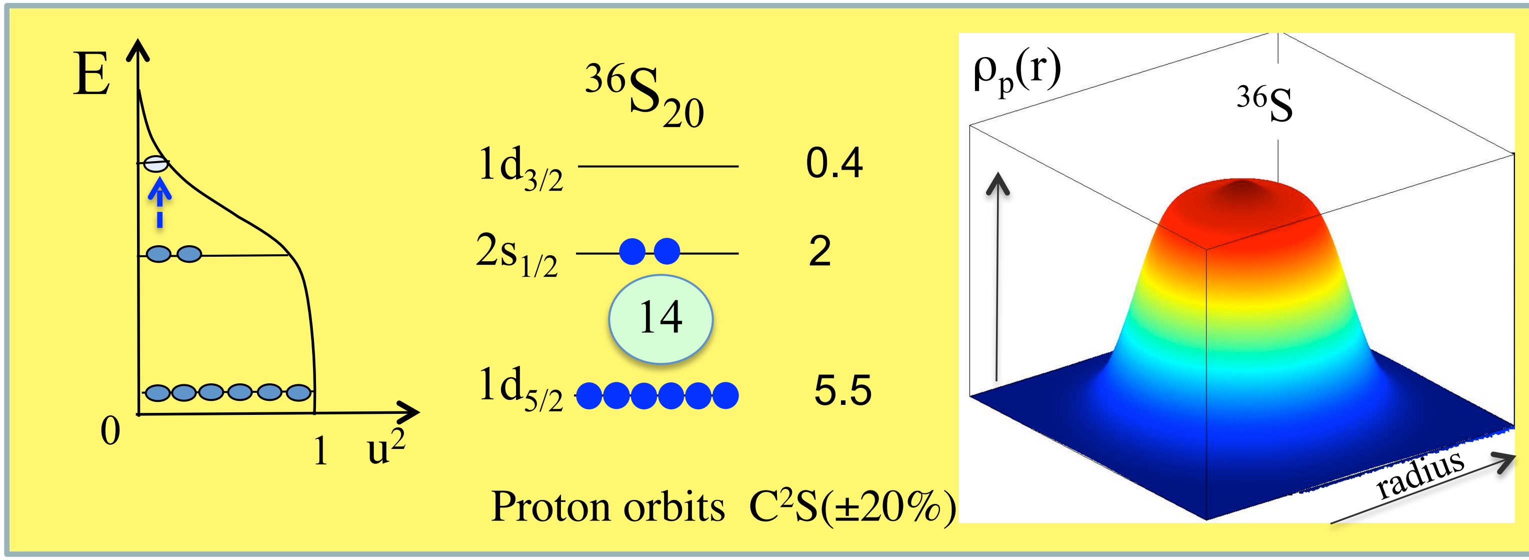
Momentum distrib.



Quasi full filling of $s_{1/2}$ and $d_{5/2}$ orbits (within errors)
Only few scattering to the upper $d_{3/2}$ orbital.

A. Mutschler et al. PRC (2016)

Proton density of ^{36}S

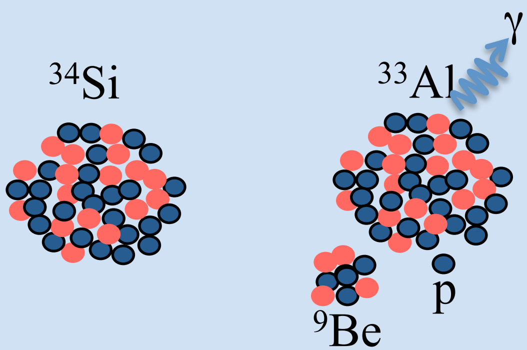


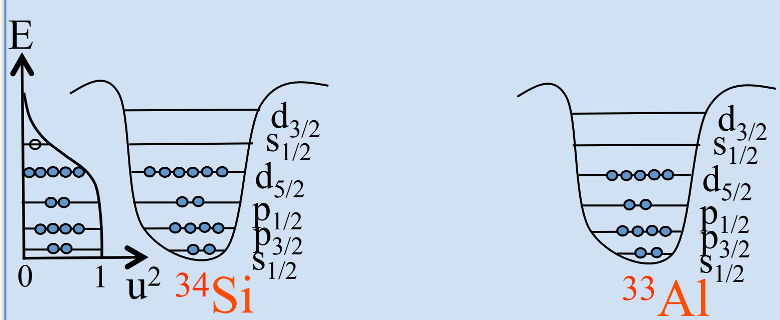
Probing proton densities in ^{34}Si

Knock-out reactions at $\beta \approx 0.4$

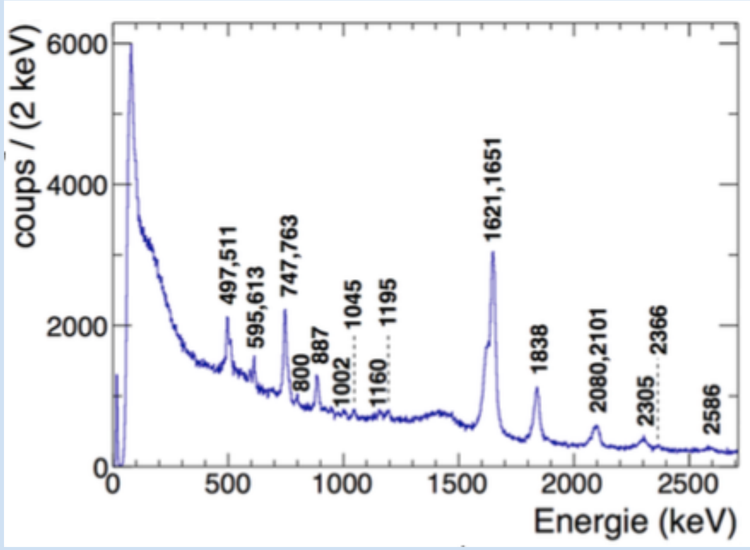
$$\sigma(n,L) = C^2 S(j,n,L) \quad \sigma_{sp}(j,S_p)\, R_S$$

