Lectures in Shell evolutions and Nuclear Forces
O. Sorlin (GANIL, France)

LECTURE 1: A bubble nucleus to probe the properties of the spin-orbit interaction

LECTURE 2: Shell evolution/ changes of magic nuclei: Which underlying forces ?

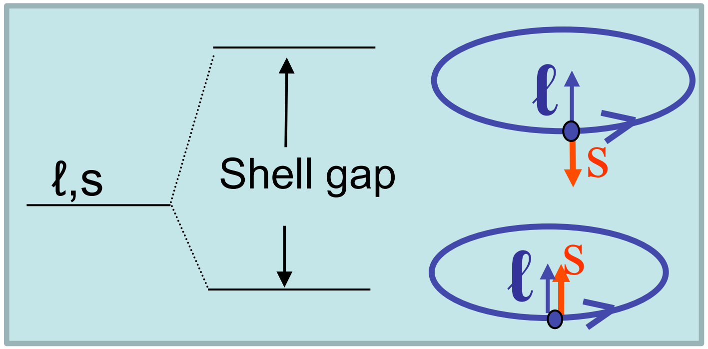
LECTURE 3: A walk on the wild side: Nuclear forces at the drip-line

Study of the spin orbit force using a bubble nucleus

O. Sorlin (GANIL)

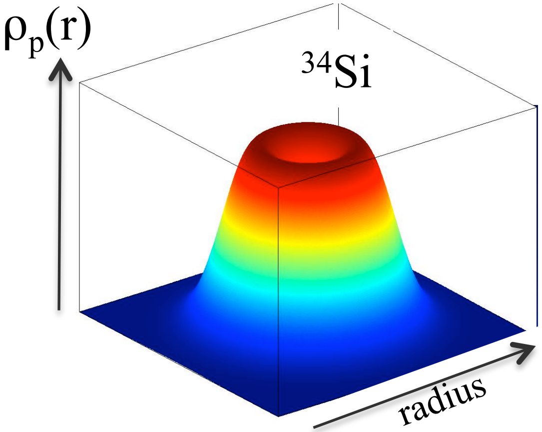
THE PITCH

The spin orbit (SO) force plays major role in nuclear structure to create shell gaps that are linked to the r process nucleosynthesis



The SO force has been postulated more than 60 years ago.
Nowadays fundamental descriptions exist but predictions differ for ab-normal nuclei
No experiment was yet able to test the SO force in 'extreme' conditions.

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



Organization of the talk

General Introduction of the atomic nucleus

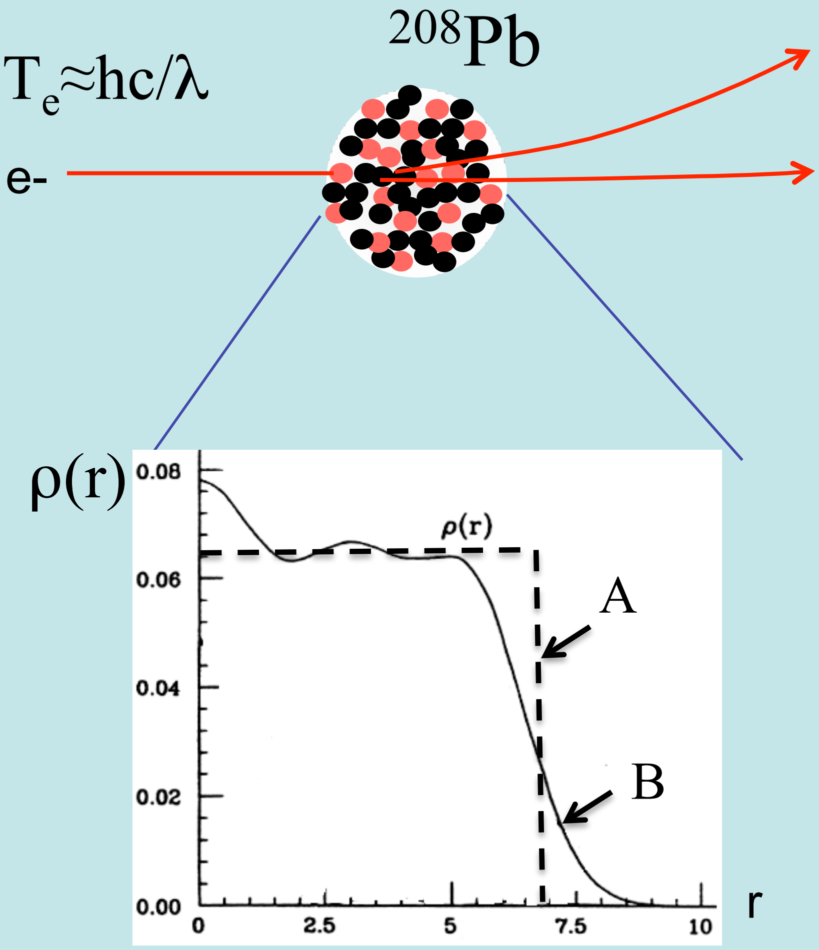
Charge density, saturation of nuclear forces, Nuclear orbits
State mixing, nuclear Fermi surfaces, Simplified Mean Field

The Spin orbit force – properties/expectations
A bubble nucleus ^{34}Si

Proton density depletion in ^{34}Si (knock-out reaction)
Spin orbit reduction (transfer reaction)

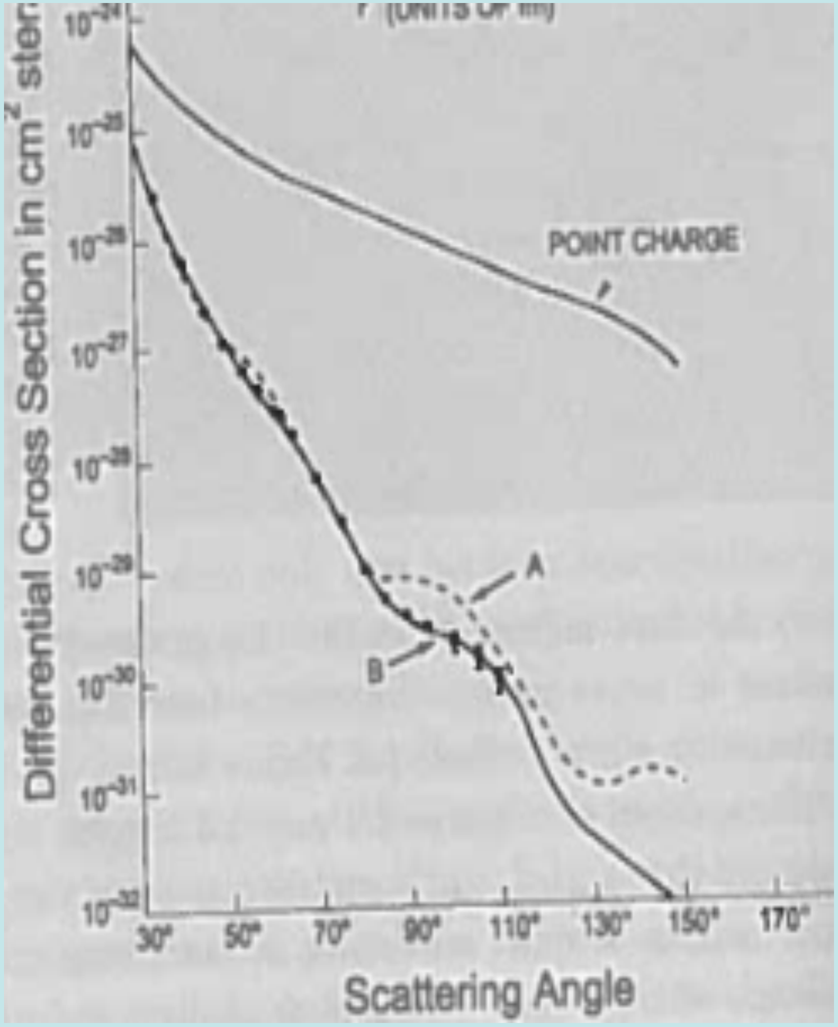
Results-

Charge density of the nucleus : ρ(r)

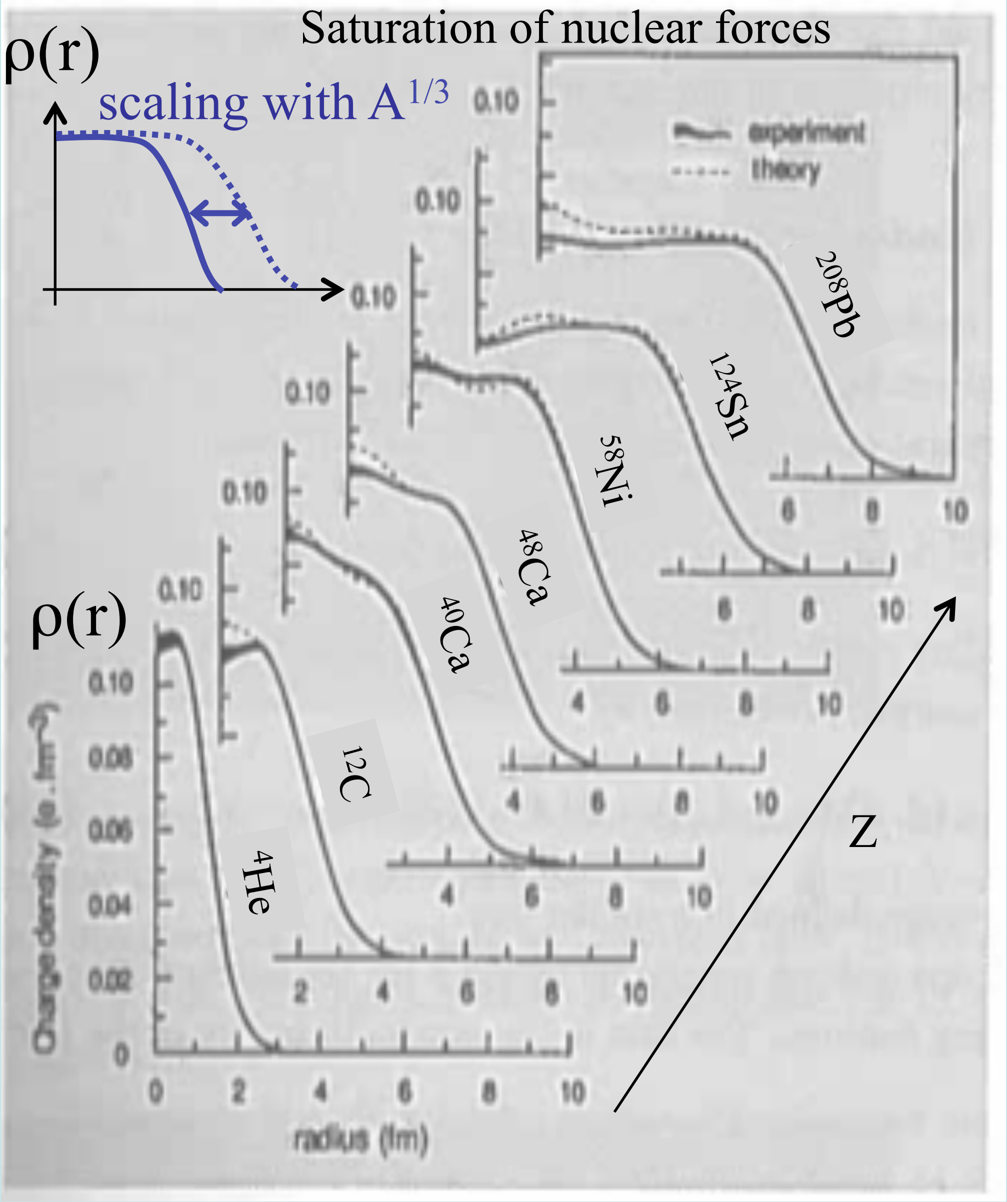


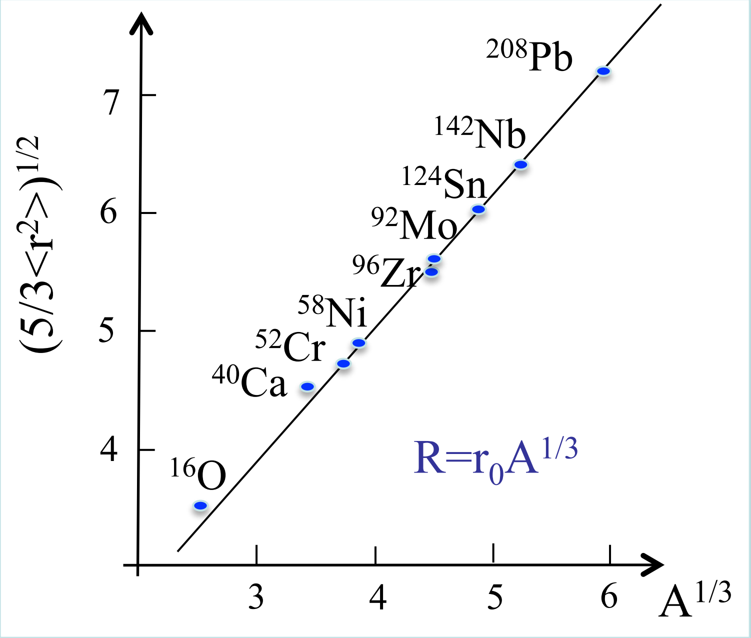
Large transferred momentum

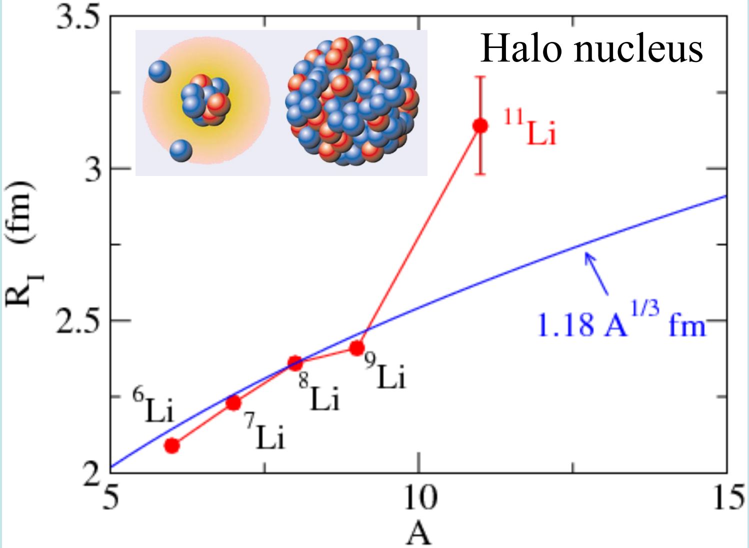
-> details of the density distribution



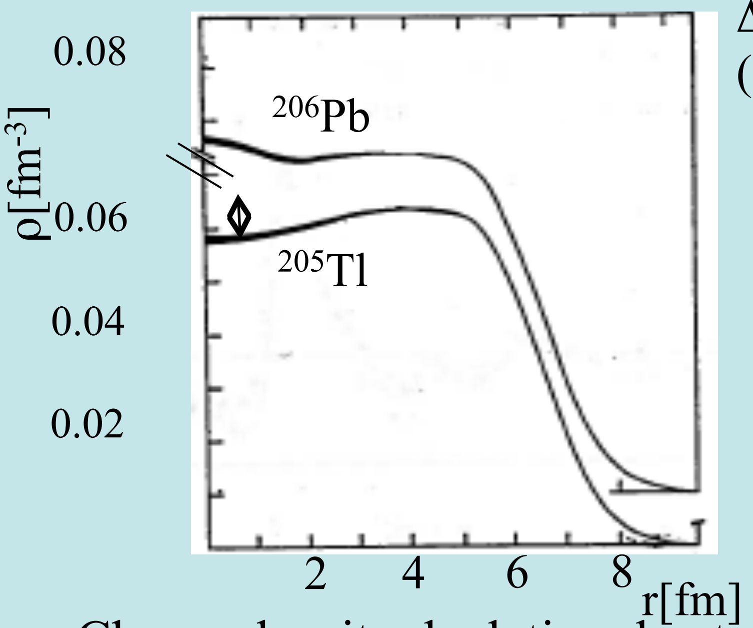
Charge density of the nucleus : ρ(r)

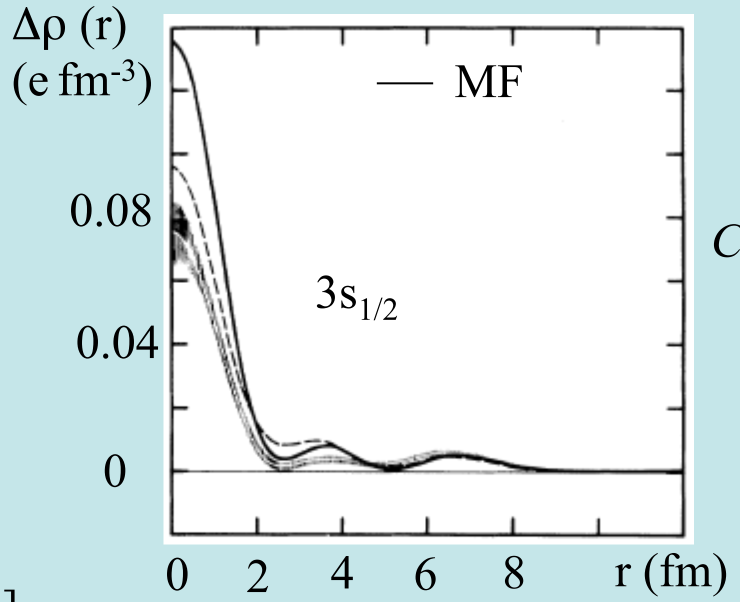






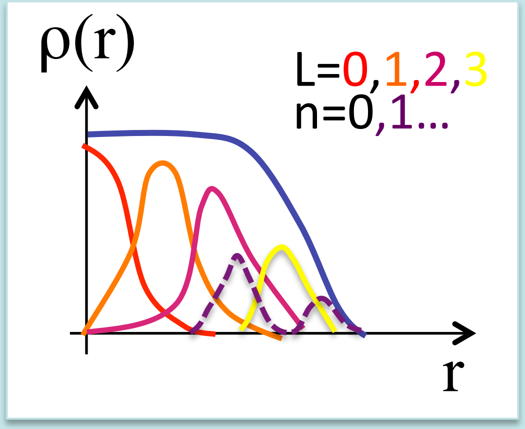
Charge density depletion in the center of the ^{205}Tl nucleus