occupancy *reaction theory*

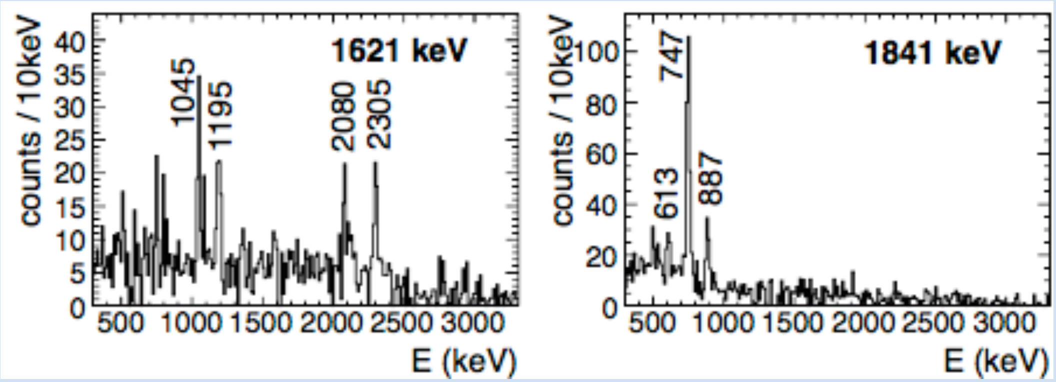




Single γ spectrum



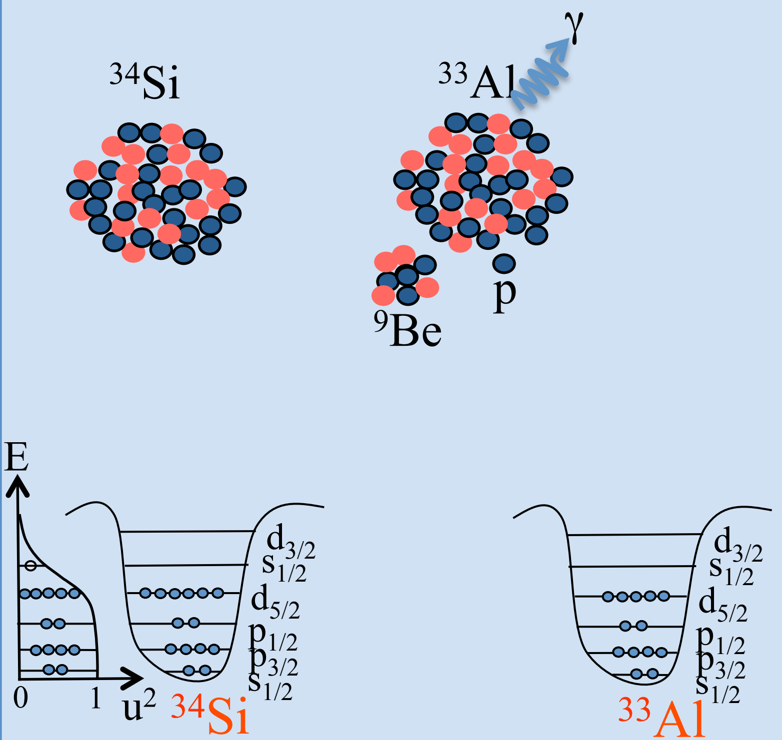
γ γ coincidences



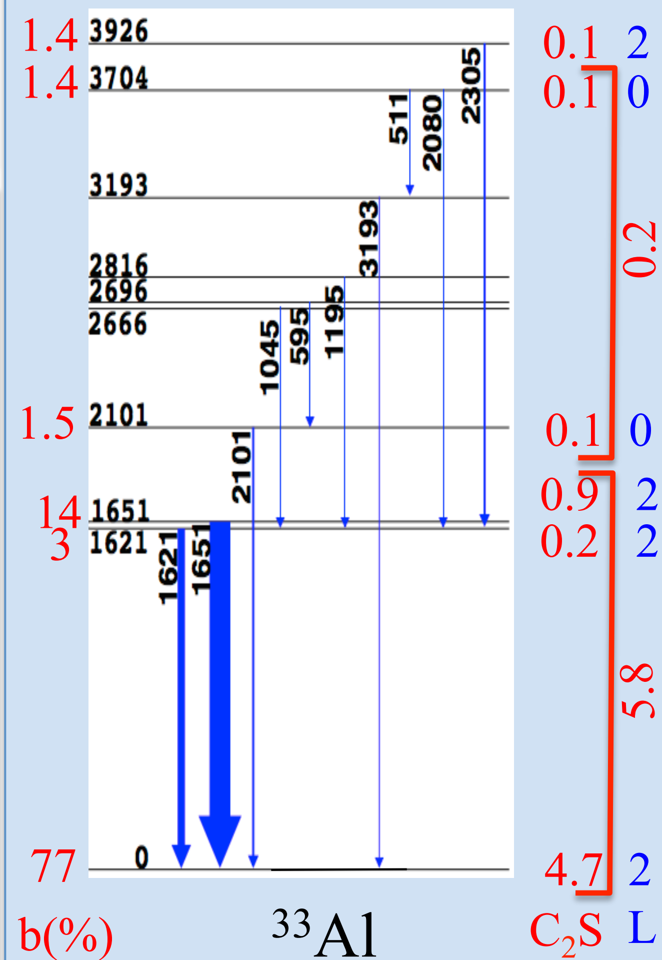
Probing proton densities in ^{34}Si

Knock-out reactions at $\beta \approx 0.4$

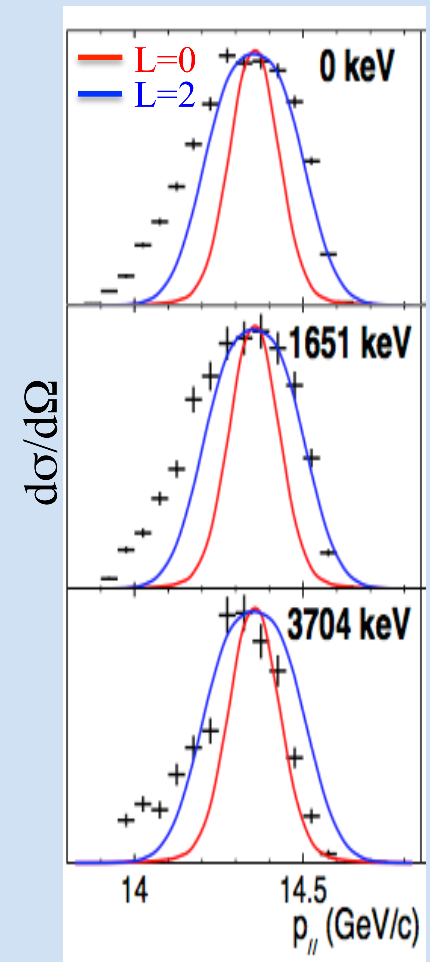
$$\sigma(n,L) = \underbrace{C^2S(j,n,L)}_{\text{occupancy}} \quad \underbrace{\sigma_{sp}(j,S_p)\, R_S}_{\text{reaction theory}}$$



Energy spectrum



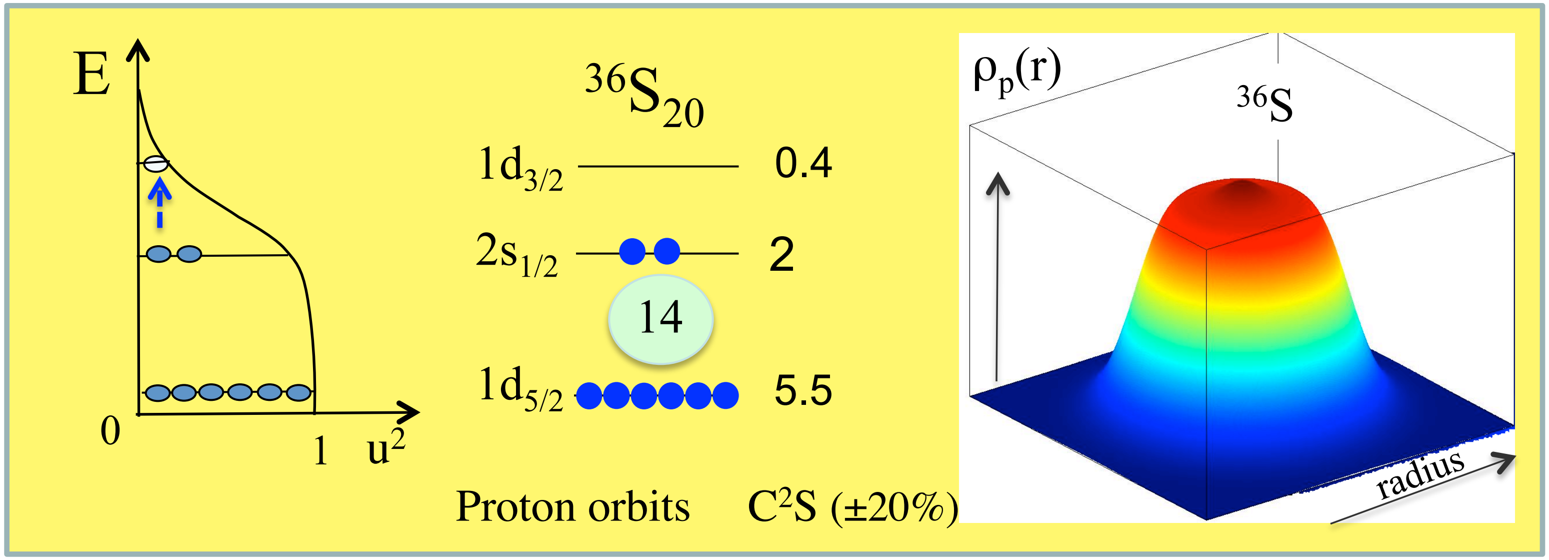
Momentum distrib.

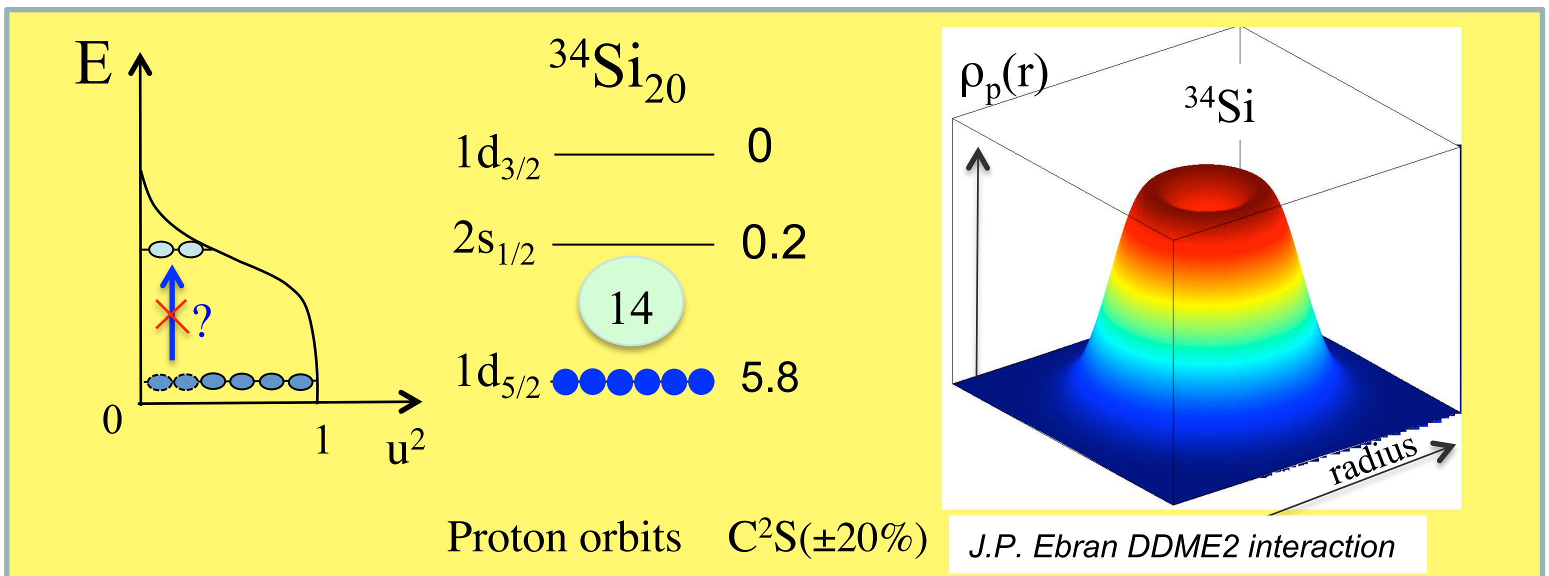


Very weak $2s_{1/2}$ occupancy -> large central density depletion

A. Mutschler et al. to be sumitted to Nature

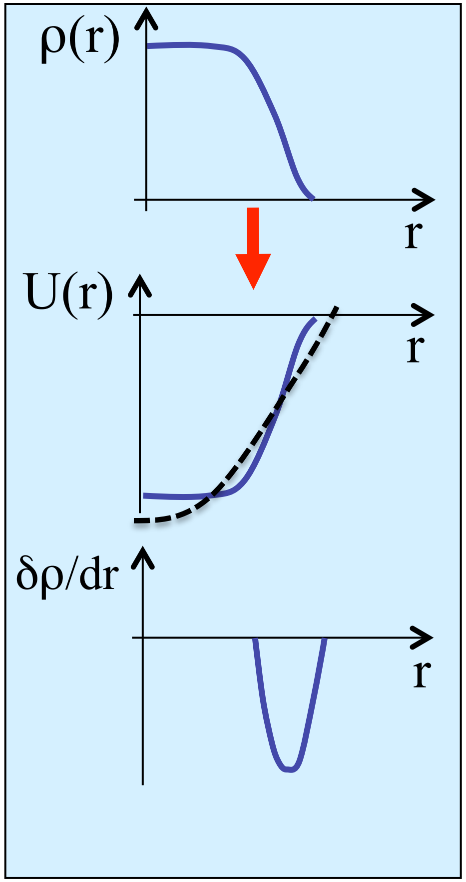
Proton density depletion in ^{34}Si

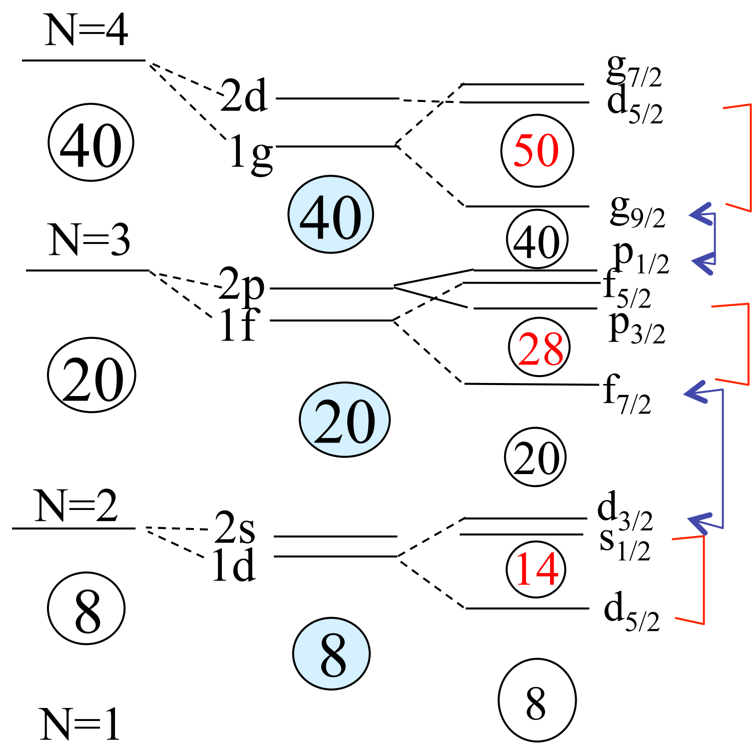




Large change in $2s_{1/2}$ occupancy (1.8) -> central proton depletion in ^{34}Si -> 'bubble' nucleus
But same neutron density profiles for the two N=20 nuclei

Simplified description of atomic nuclei





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

Harmonic Oscillator
8, 20, 40

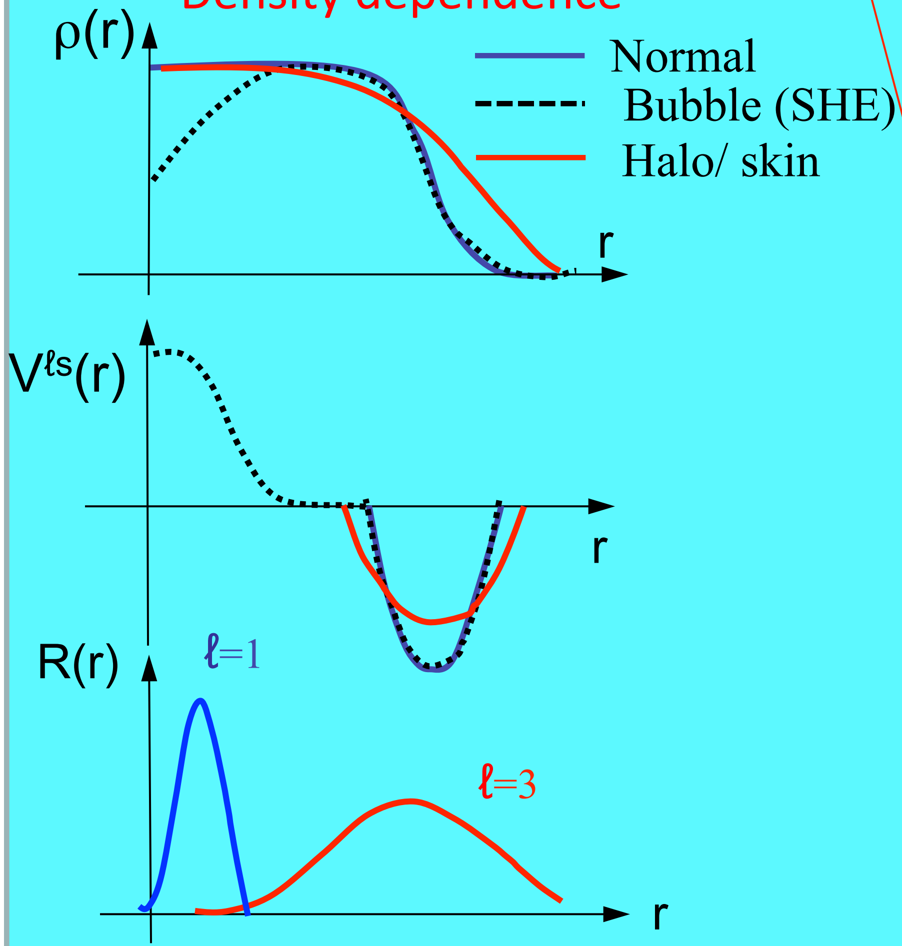
$U(r) = \text{H.O} + L^2 - \delta\rho/dr\ \vec{L}.\vec{S}$

$$U(r) = \int_{vol} \rho(r')v(r,r')d^3r' = \int_{vol} \rho(r')[-v_0\partial(r-r')]d^3r' = -v_0\rho(r)$$