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 obtained from a
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

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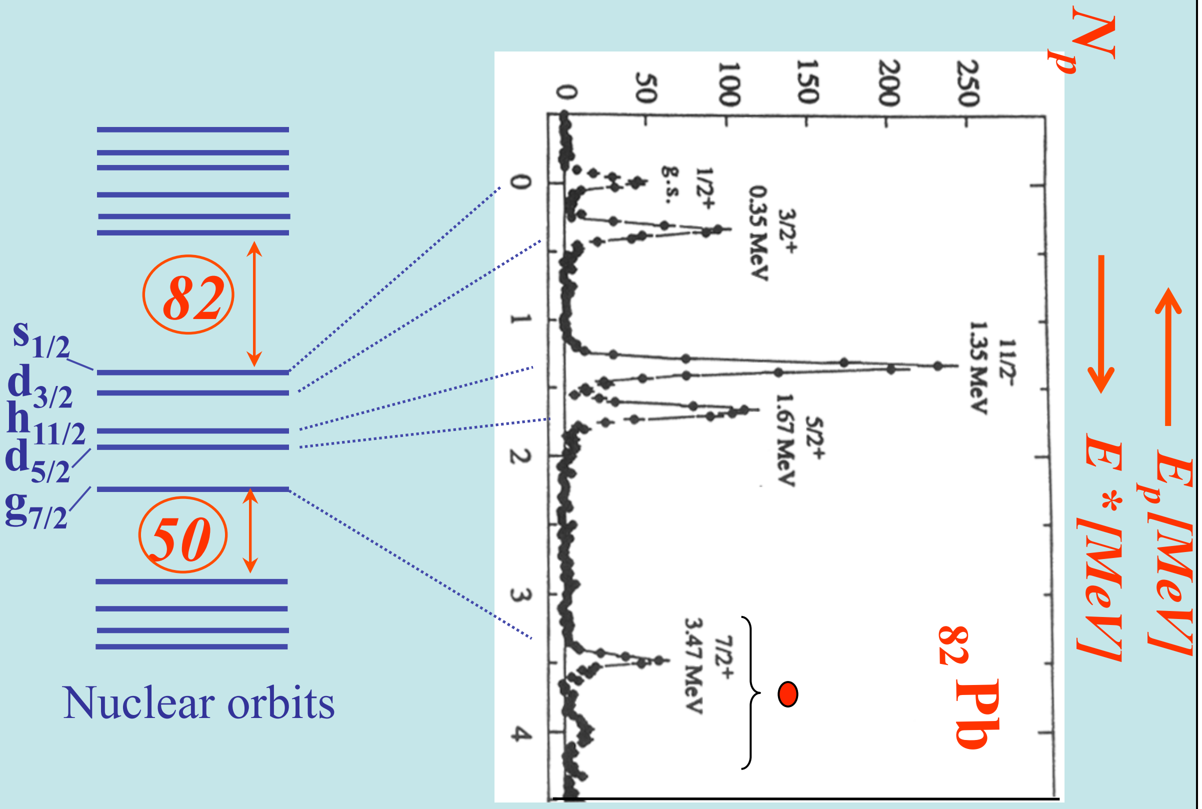
example :
$h_{11/2}$: L=5, J=11/2,
L and s aligned
contains 12 nucleons



->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%

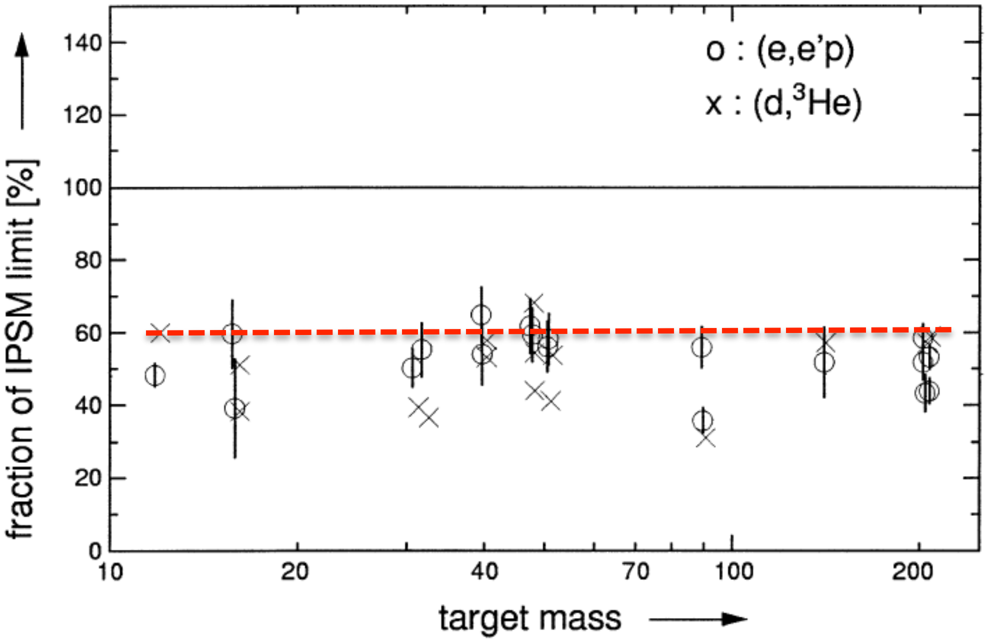
-> Mixing with collective states at high E* ●

-> Study limited (so far) to STABLE nuclei

Quenching of occupancy values

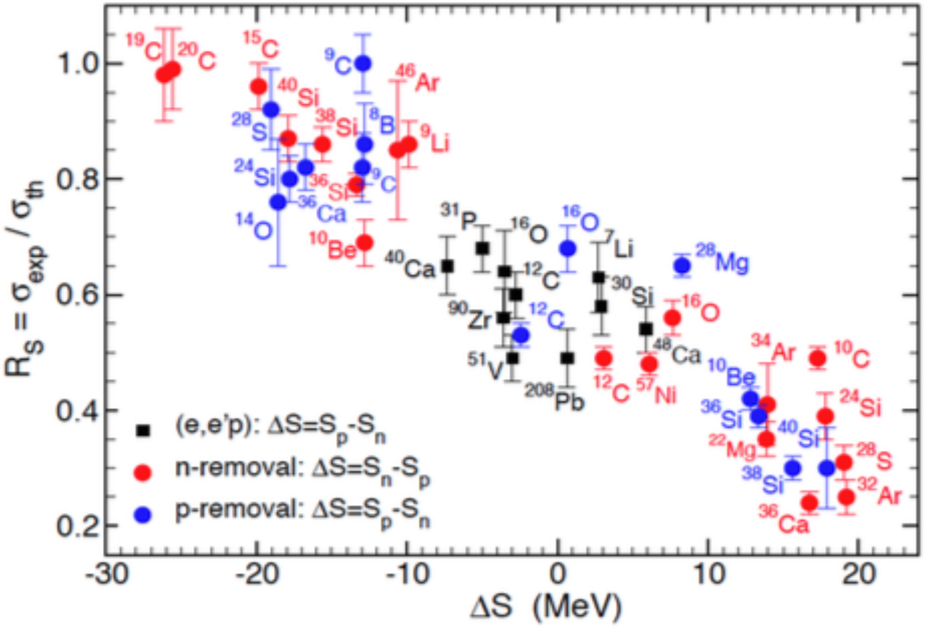
'At any time only 2/3 of the nucleons in the nucleus act as independent particles moving in the nuclear mean field. The remaining third of the nucleons are correlated'

Pandharipande et al. Rev. Mod. Phys. 69 (1997) 981



Constant quenching factor of about 60%

Kramer et al. NPA 679 (2001) 267



Quenching factor depends on ΔS

Tostevin and Gade, PRC 90 (2014)

Short range correlations

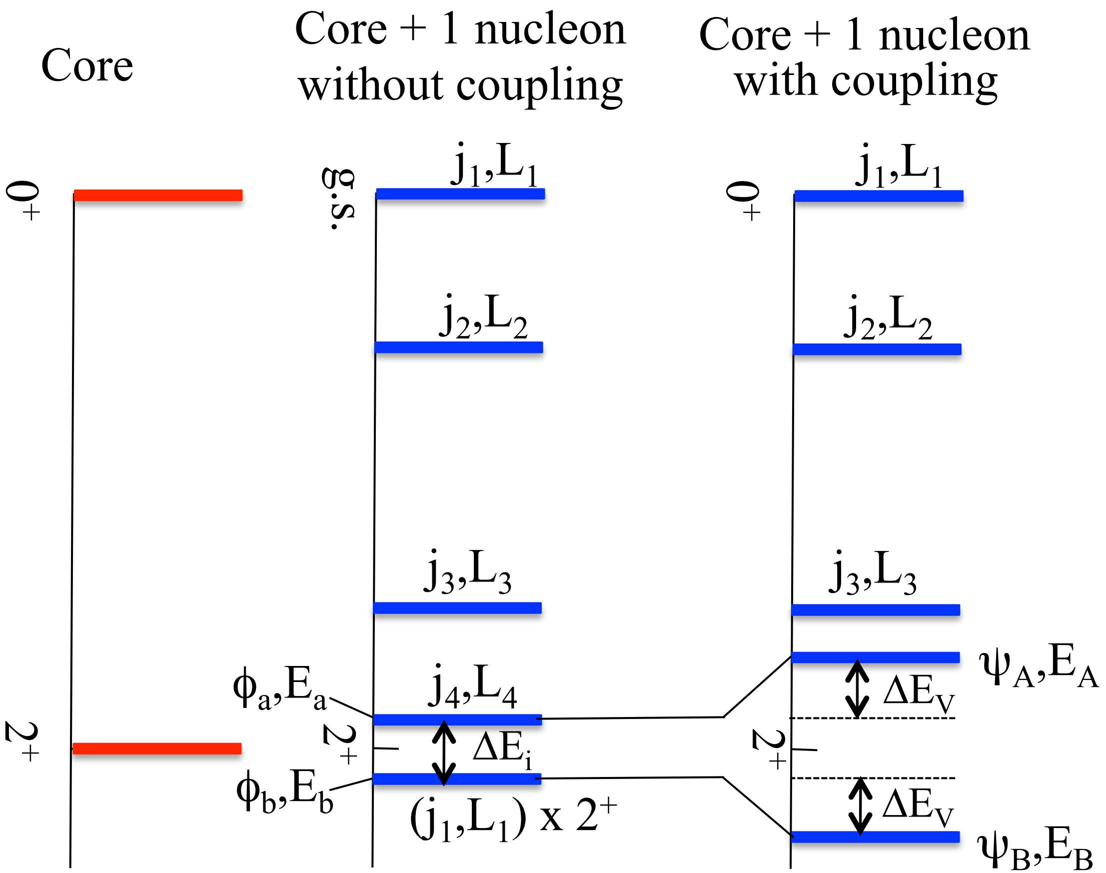
AND

Coupling to collective resonances

Barbieri et al. PRL 103 (2009) 202502

- Occupancy value is not an observable (derived from models)
- Some publications renormalize their occupancy values (without specifying)

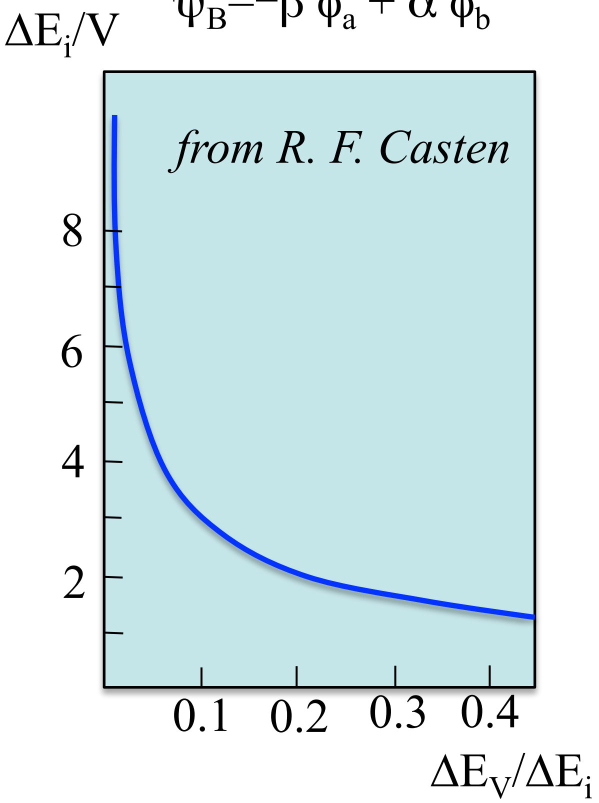
Mixing with ‘collective’ states: which consequences?



State mixing

$\psi_A = \alpha\ \phi_a + \beta\ \phi_b$

$\psi_B = -\beta\ \phi_a + \alpha\ \phi_b$



from R. F. Casten

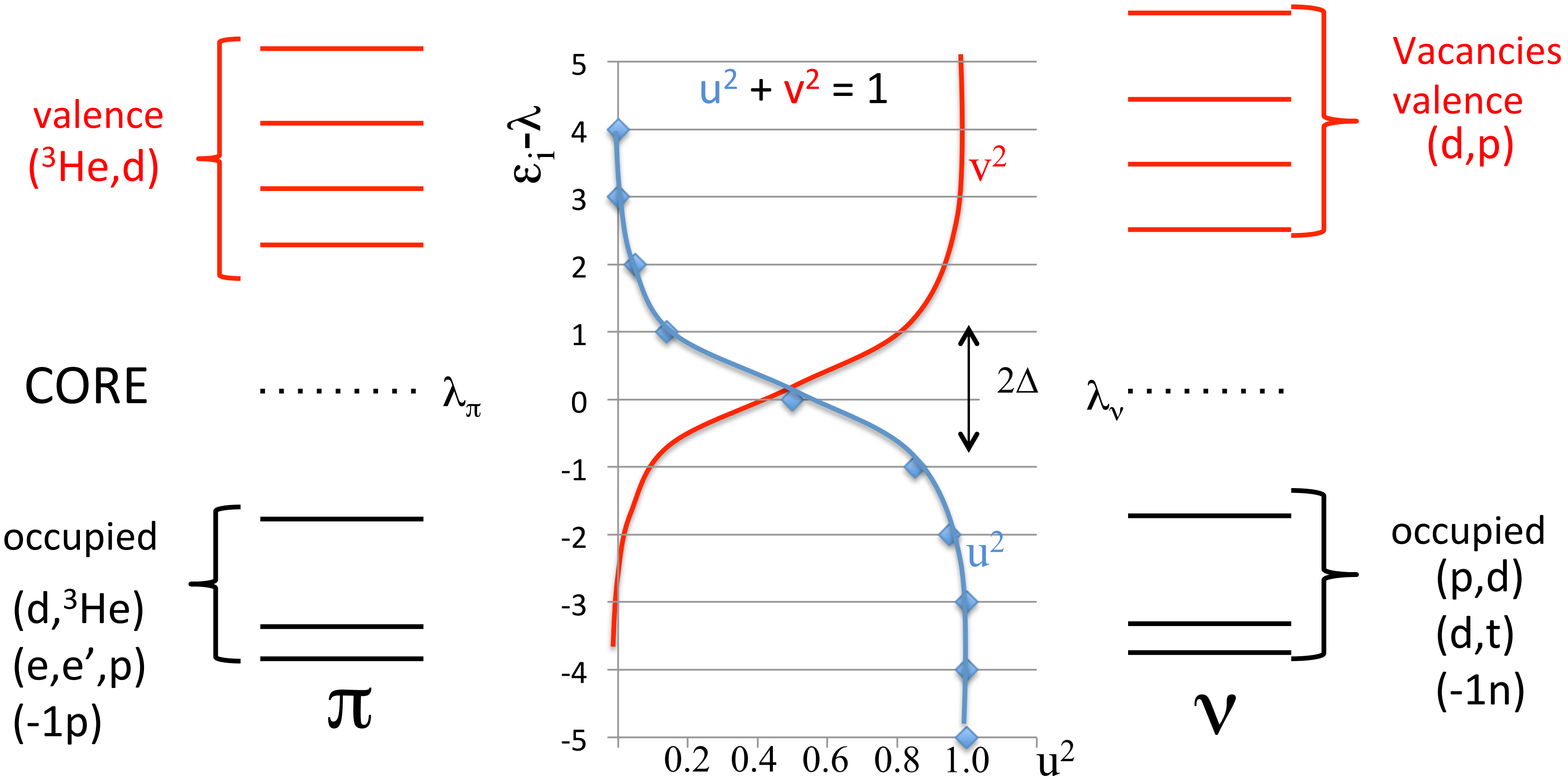
Mixing between states having same J^π configurations
Final wave function contains mixed contributions of the two initial states
Significant repulsion between levels when ΔE_i small and/or V large

Due to mixing -> collect all states to determine the energy centroid (often not feasible)

Which 'transfer' reaction, what for ?