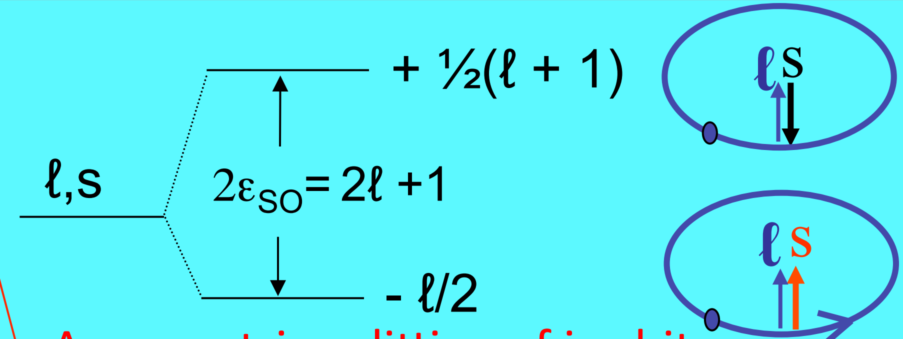
The spin-orbit (SO) interaction

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

Density dependence



Reduced SO for bubble and diffuse nuclei



Asymmetric splitting of j orbits

Isospin dependence

$$W_2 \approx 1/2\, W_1 \quad (MF)$$

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

No isospin dependence in RMF

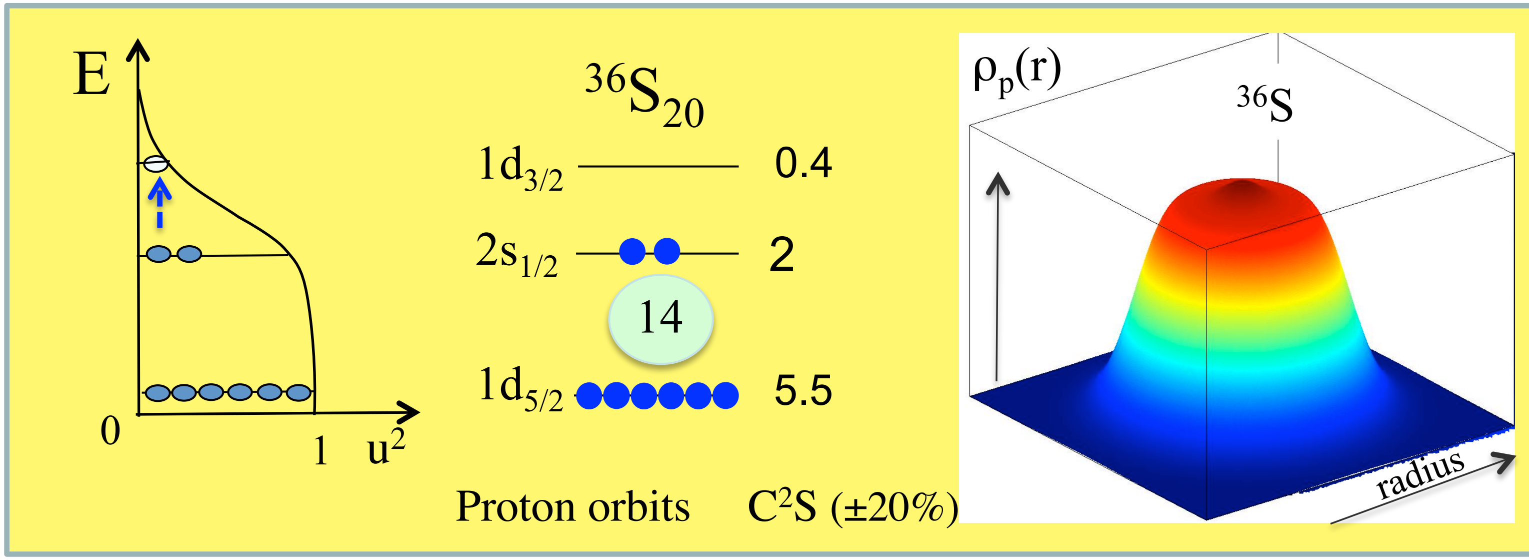
PROPOSED GOAL

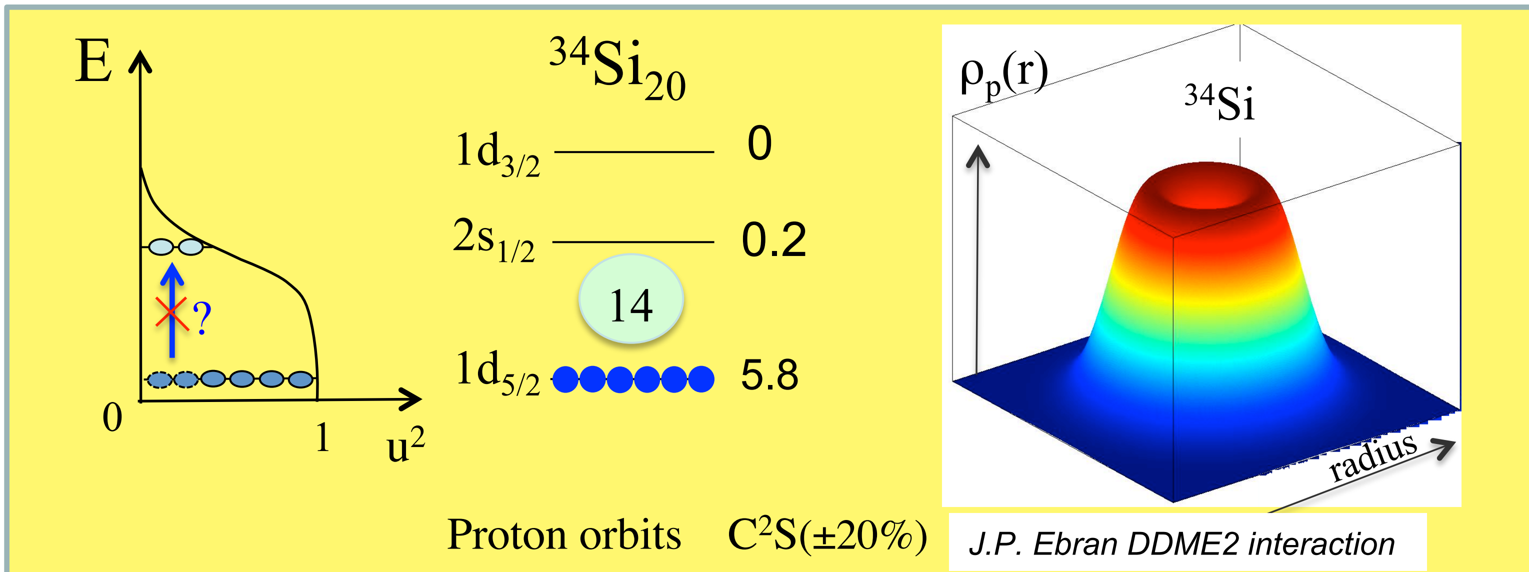
Determine ρ and τ SO dependence

^{34}Si: proton central depletion but not neutron

Red. of neutron SO due to *proton* depletion

Proton density depletion in ^{34}Si





Large change in $2s_{1/2}$ occupancy (1.8) -> central proton depletion in ^{34}Si -> ‘bubble’ nucleus
But same neutron density profiles for the two N=20 nuclei