Choose the appropriate probe to determine occupancies / vacancies of orbits

Role of correlations (pairing, quadrupole) ➔ dilution of the Fermi surface



valence
(^{3}He,d)

CORE

λ_π

occupied
(d,^{3}He)
(e,e',p)
(-1p)

π

Vacancies
valence
(d,p)

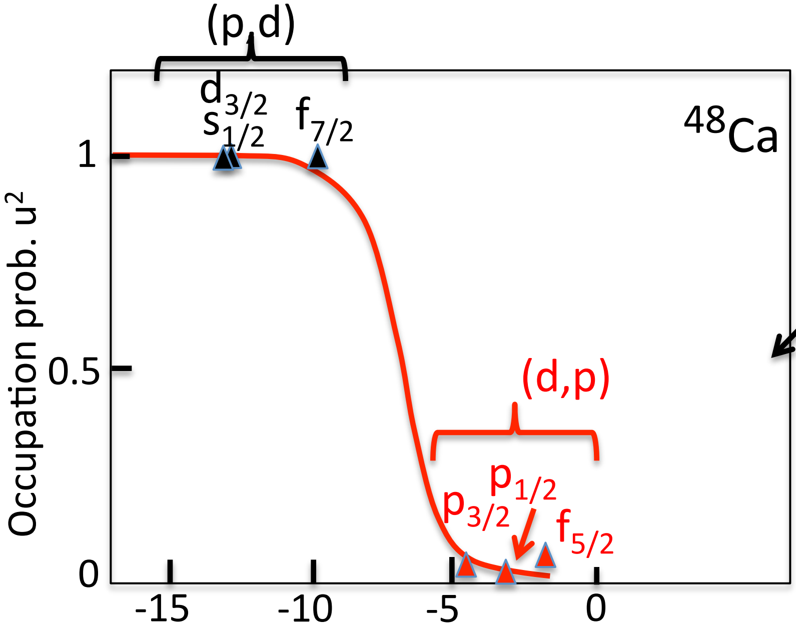
λ_ν

occupied
(p,d)
(d,t)
(-1n)

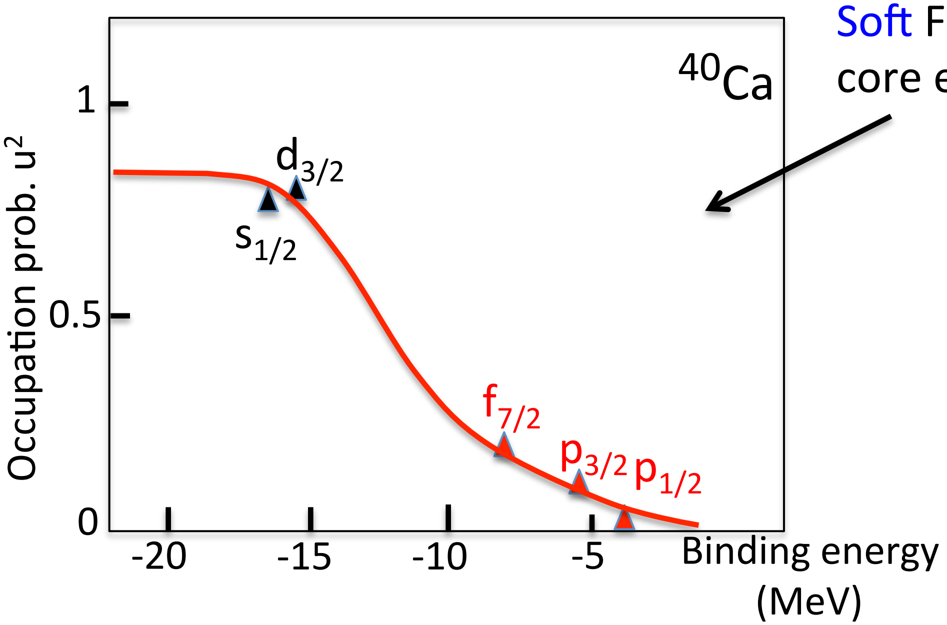
ν

$$u_i^2 = \frac{1}{2}\left[1 - \frac{\varepsilon_i - \lambda}{\sqrt{(\varepsilon_i - \lambda)^2 + \Delta^2}}\right]$$

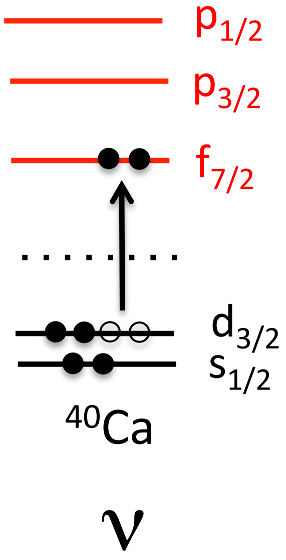
The ‘Fermi surfaces’ of ^{40,48}Ca derived from transfer reactions



^{48}Ca has a stiff Fermi surface
-> good closed shell nucleus



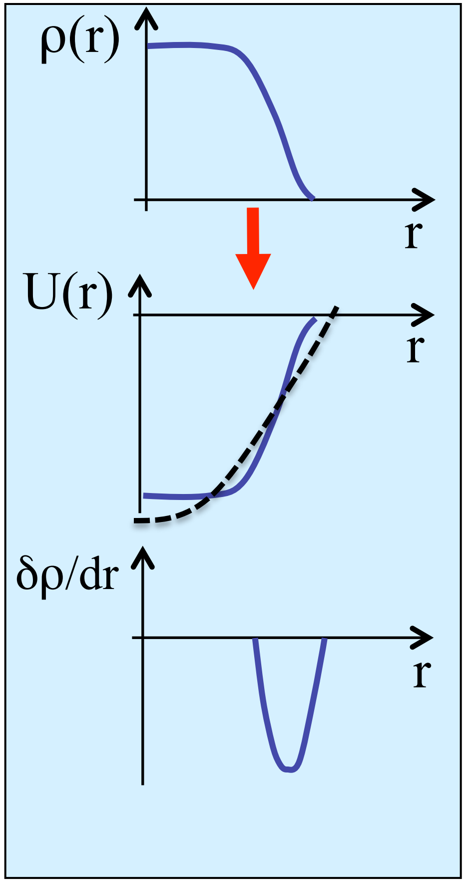
Soft Fermi surface significant core excitations

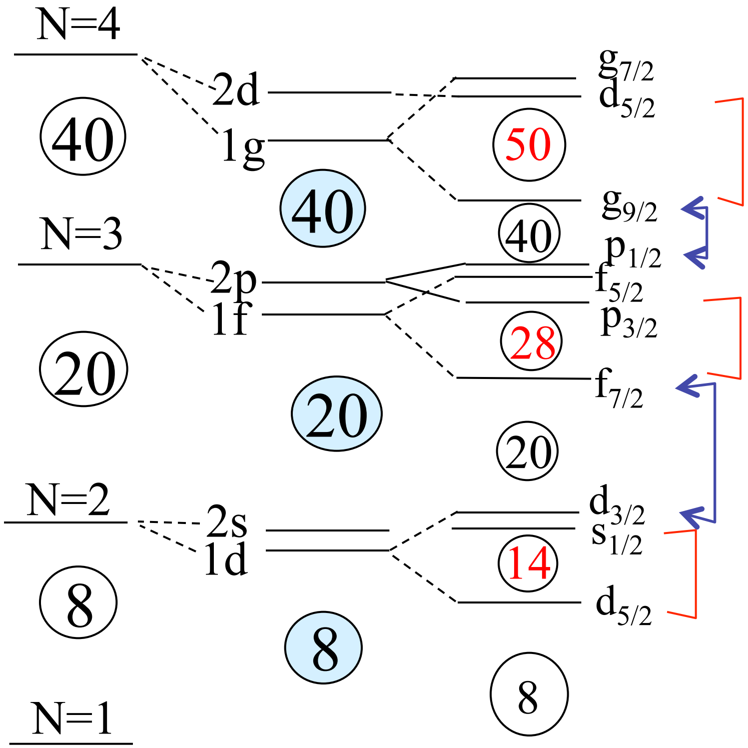


Hole strength (p,d): Martin et al. NPA 185(1972)465

Particle strength (d,p): Uozumi et al. NPA 576 (1994) 123, Uozumi et al. PRC 50 (1994) 263

Simplified mean-field approach for atomic nuclei





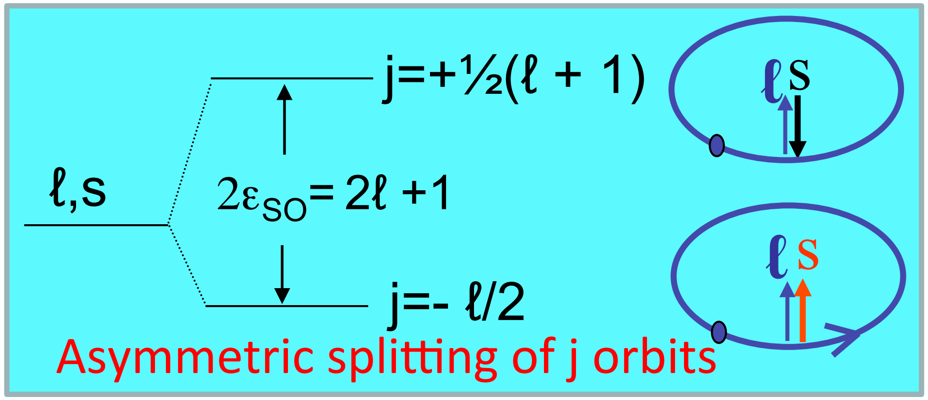
Spin Orbit
6, 14, 28, 50, 82, 126

Harmonic Oscillator
8, 20, 40

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

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

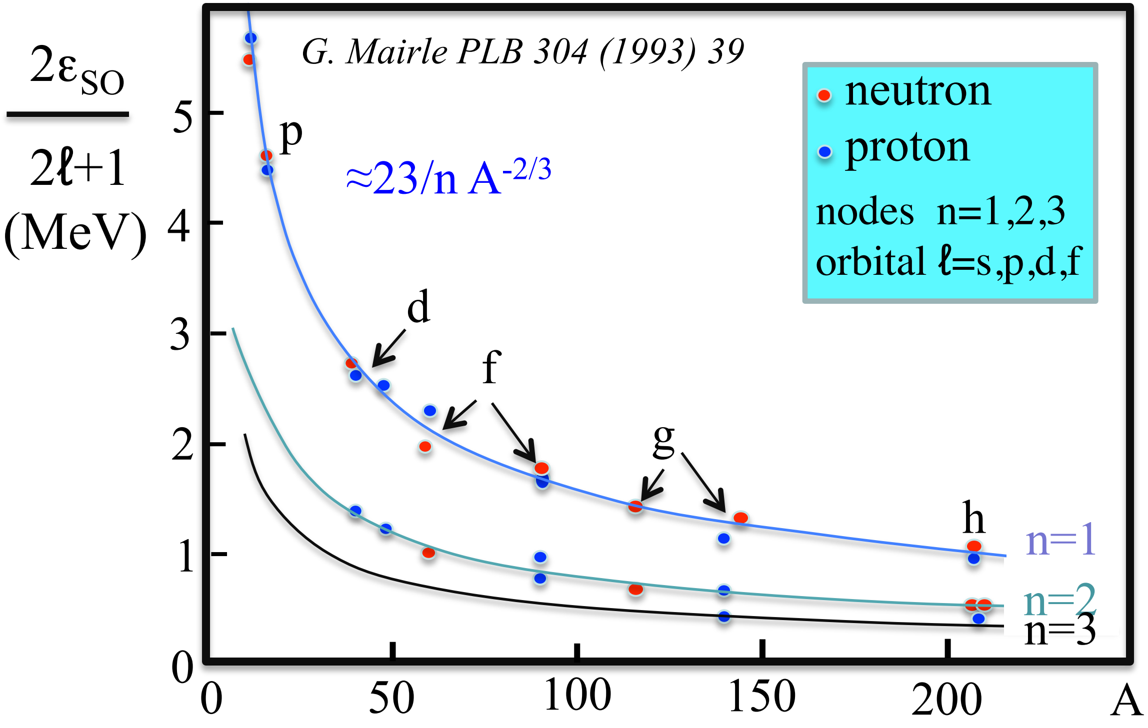
Some properties of the spin orbit interaction



Asymmetric splitting of j orbits

SO splitting is often very large
-> creation of shell gaps

Hard to access both SO partners experimentally …



$1p_{1/2}$-$1p_{3/2}$ ≈ 11 MeV for A=15

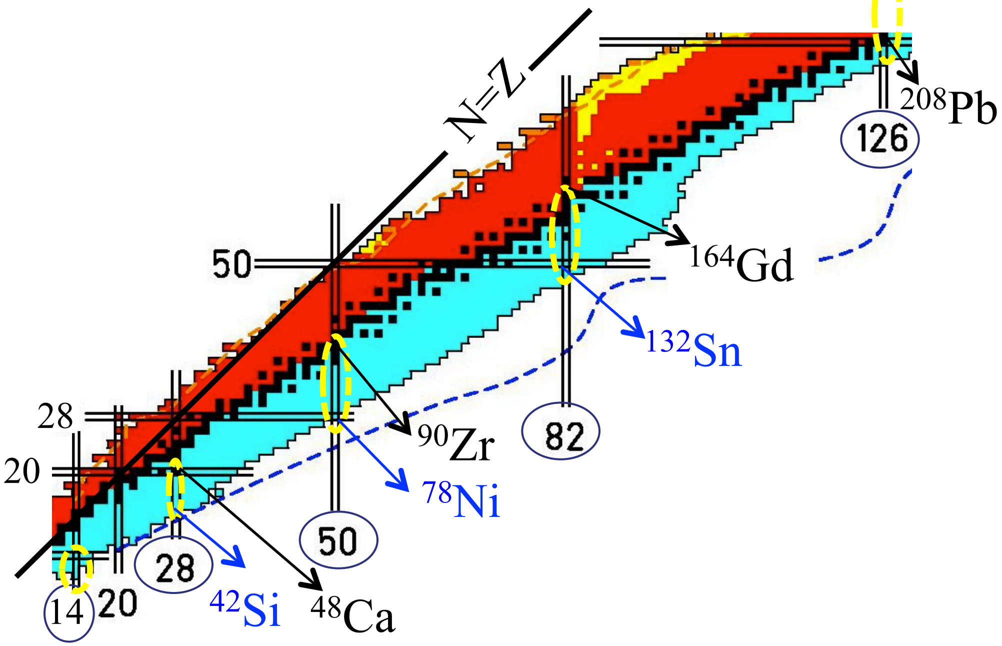
$1d_{3/2}$-$1d_{5/2}$ ≈ 5 MeV for A=40

$1f_{5/2}$-$1f_{7/2}$ ≈ 7 MeV for A=40

$1h_{9/2}$-$1h_{11/2}$ ≈ 11 MeV for A=130

$2p_{1/2}$-$2p_{3/2}$ ≈ 1.5 MeV for A=40
Here the SO splitting is rather small
-> study its evolution

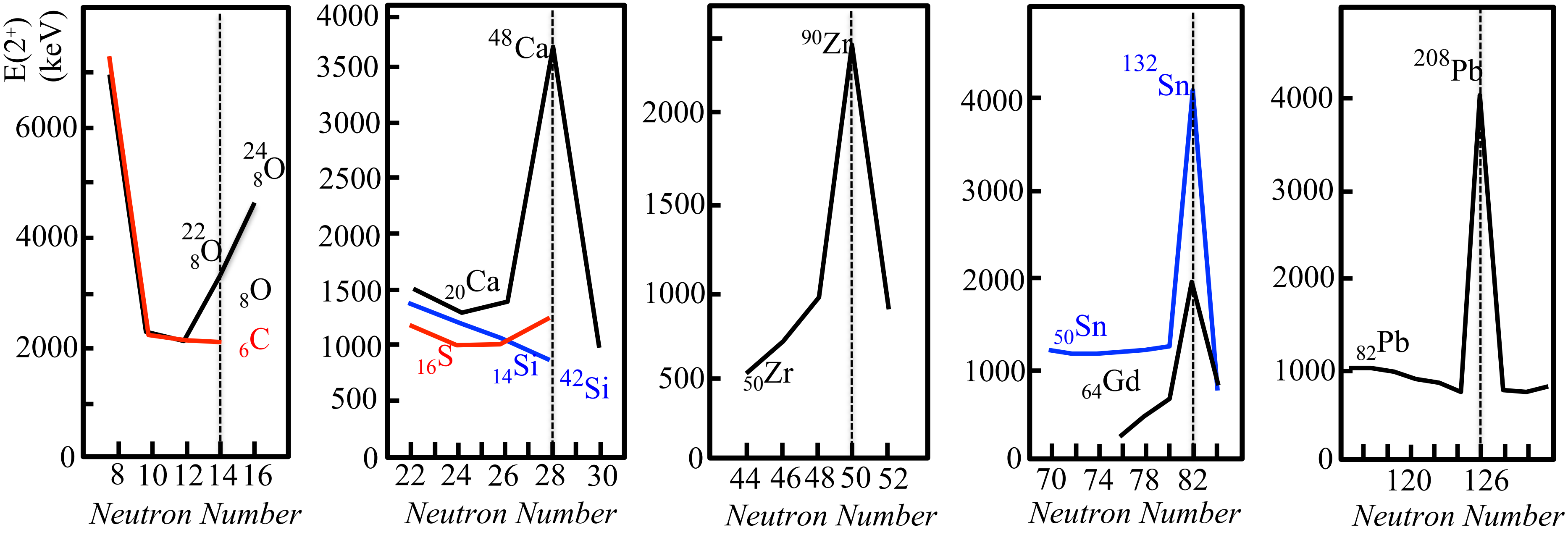
Spin Orbit magic numbers



The SO force leads to large shell gaps

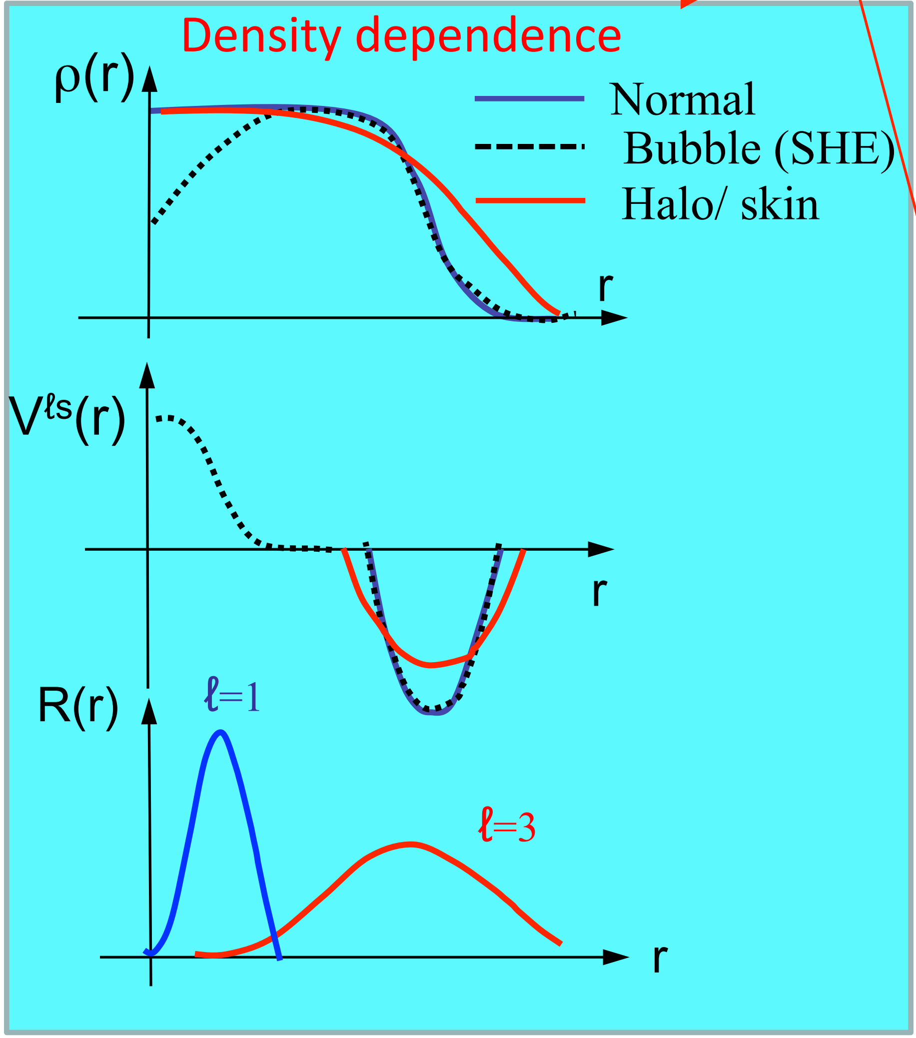
High 2^+ energies are found at the N=14, 28, 50, 82, 126 numbers

What happens in extreme conditions ? (diffuse matter, large N/Z, SHE…)

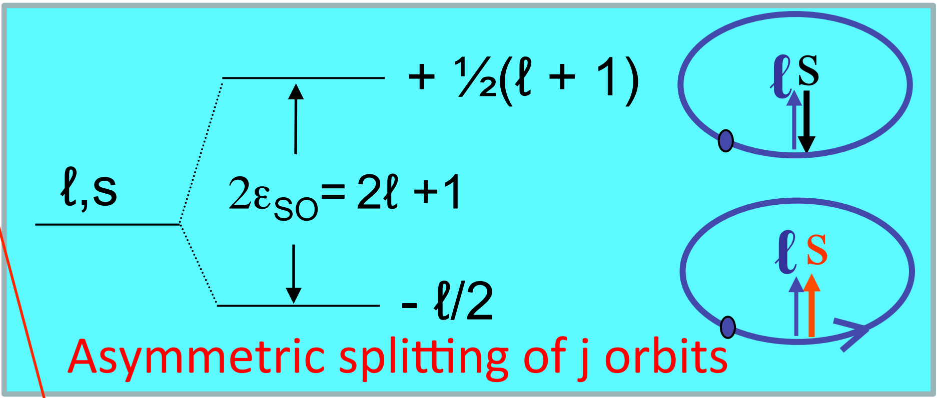


The spin-orbit (SO) interaction

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



Density dependence



Asymmetric splitting of j orbits

Isospin dependence

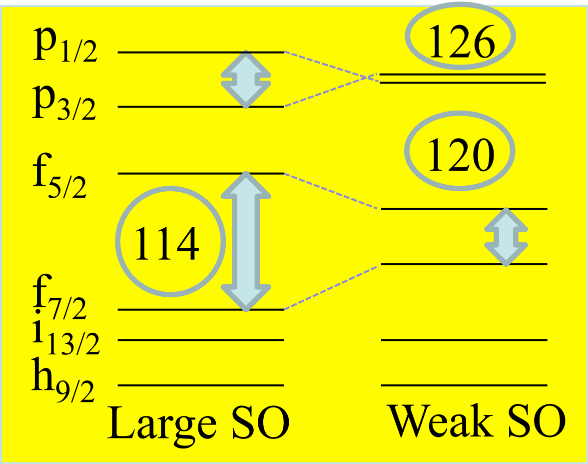
$$W_1 \approx 2W_2 \quad (MF)$$

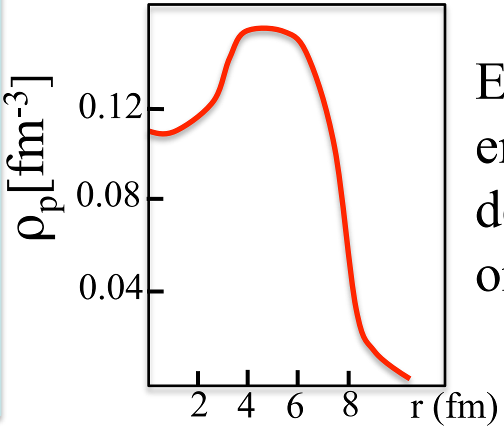
$$W_1 \approx W_2 \quad (RMF)$$

No isospin dependence in RMF

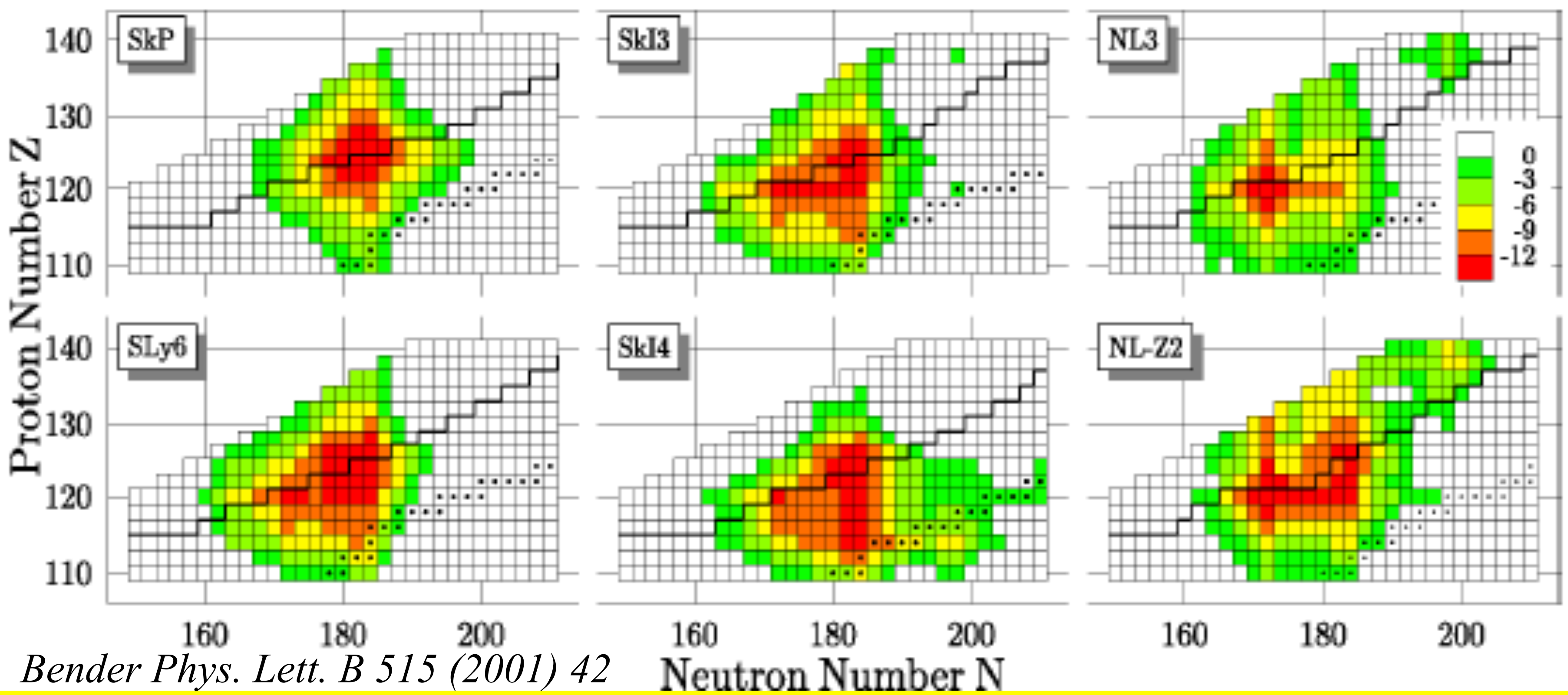
-> test density and isospin dep. of SO from orbits probing the nucleus interior by looking at n SO change from p depletion

Spin Orbit and Super Heavy Elements (SHE)



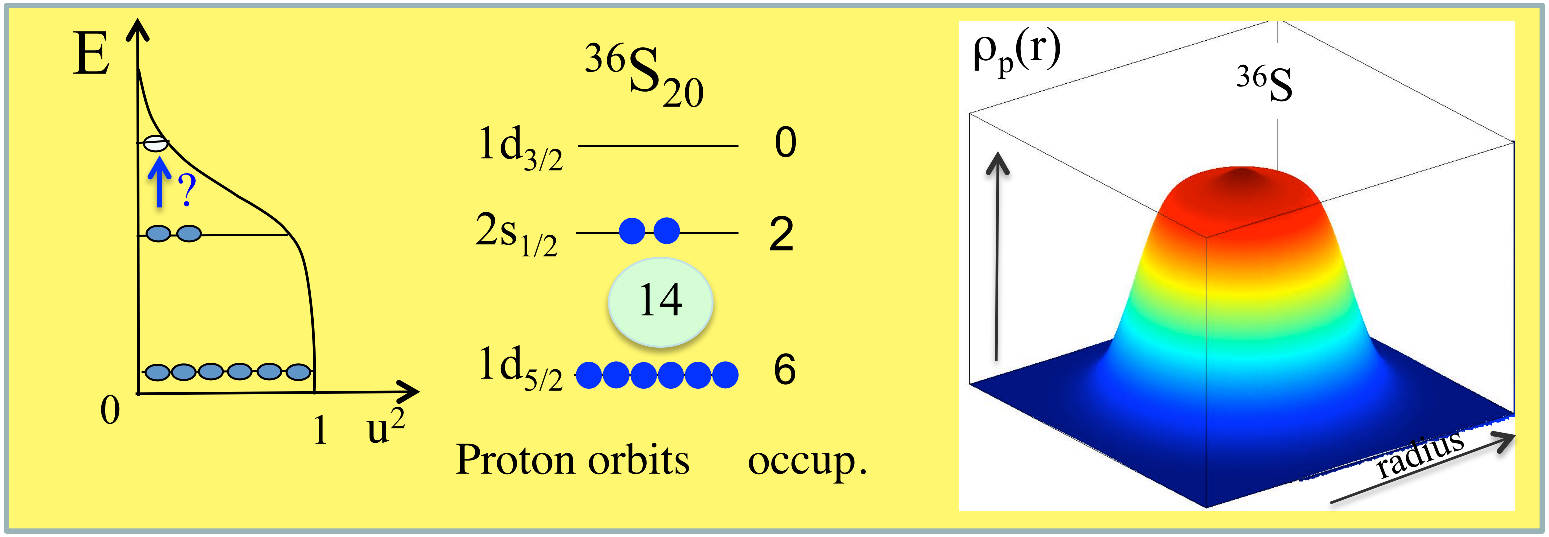


Existence / location of island of enhanced stability for SHE depends strongly (but not only) on the modeling of the SO interaction



Bender Phys. Lett. B 515 (2001) 42

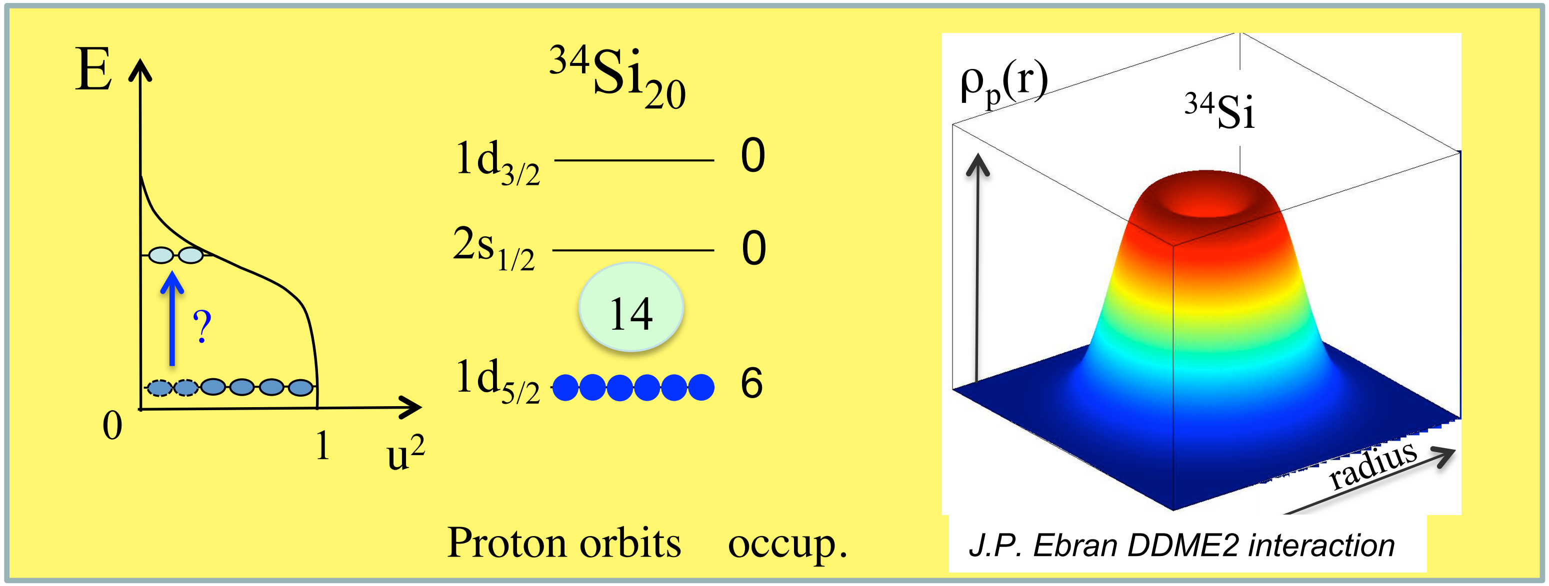
Proton density depletion in ^{34}Si as compared to ^{36}S?