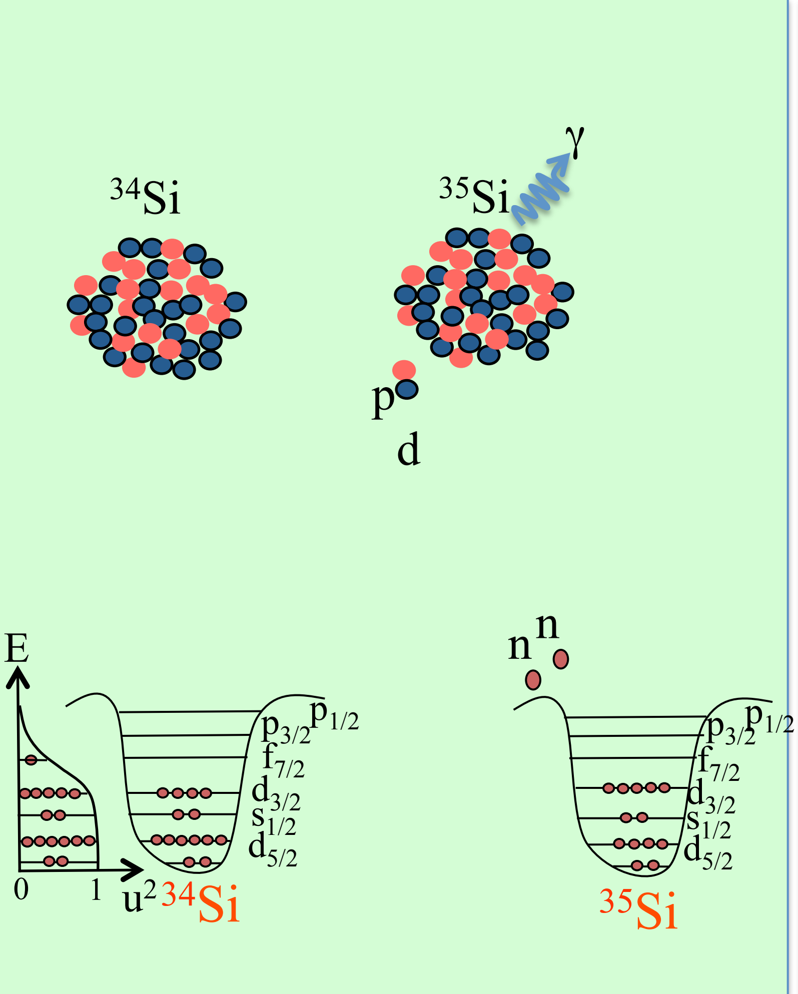
^{34}Si(d,p) reaction in inverse kinematics

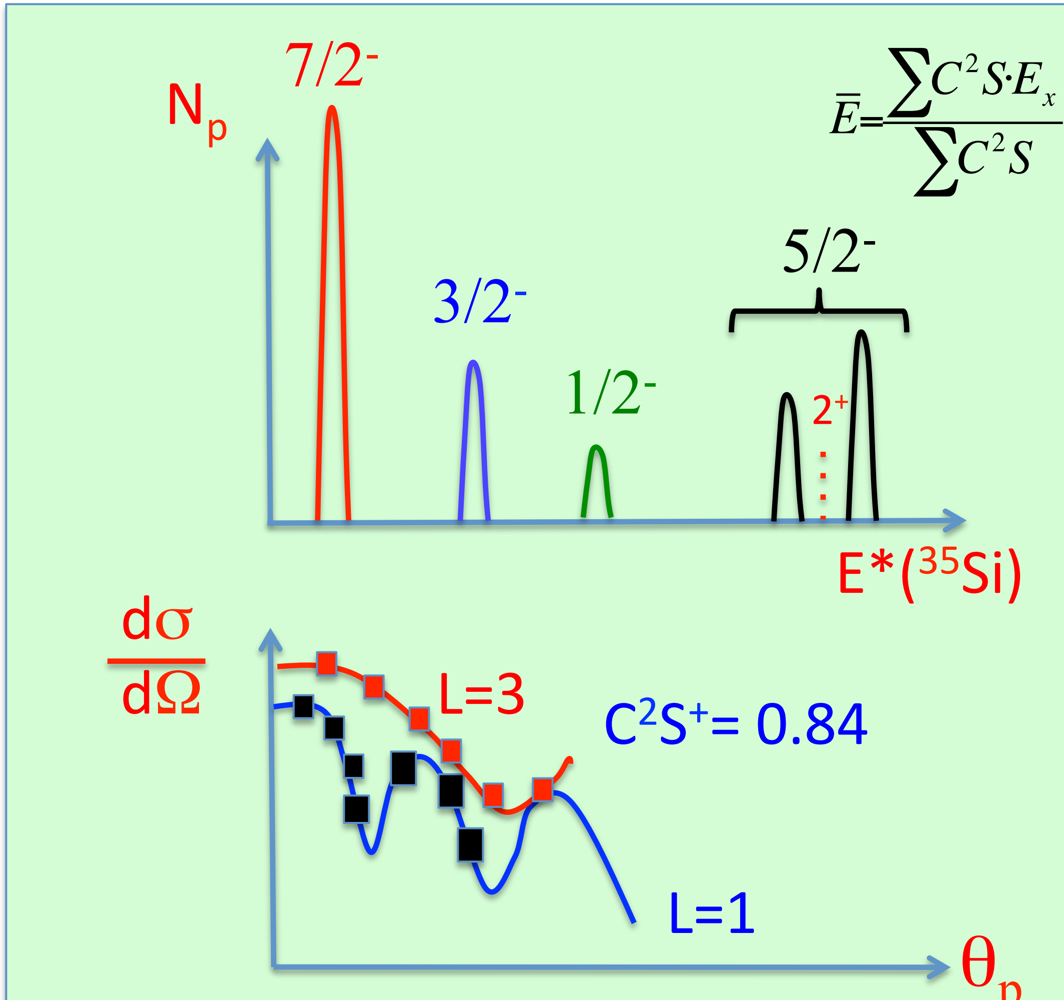
Transfer reaction (d,p) at $\beta \approx 0.15$

$$\frac{d\sigma(n,L,\theta)}{d\Omega} = (2j+1)\, C_2S^+ \, \frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}$$

vacancy *reaction theory*

Proton energy -> (binding) energy of orbit
Proton angle -> orbital momentum L
Cross section -> vacancy of the orbit
Appropriate momentum matching required



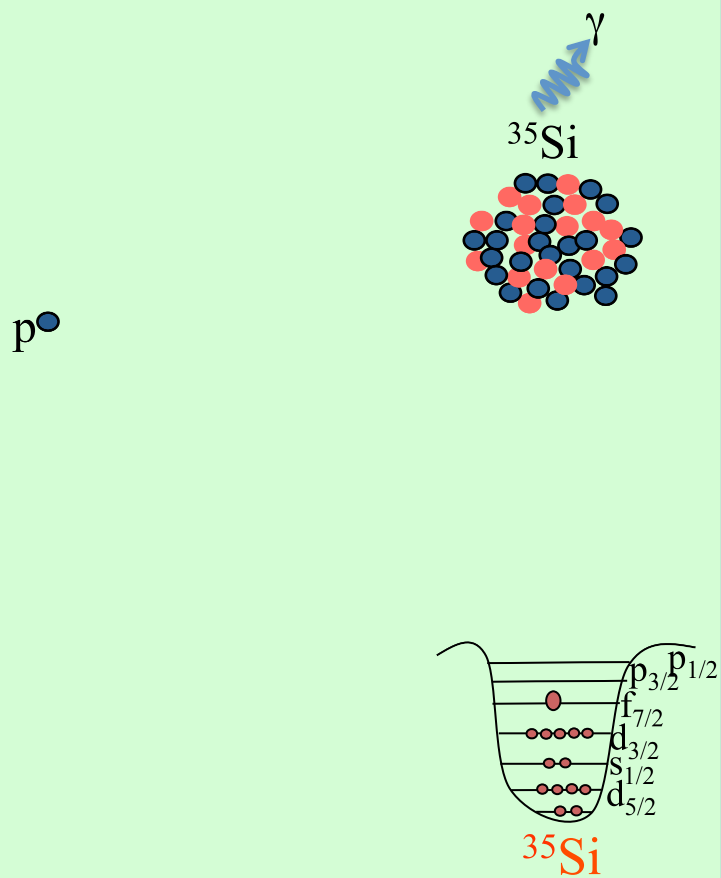


^{34}Si(d,p) reaction in inverse kinematics

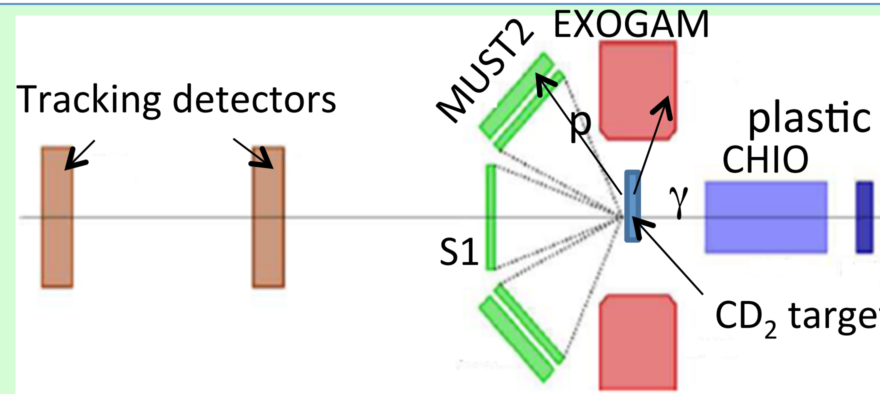
Transfer reaction (d,p) at $\beta \approx 0.15$

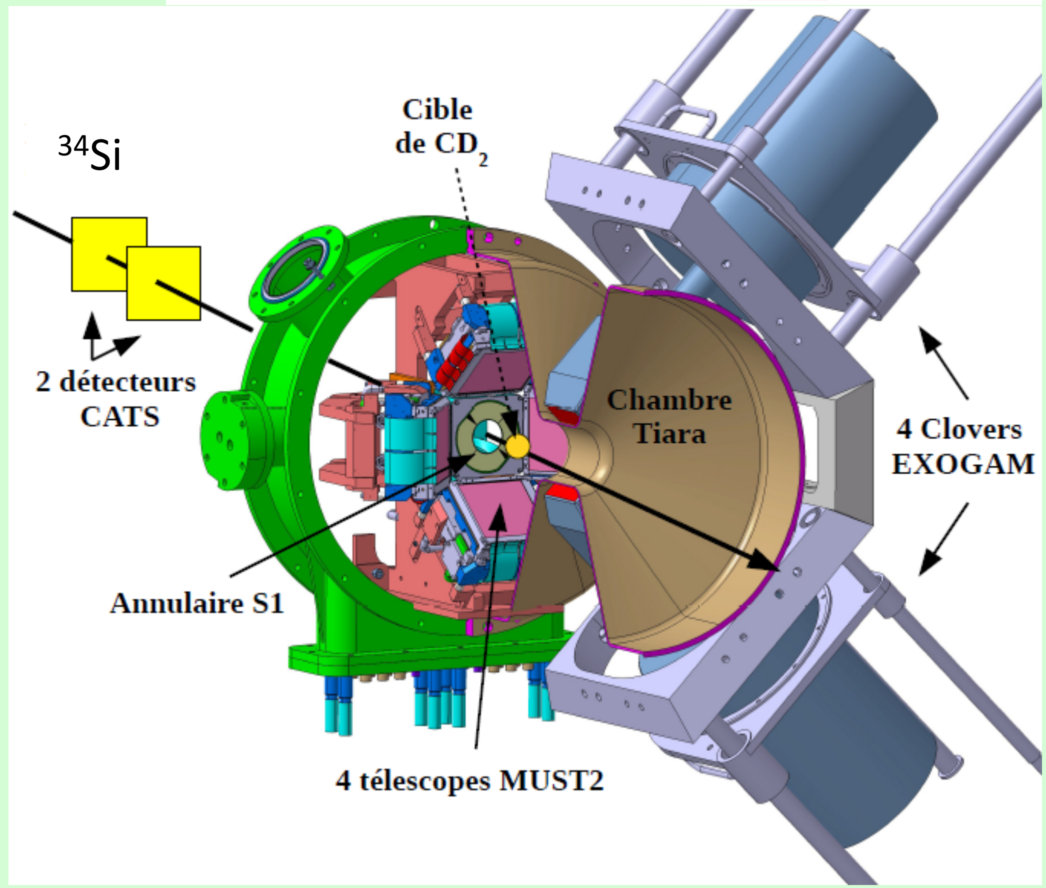
$$\frac{d\sigma(n,L,\theta)}{d\Omega} = (2j+1)\, C_2S^{+} \frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}$$

vacancy *reaction theory*



^{34}Si
10^5pps
20A.MeV
GANIL





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

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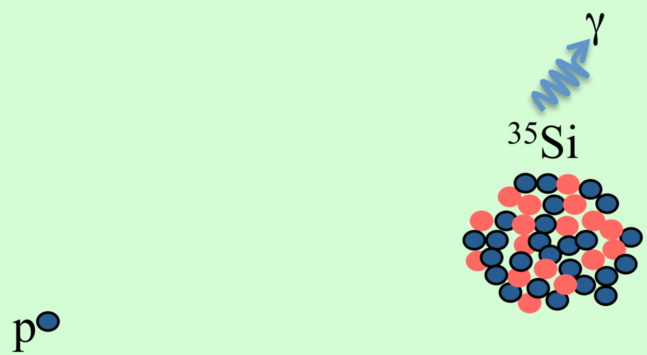
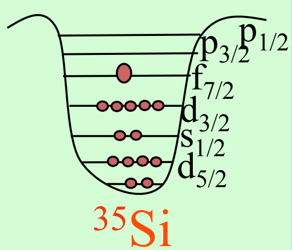
$$\frac{d\sigma(n,L,\theta)}{d\Omega} = (2j+1)\, C_2S^+ \, \frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}$$

vacancy *reaction theory*



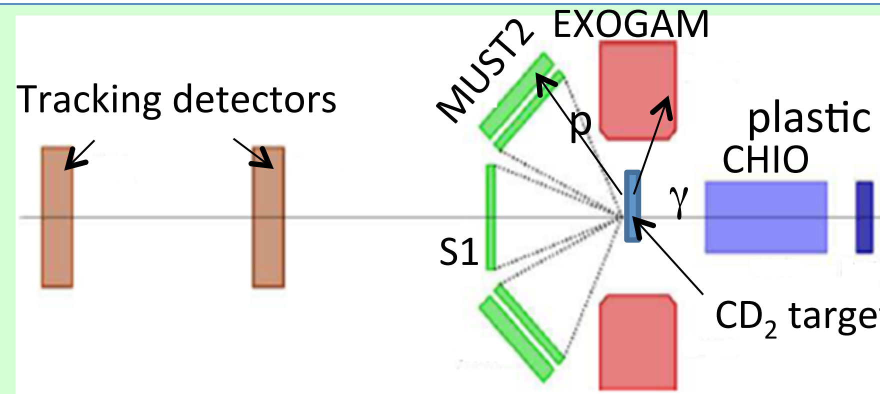


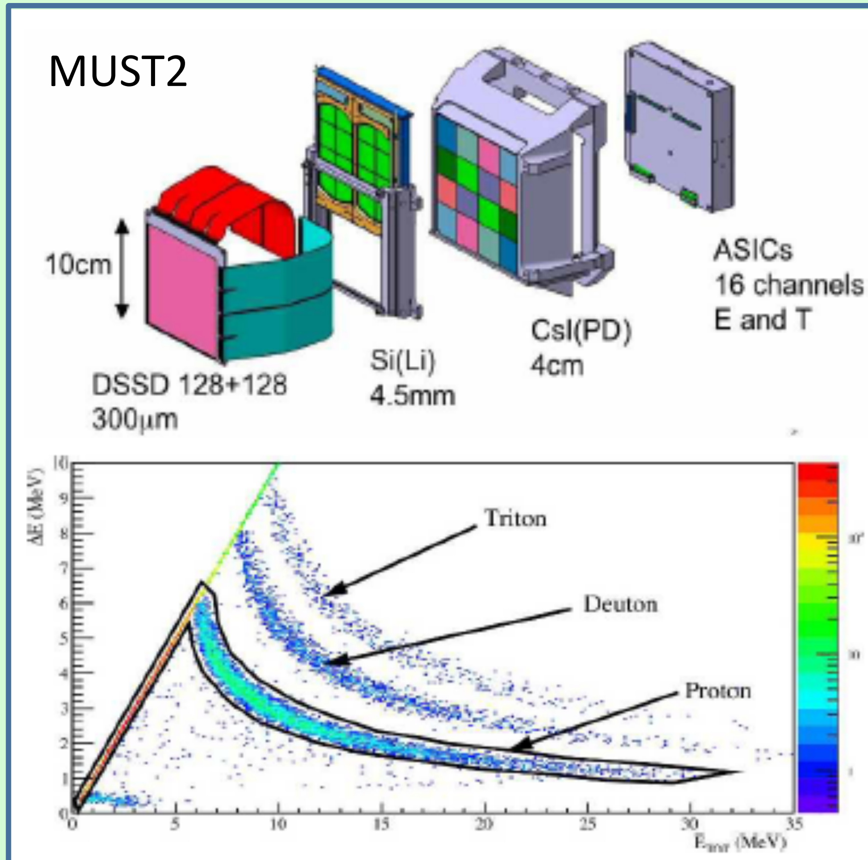
^{34}Si

10^5pps

20A.MeV

GANIL



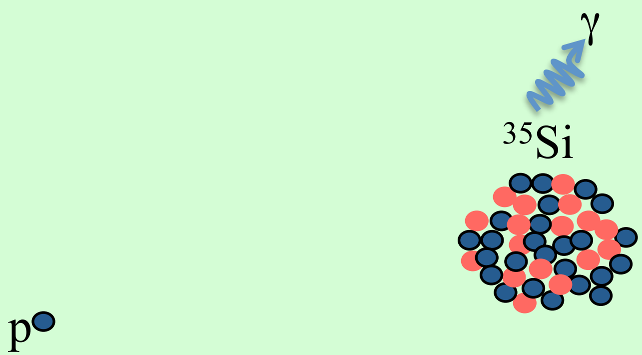


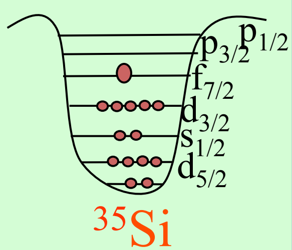
^{34}Si(d,p) reaction in inverse kinematics at GANIL