$^{36}S_{20}$

Proton orbits	occup.
$1d_{3/2}$	0
$2s_{1/2}$	2
$1d_{5/2}$	6

14



$^{34}Si_{20}$

Proton orbits	occup.
$1d_{3/2}$	0
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$1d_{5/2}$	6

14

J.P. Ebran DDME2 interaction

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

Pairing and quadrupole correlations can reduce the amplitude of this depletion

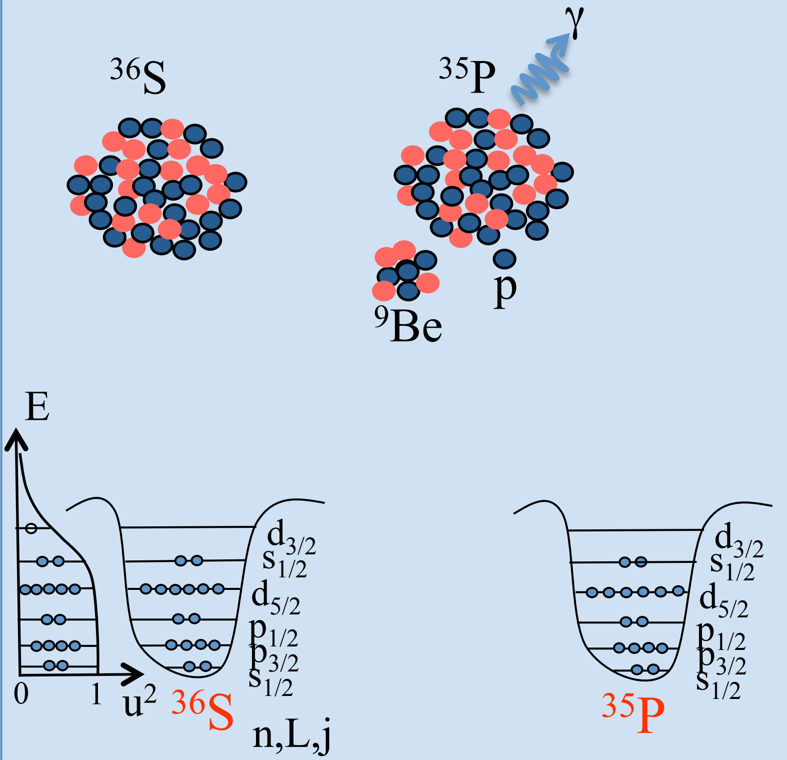
The two nuclei have similar neutron occupancies (N=20)

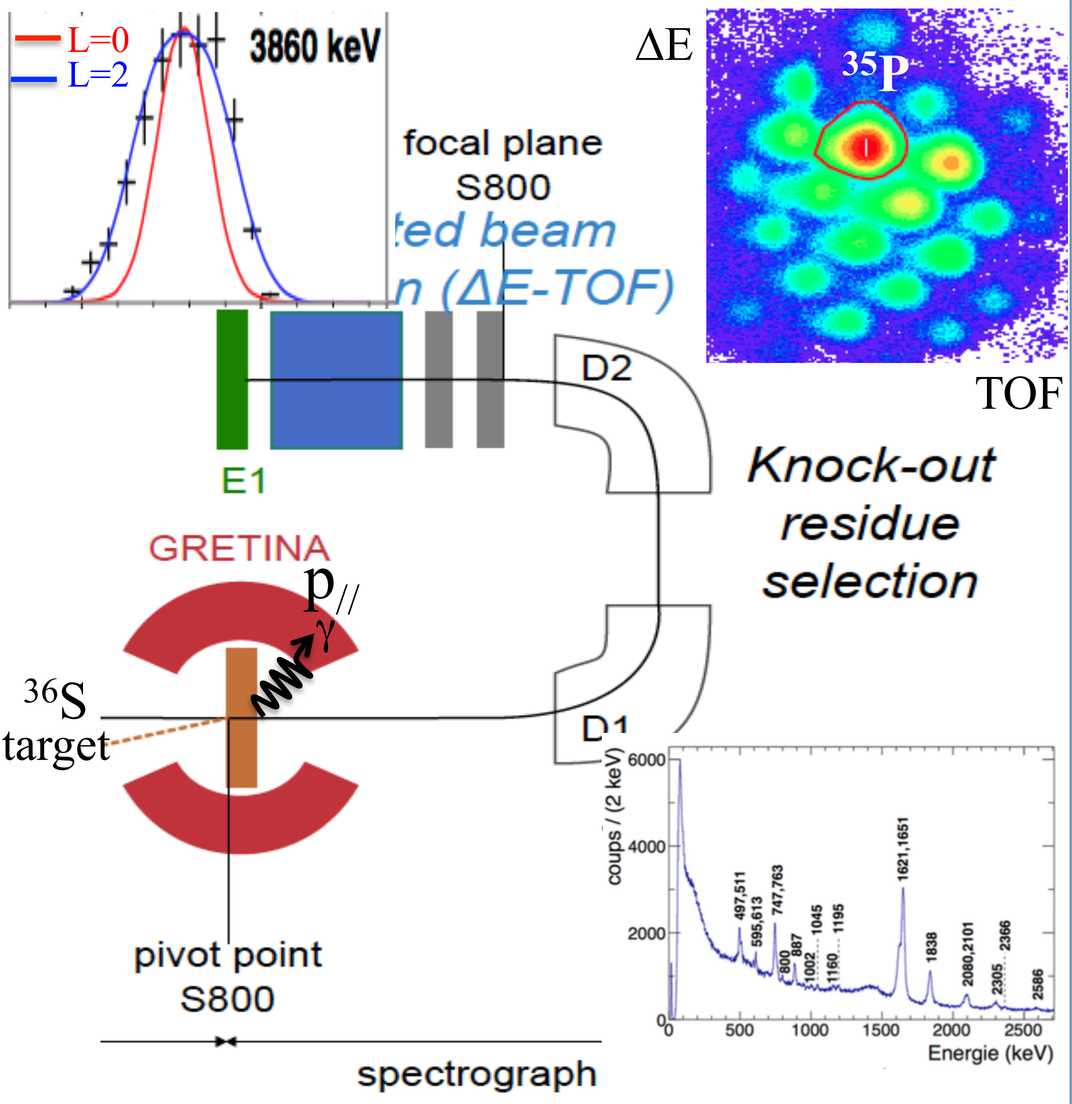
Probing proton density in ^{36}S

Knock-out reactions at β≈0.4

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

normalized occupancy *reaction theory*





REMARK

Occupancy is not an observable, it is derived from a model

It may differ when various experimental techniques (and models) are used

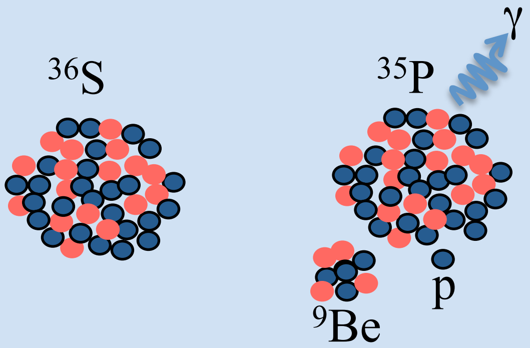
Relative occupancy values are more relevant

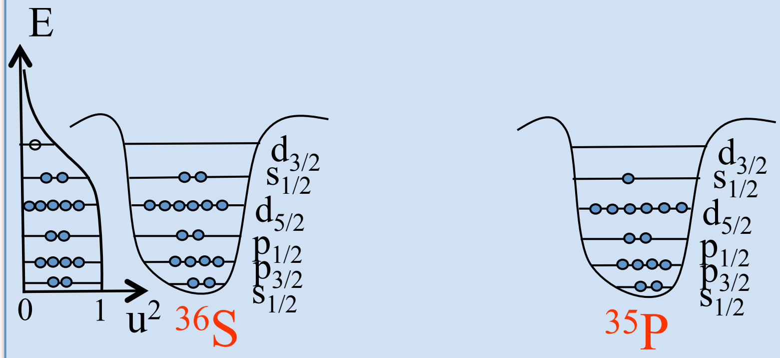
Probing proton densities in ^{36}S

Knock-out reactions at β≈0.4

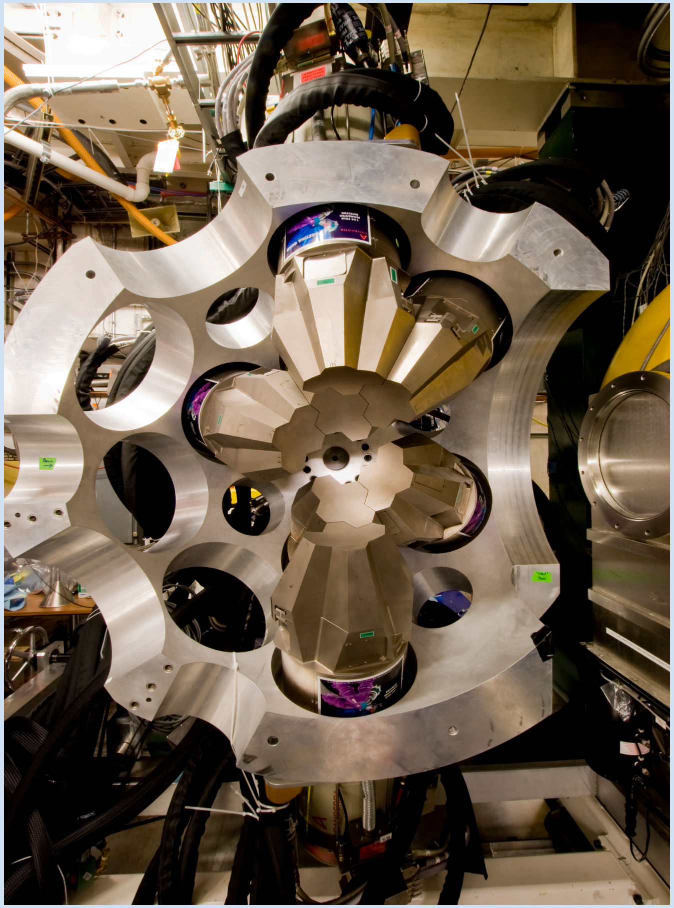
$$\sigma(n,L) = C^2S(j,n,L) \quad \sigma_{sp}(j,S_p)\, R_S$$

occupancy *reaction theory*





Gretina array: segmented Ge detectors



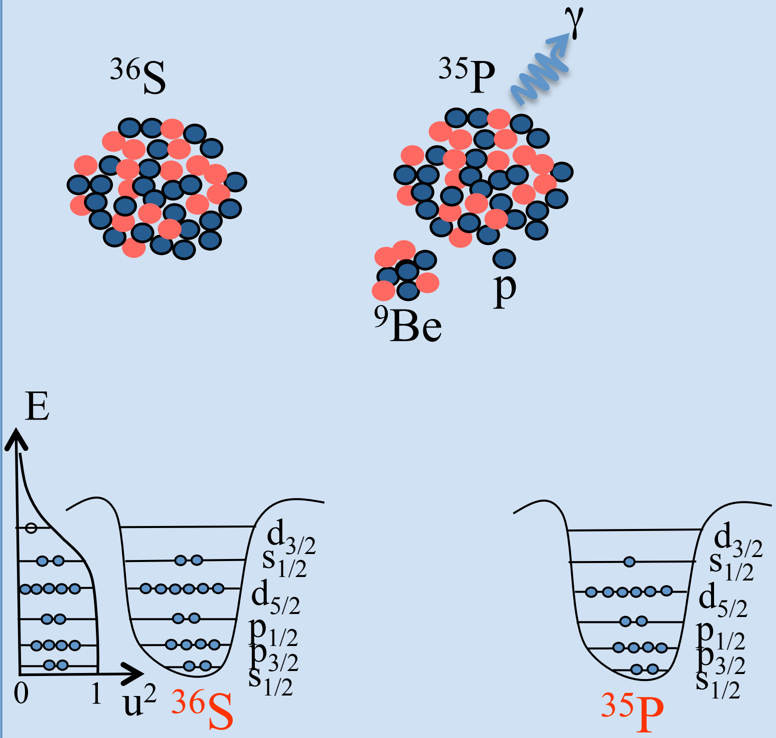
In-flight γ-ray detection-> Doppler corrections

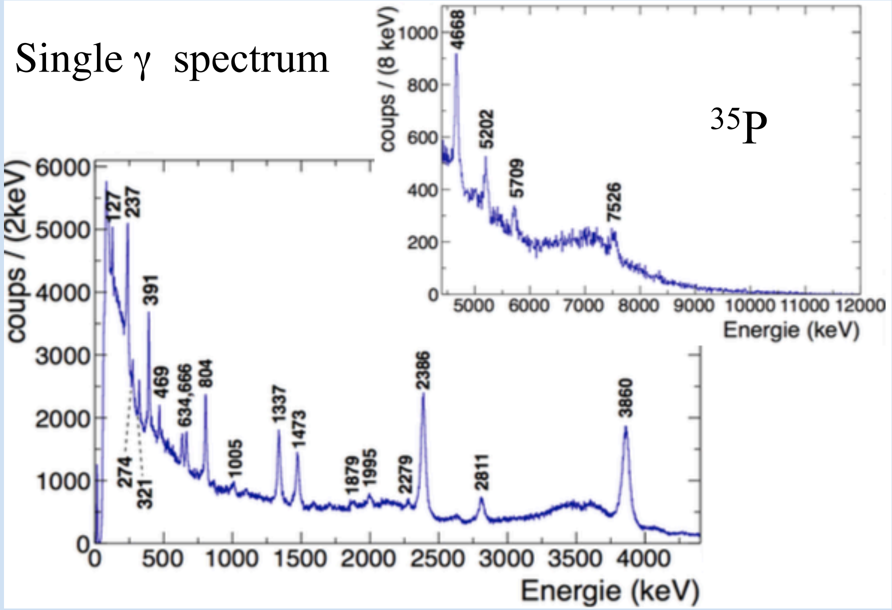
Probing proton densities in ^{36}S

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

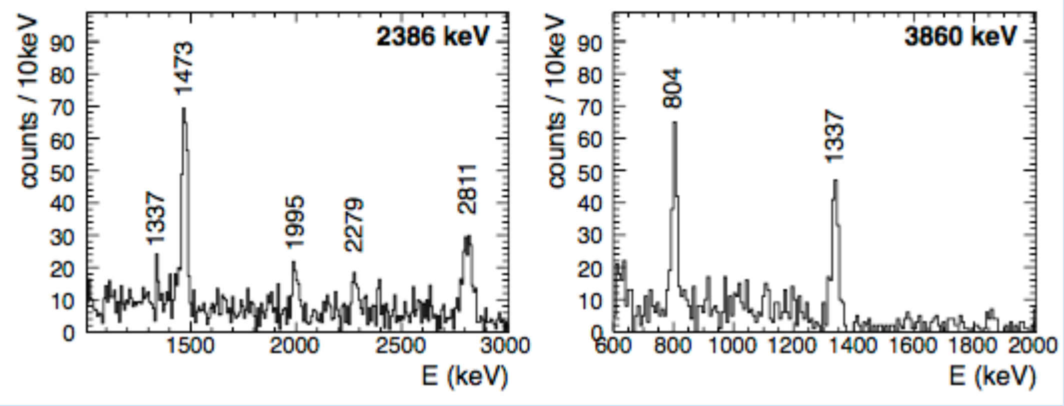
$$\sigma(n,L) = C^2S(j,n,L) \quad \sigma_{sp}(j,S_p)\ R_S$$