Transfer reaction (d,p) at $\beta \approx 0.15$

$$\frac{d\sigma(n,L,\theta)}{d\Omega} = (2j+1)\, C_2S^{+} \frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}$$

vacancy — *reaction theory*



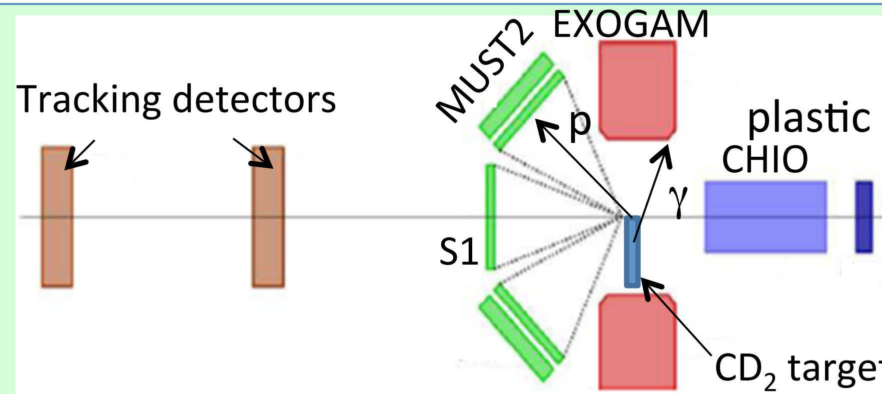


^{34}Si

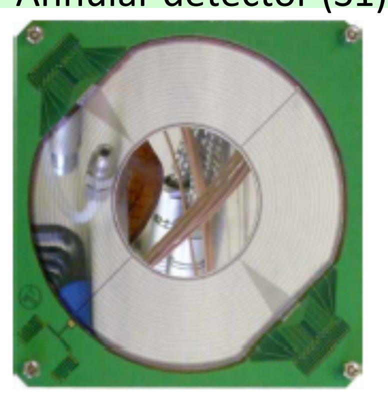
10^5pps

20A.MeV

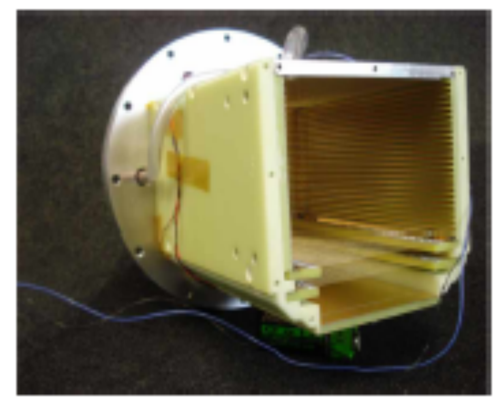
GANIL

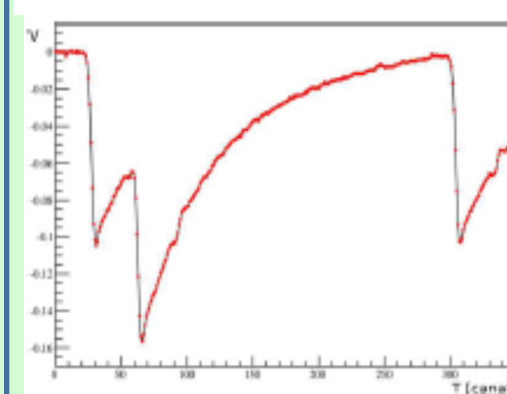


Annular detector (S1)

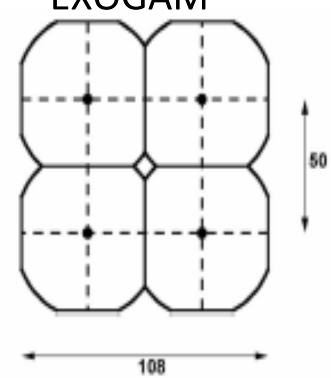


Ionization chamber (CHIO)





EXOGAM



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

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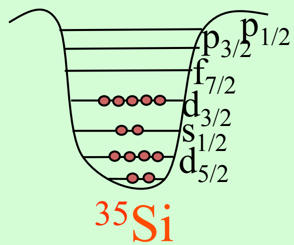
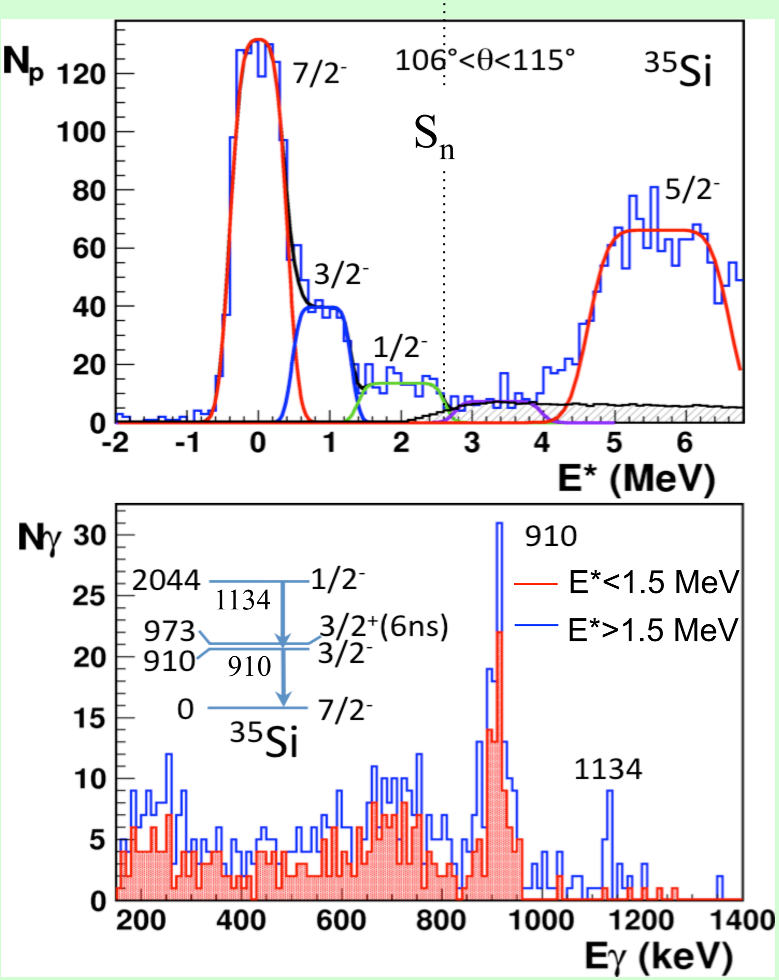
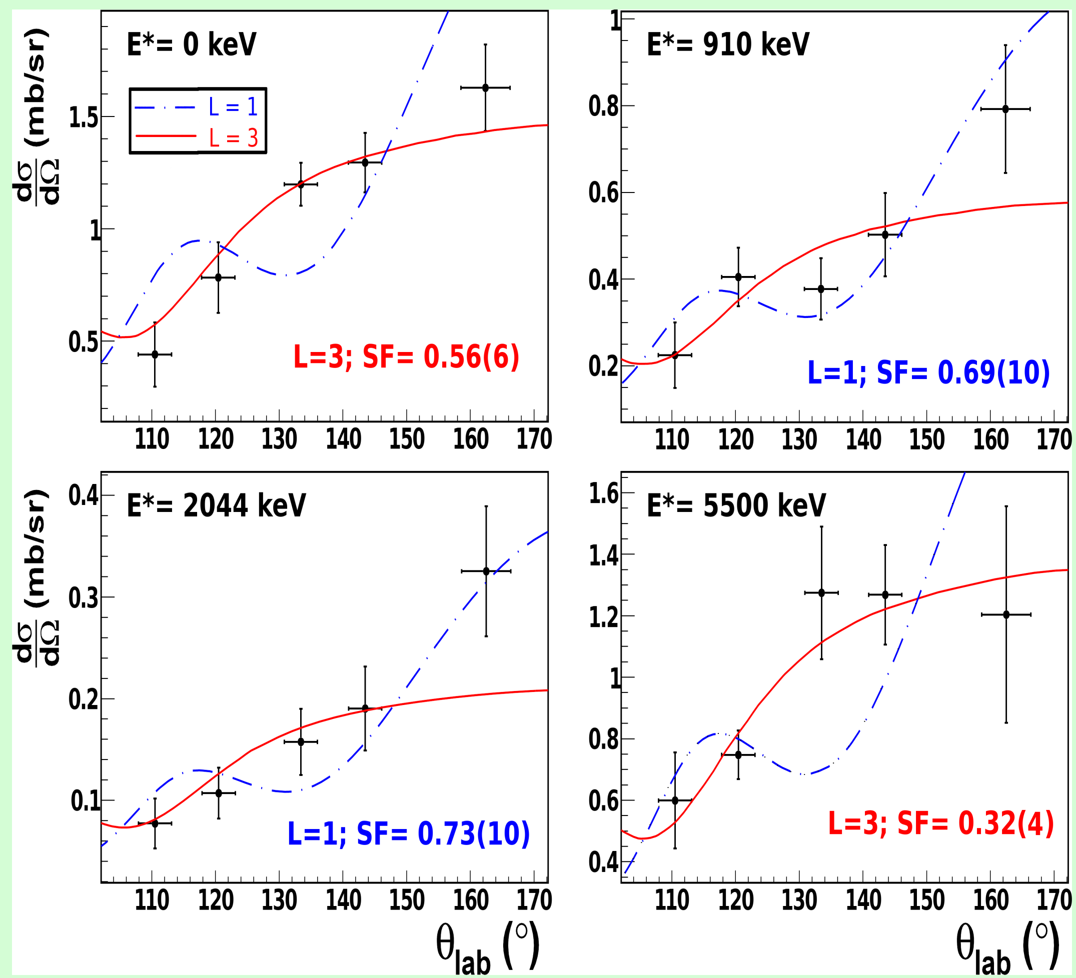
vacancy *reaction theory*