occupancy *reaction theory*





γ γ coincidences

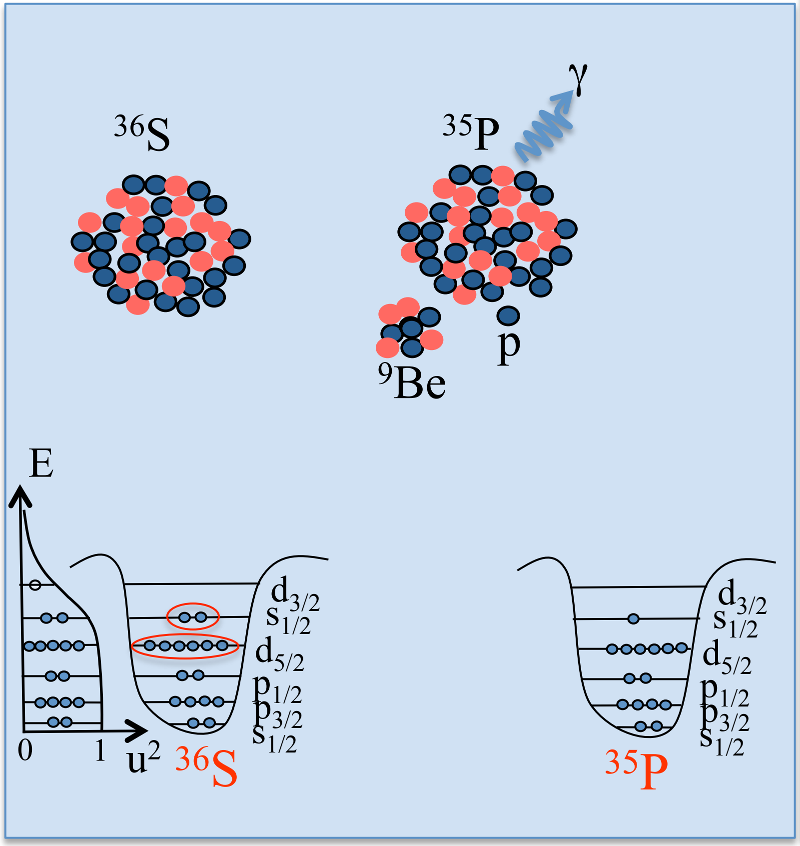


Probing proton densities in ^{36}S

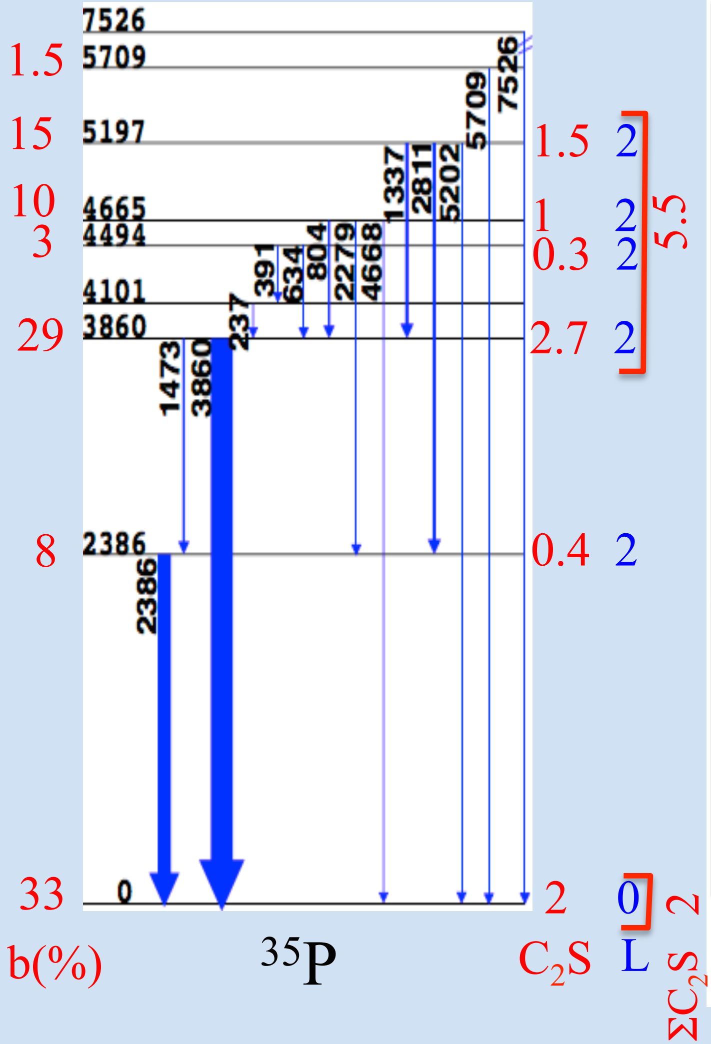
Knock-out reactions at β≈0.4

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

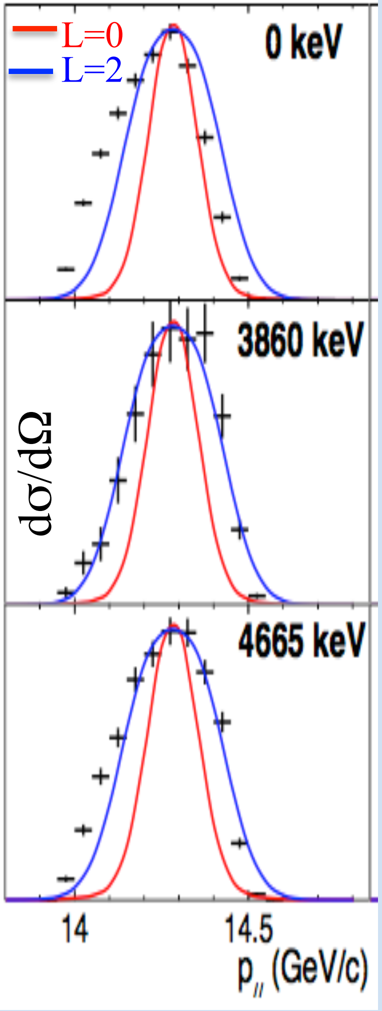
occupancy *reaction theory*



Energy spectrum



Momentum distrib.



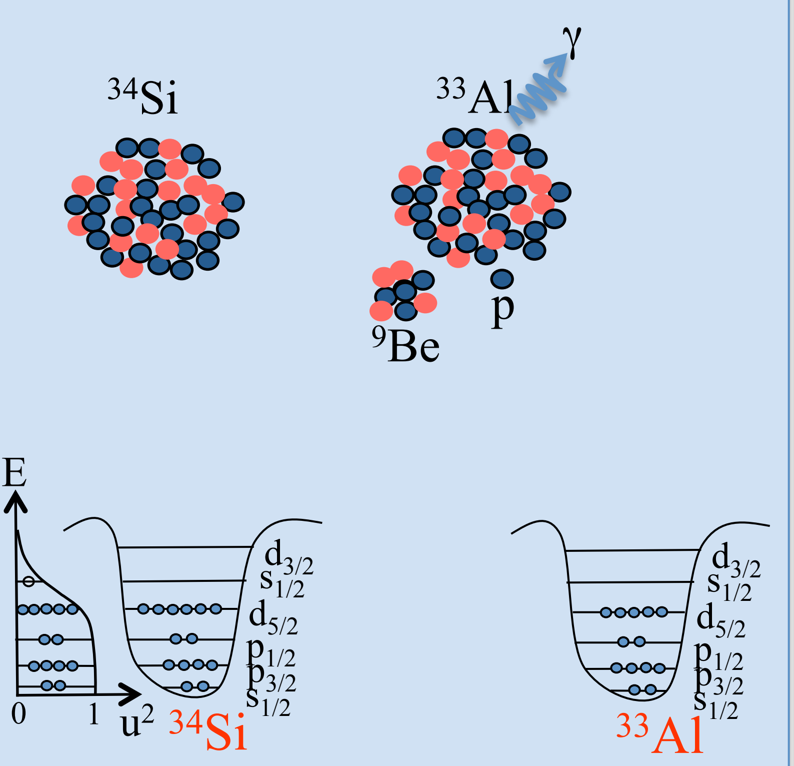
Quasi full filling of $s_{1/2}$ and $d_{5/2}$ orbits (within errors)
Only few scattering to the upper $d_{3/2}$ orbital.

Probing proton densities in ^{34}Si

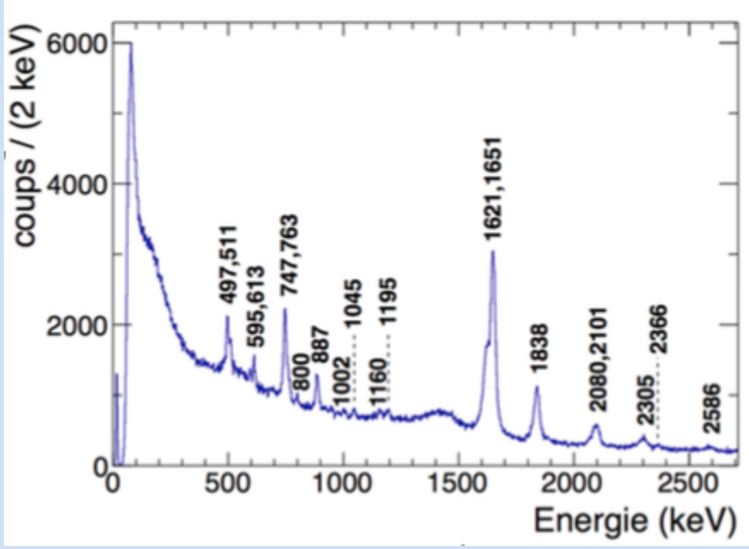
Knock-out reactions at $\beta \approx 0.4$

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

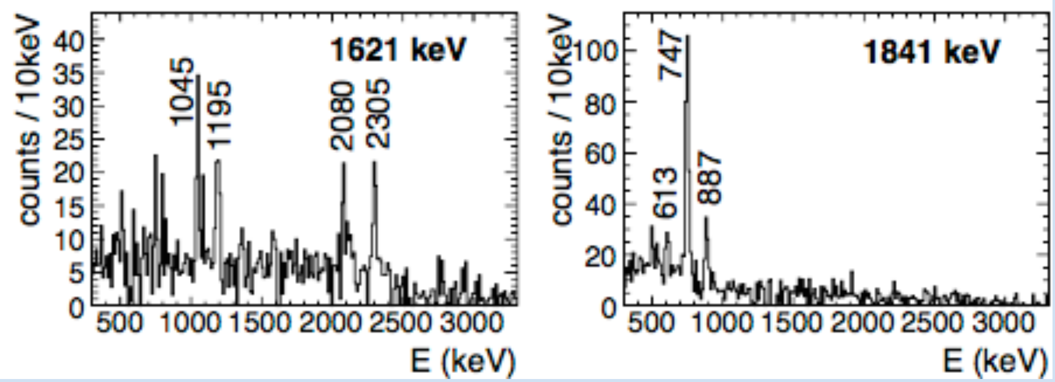
occupancy *reaction theory*



Single γ spectrum



γ γ coincidences

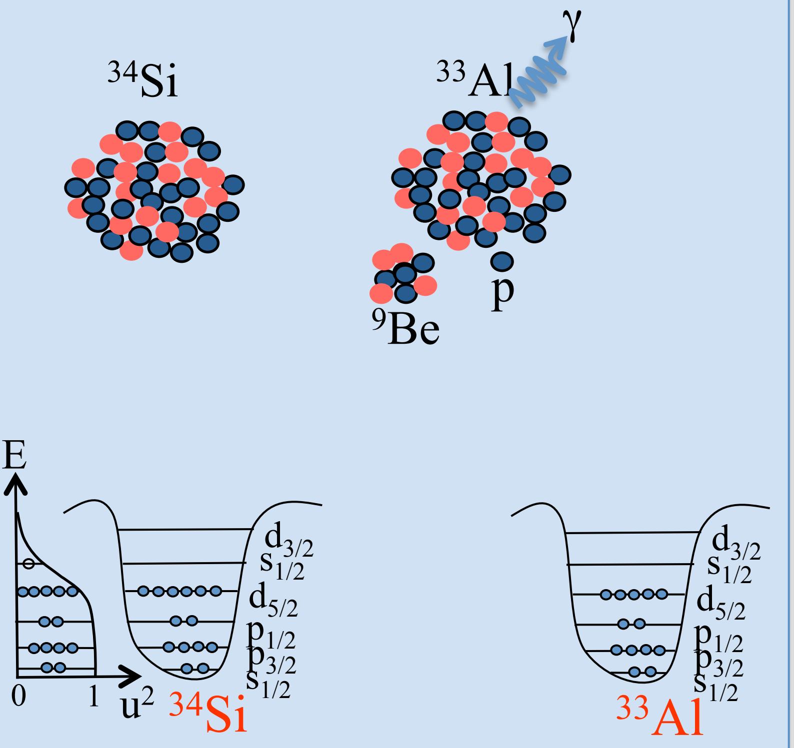


Probing proton densities in ^{34}Si

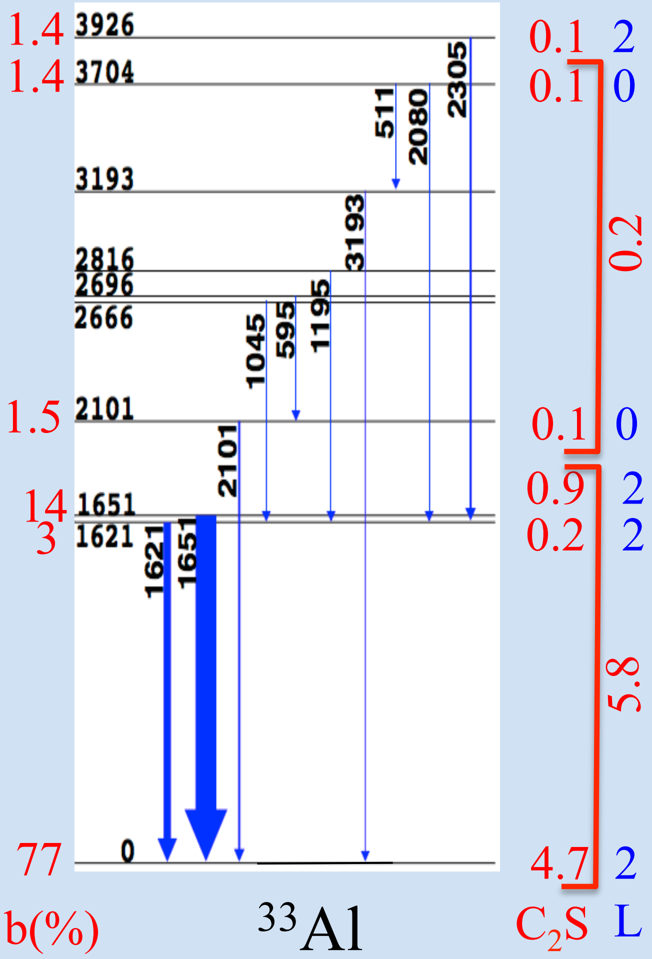
Knock-out reactions at β≈0.4

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

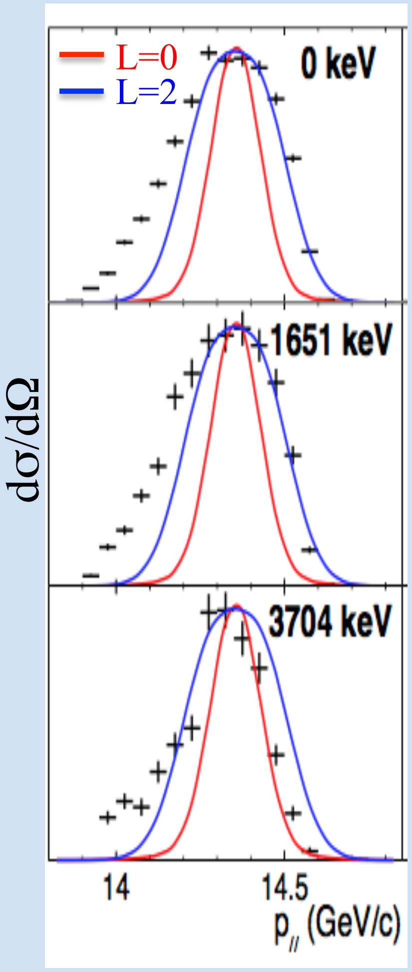
occupancy *reaction theory*



Energy spectrum

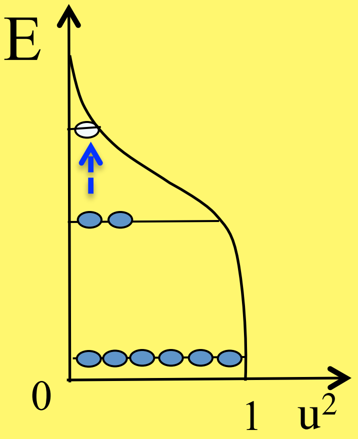


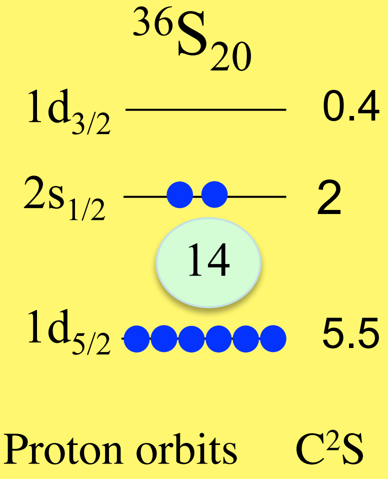
Momentum distrib.



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

Proton density depletion in ^{34}Si




$^{36}S_{20}$

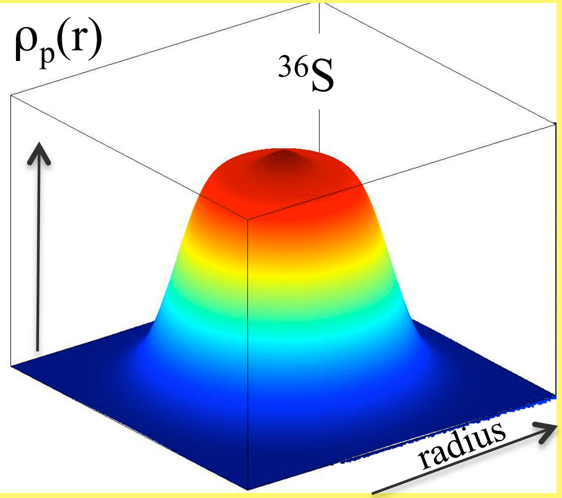
$1d_{3/2}$ 0.4

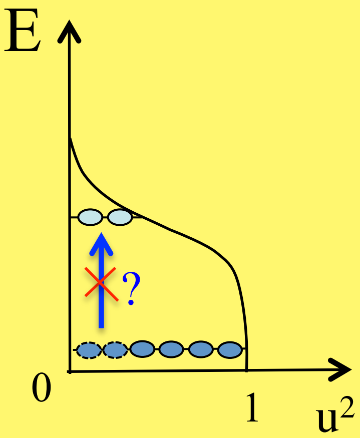
$2s_{1/2}$ 2

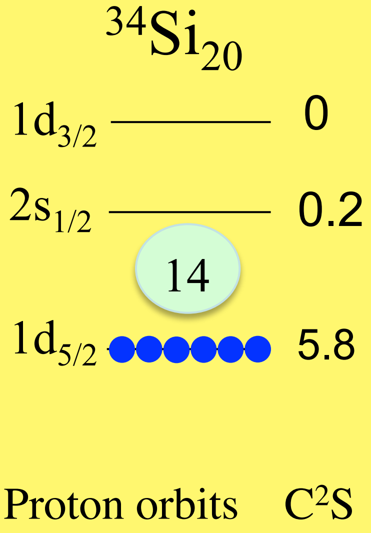
14

$1d_{5/2}$ 5.5

Proton orbits C^2S






$^{34}Si_{20}$

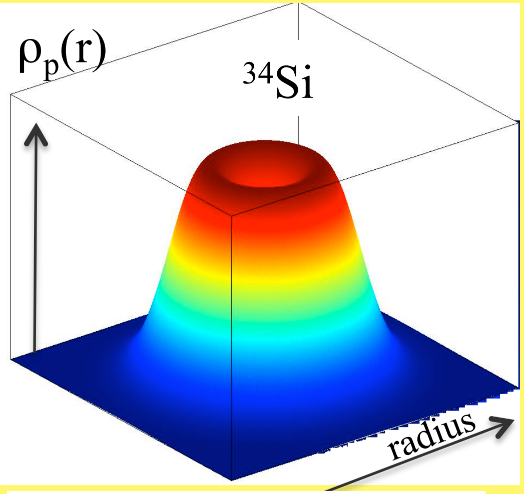
$1d_{3/2}$ 0

$2s_{1/2}$ 0.2

14

$1d_{5/2}$ 5.8

Proton orbits C^2S



J.P. Ebran DDME2 interaction

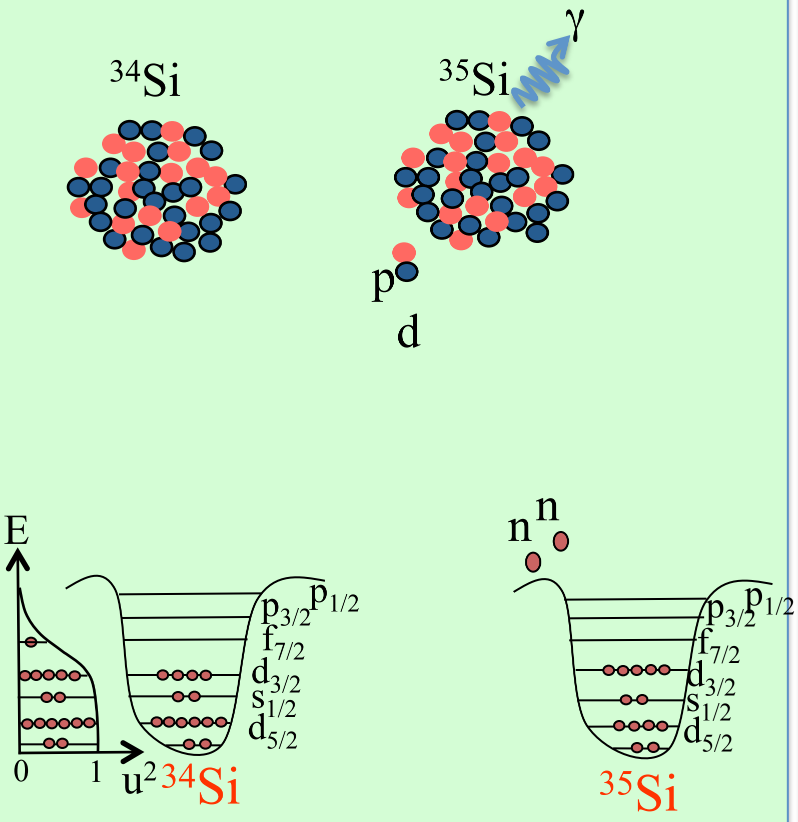
Large change in $2s_{1/2}$ occupancy (1.8) -> central proton depletion in ^{34}Si -> 'bubble' nucleus
Error bar of about 20%.

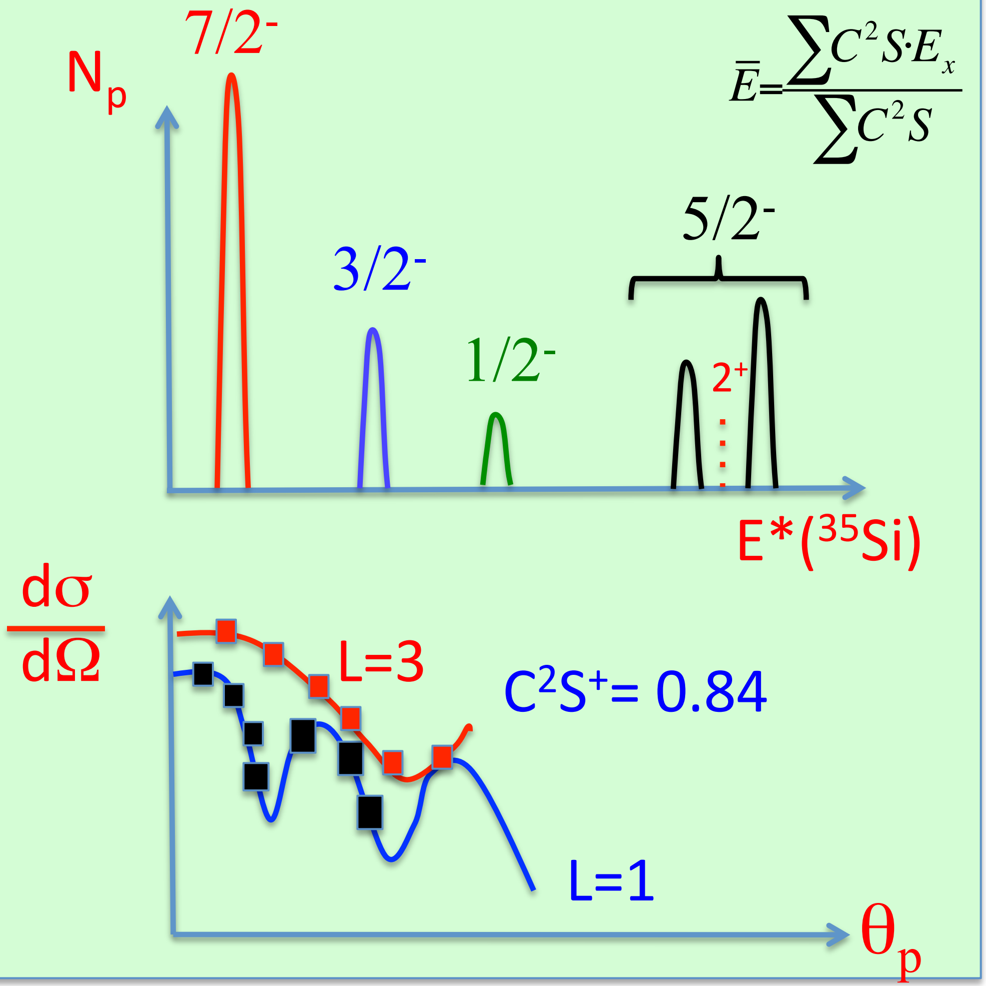
^{34}Si(d,p) reaction in inverse kinematics

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

$$\frac{d\sigma(n,L,\theta)}{d\Omega} = (2j+1)\, \underbrace{C^2S^+}_{\textit{vacancy}} \underbrace{\frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}}_{\textit{reaction theory}}$$

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





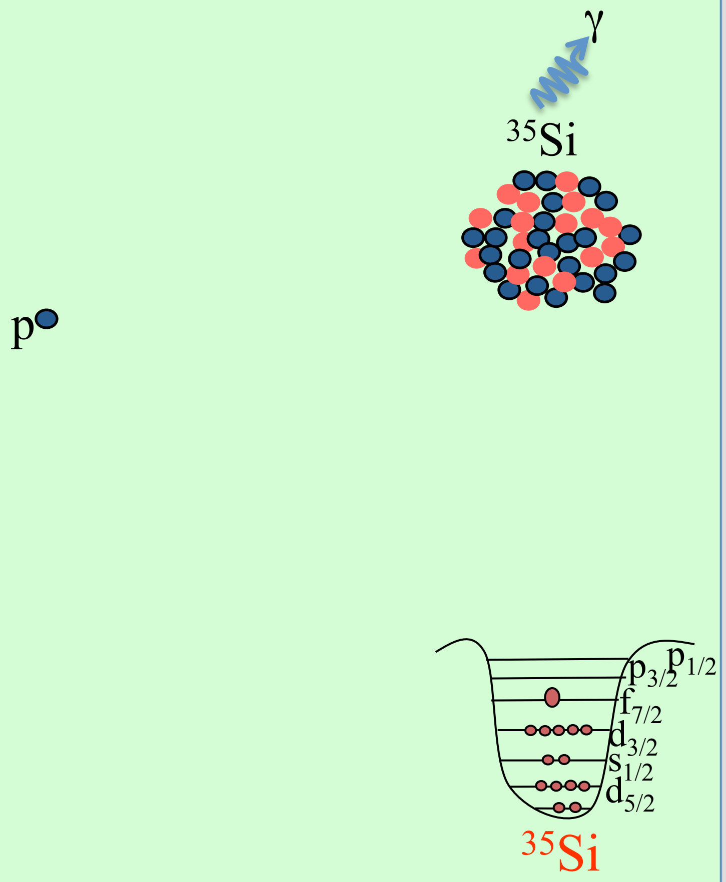
^{34}Si(d,p) reaction in inverse kinematics

Transfer reaction (d,p) at β≈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

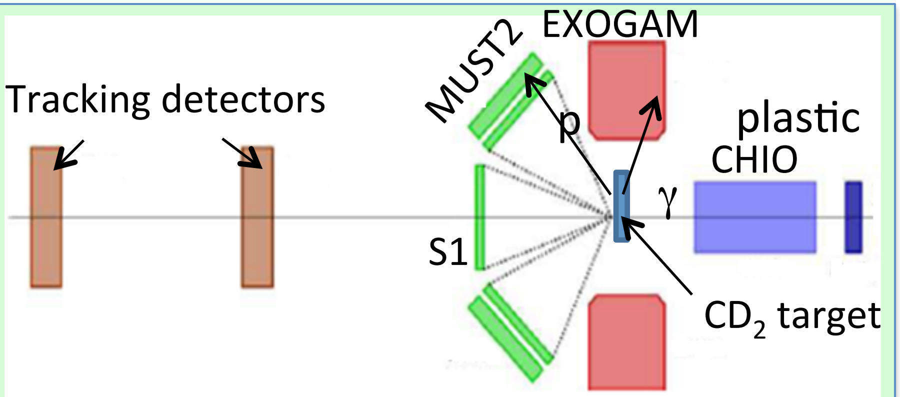


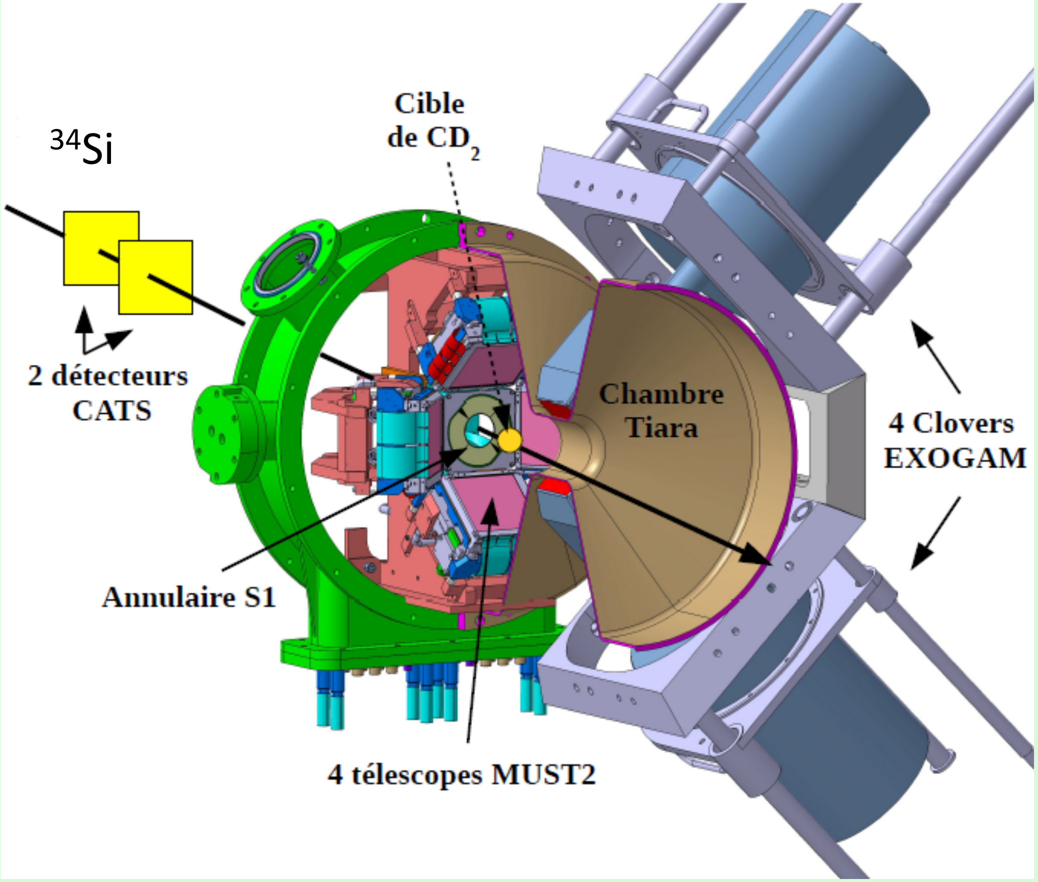
^{34}Si

10^5pps

20A.MeV

GANIL

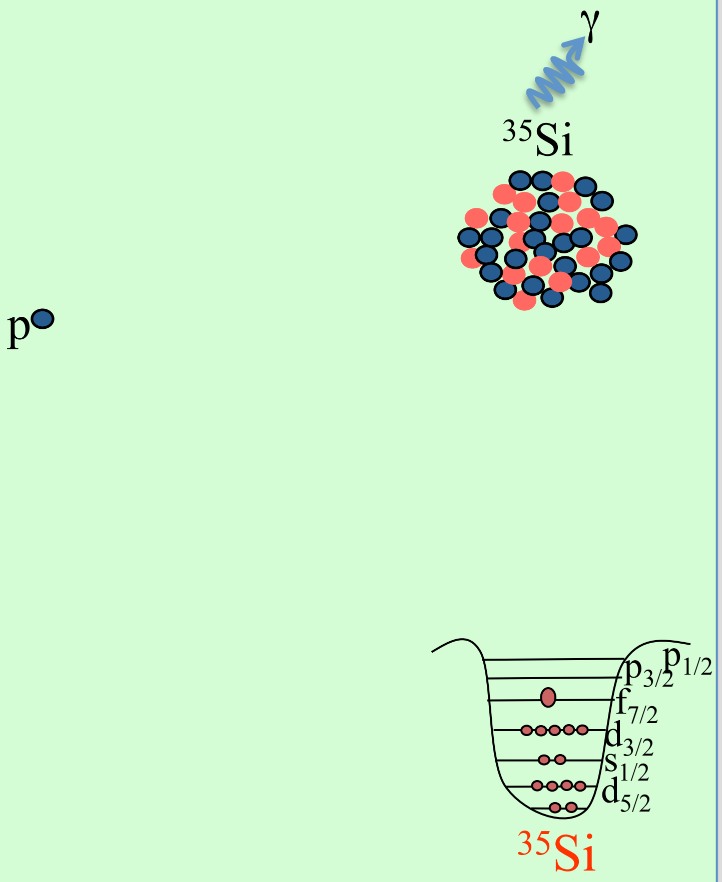




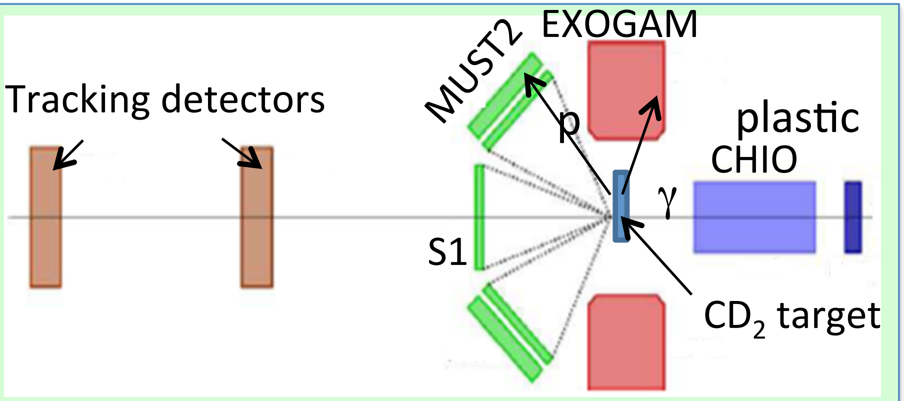
^{34}Si(d,p) reaction in inverse kinematics

Transfer reaction (d,p) at β≈0.15

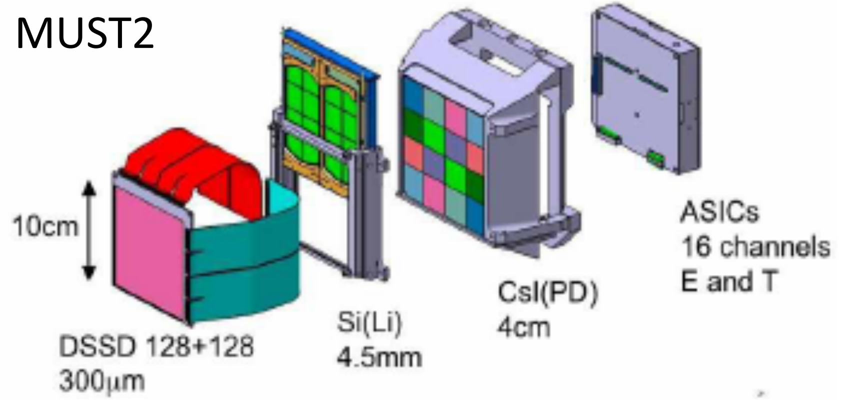
$$\frac{d\sigma(n,L,\theta)}{d\Omega} = \underset{\text{vacancy}}{(2j+1)\, C^2S^+} \underset{\text{reaction theory}}{\frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}}$$