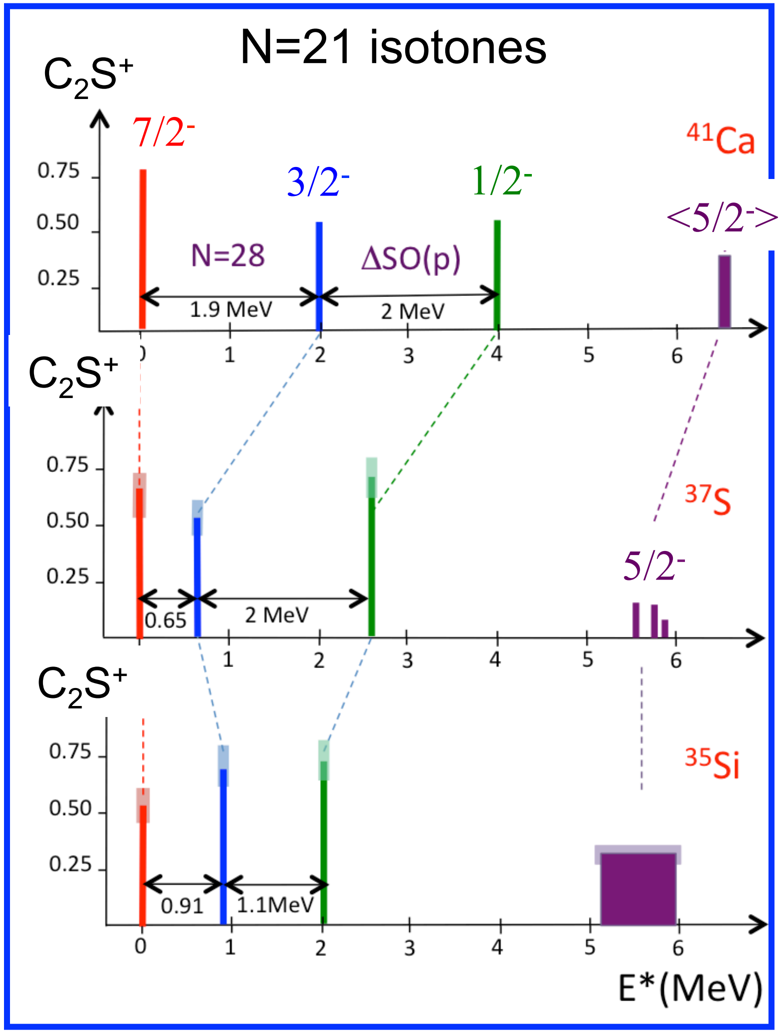


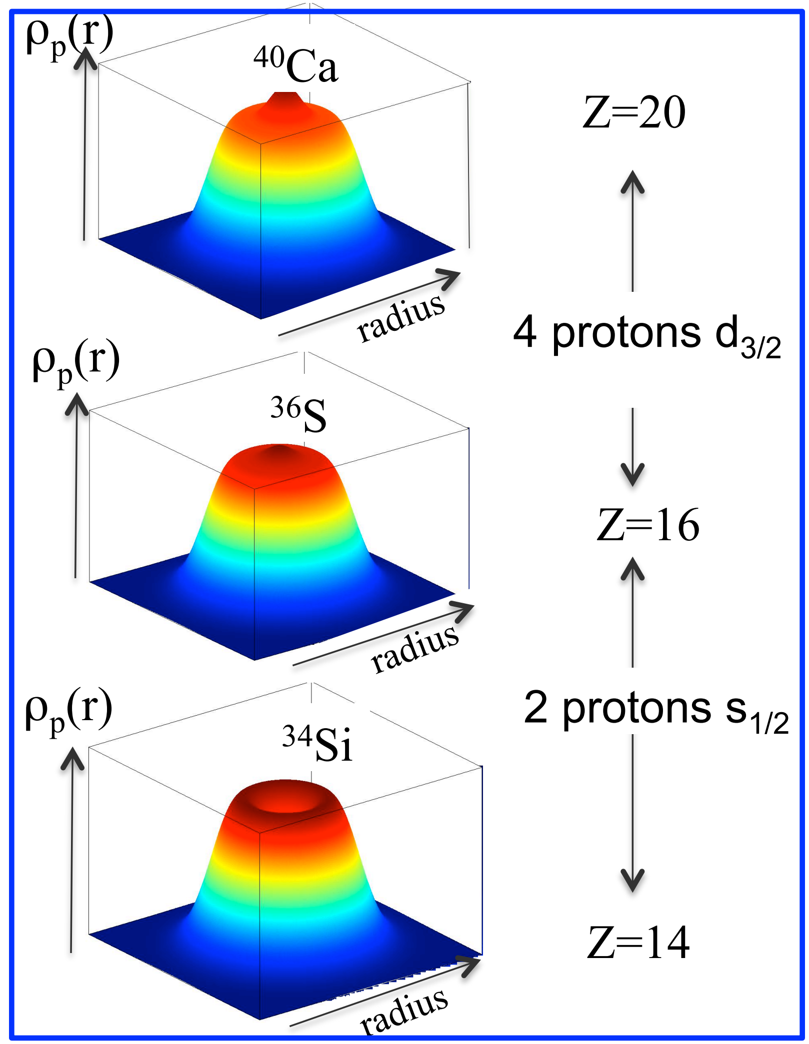
E_p-> (binding) energy of orbit
θ_p-> orbital momentum L
σ-> vacancy of the orbit





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 $f_{7/2}$-$f_{5/2}$

G. Burgunder et al. PRL 112 (2014) 042502

Density and Isospin dependence of the SO interaction

Knockout reactions from ^{36}S and ^{34}Si beams at NSCL / MSU

-> First 'evidence' of a significant central depletion in the atomic nucleus ^{34}Si

-> Asymmetry between proton and neutron density depletions in ^{34}Si

-> unique candidate to probe the spin-orbit interaction in 'unusual ' condition

$^{34}Si(d,p)^{35}Si$ transfer reaction at GANIL

-> Show a drastic reduction of SO interaction as compared to N=20 isotones

Better constraints on the models -> choose the correct one(s)

Evaluate the reduction of SO splitting when reaching the neutron drip-line

Consequence for the r-process nucleosynthesis -> neutron-star mergers

Location of 'stable' Super Heavy Elements to be revisited / better constrained ?