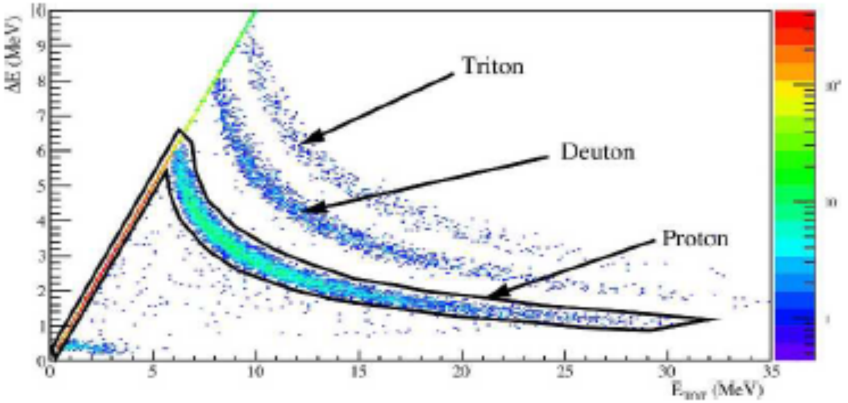


^{34}Si
10^5pps
20A.MeV
GANIL



MUST2



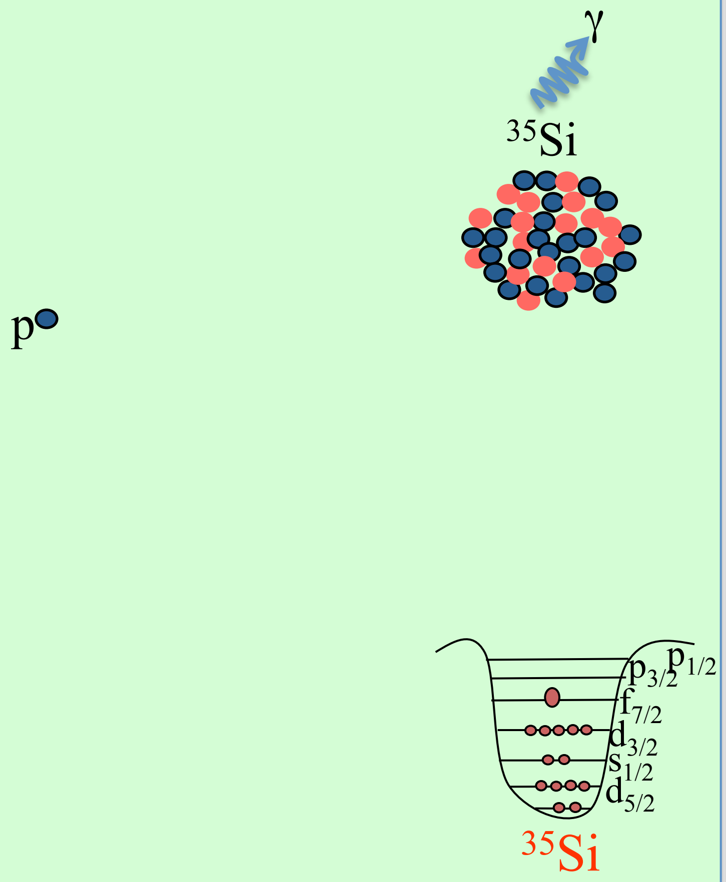


^{34}Si(d,p) reaction in inverse kinematics at GANIL

Transfer reaction (d,p) at β≈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*

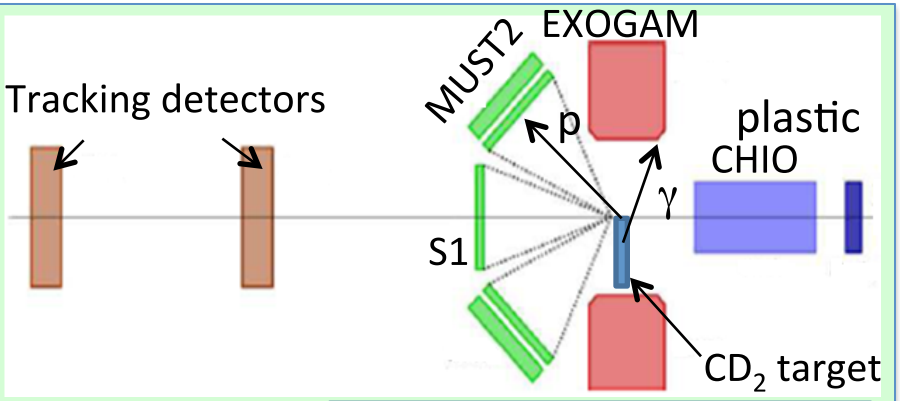


^{34}Si

10^5pps

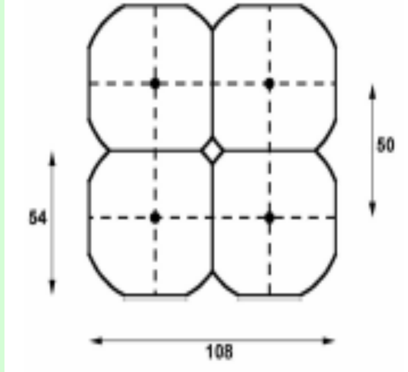
20A.MeV

GANIL

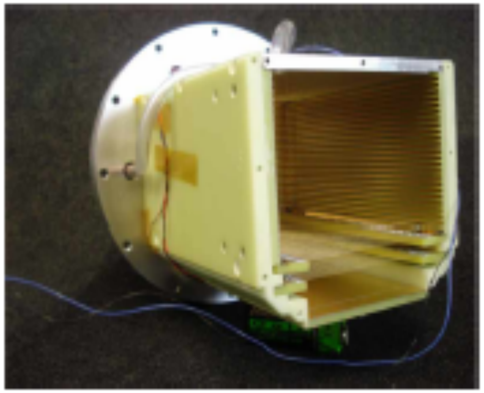


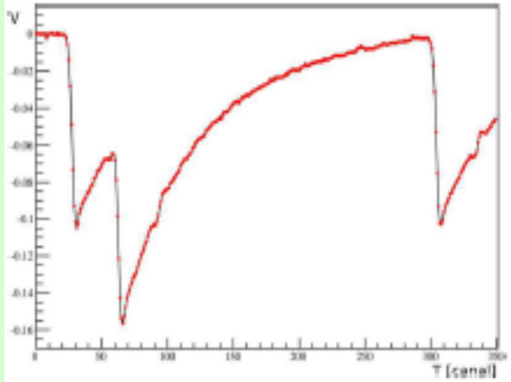
Annular detector (S1)

EXOGAM



Ionization chamber (CHIO)



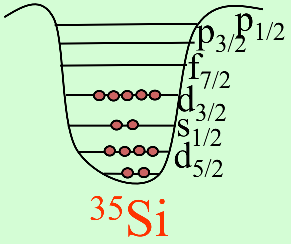


^{34}Si(d,p) reaction in inverse kinematics

Transfer reaction (d,p) at β≈0.15

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

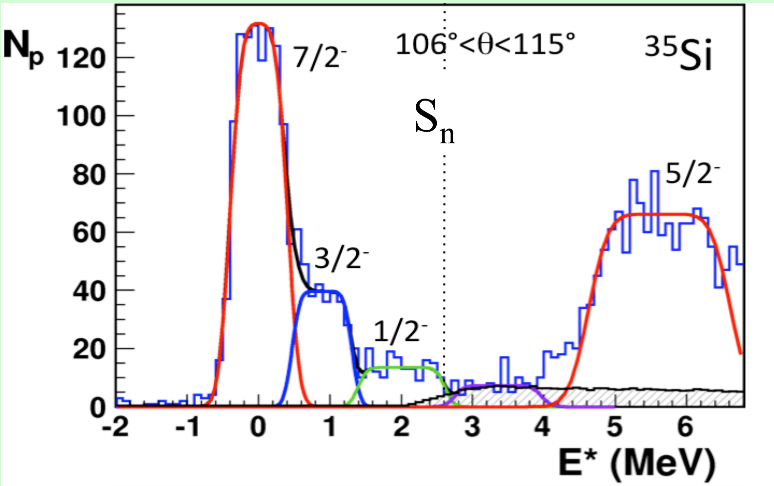
vacancy *reaction theory*

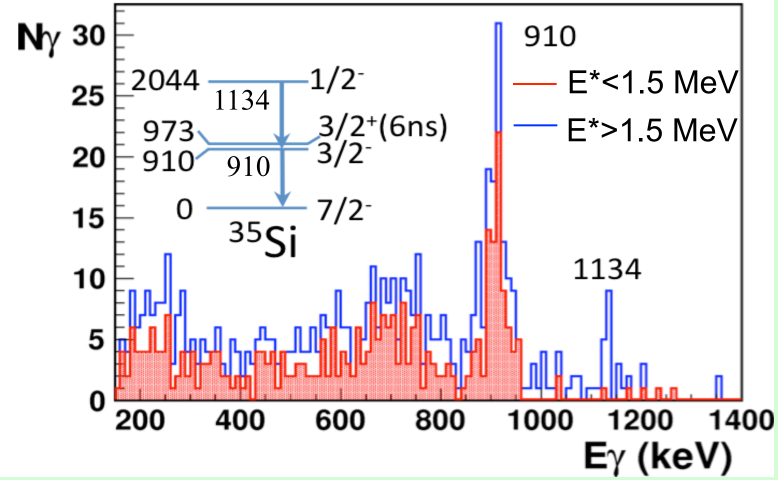


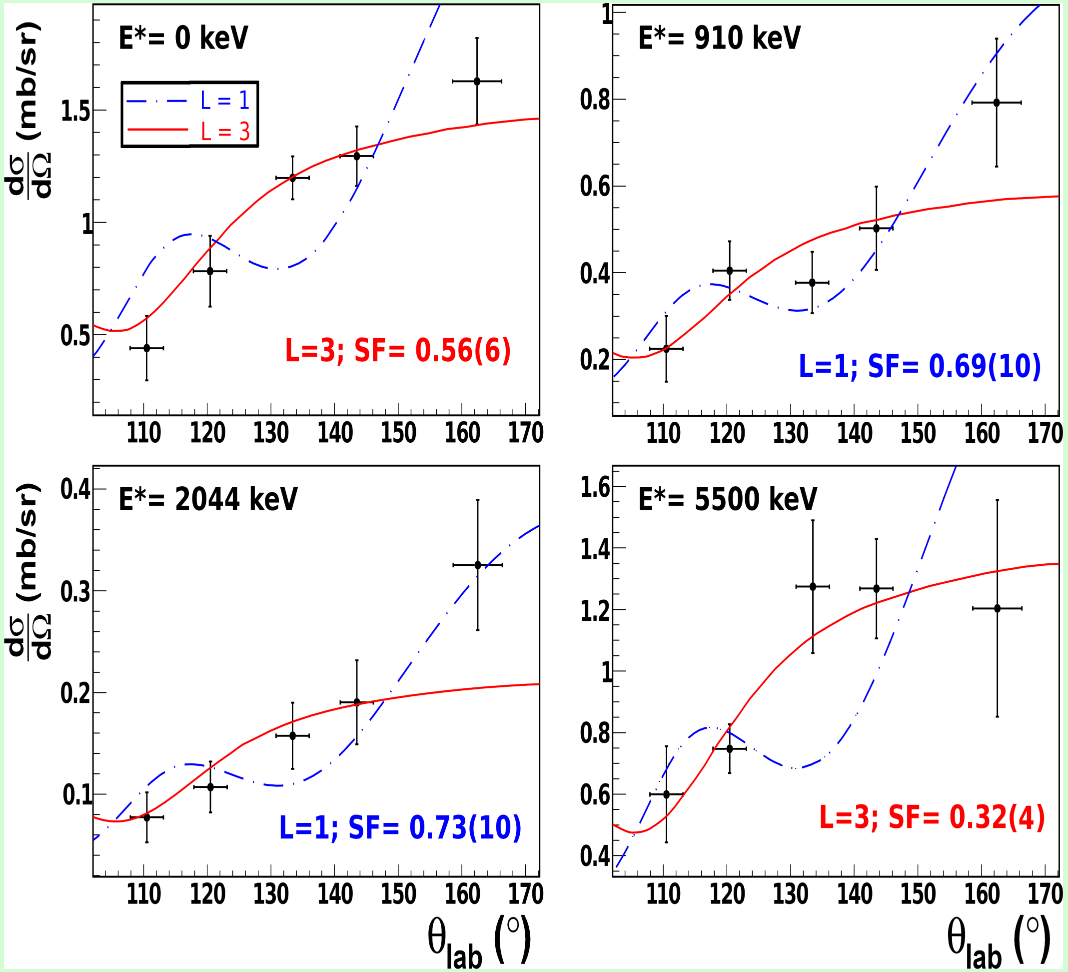
E_p-> (binding) energy of orbit

θ_p-> orbital momentum L

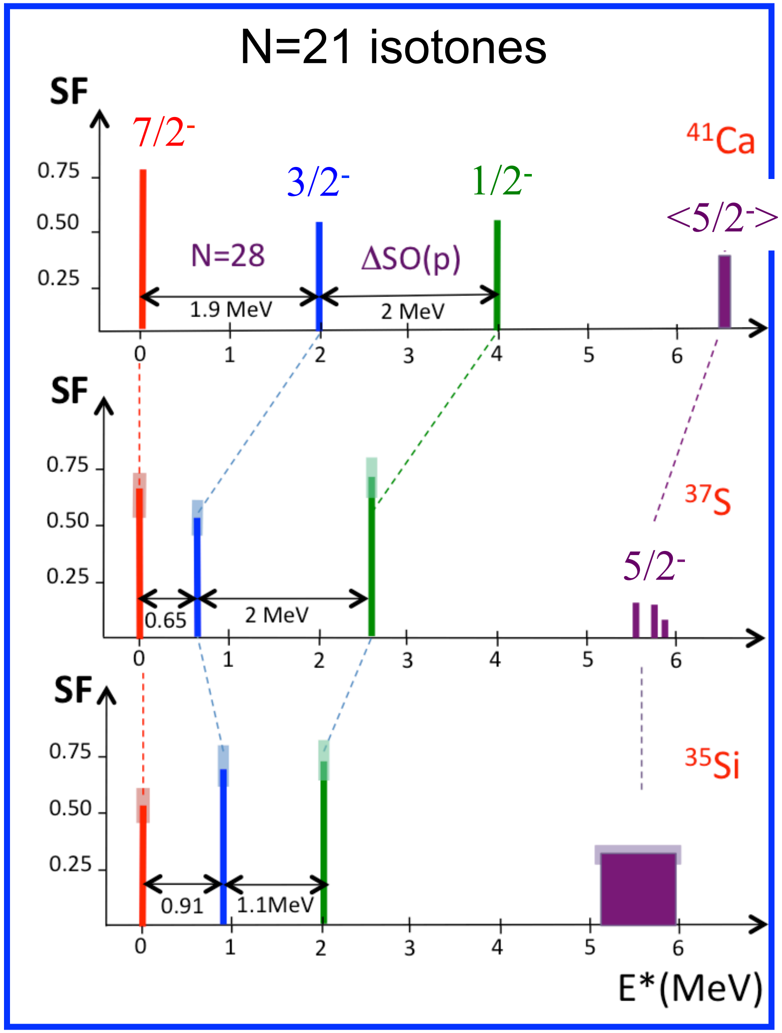
σ-> vacancy of the orbit

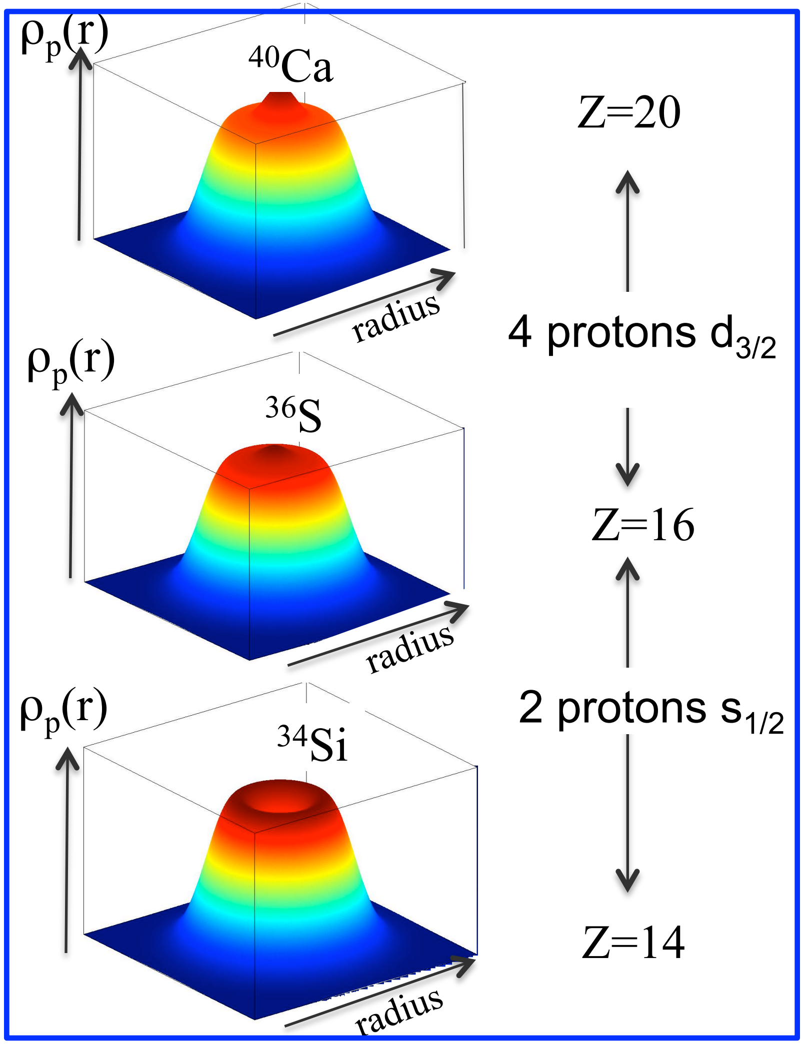






Evolution of the $p_{3/2}$-$p_{1/2}$ SO splitting





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

- END OF PART I