Study of the spin orbit force using a bubble nucleus

O. Sorlin (GANIL)

I . General introduction to the atomic nucleus
    Charge density, nuclear orbits
    Shell gaps-> magic nuclei

II. The spin orbit force
    History
    Mean field theories
    Implications to explosive stellar nucleosynthesis
        super heavy nuclei

III. Probing the spin orbit force
    The use of a bubble nucleus^{34}Si
    Production of ^{34}Si at the GANIL accelerator
    Determine the neutron SO splitting using ^{34}Si(d,p)^{35}Si
    Results

IV Conclusions/ Perspectives

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

Russbach, March 2014

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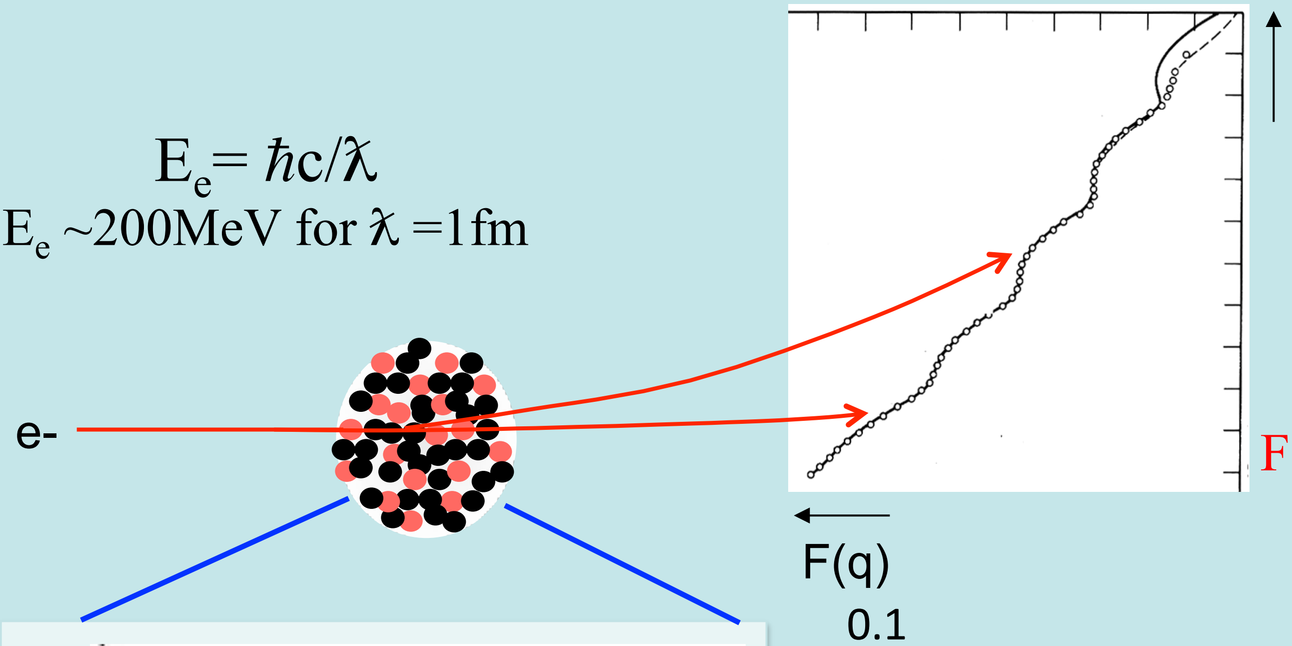
Charge density of the nucleus : ρ(r)

$$E_e = \hbar c/\bar{\lambda}$$

E_e ~200MeV for $\bar{\lambda}$ =1fm

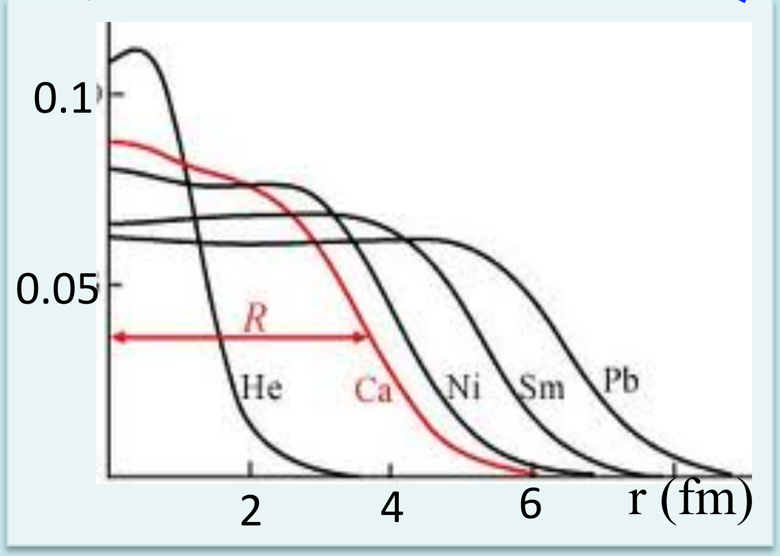


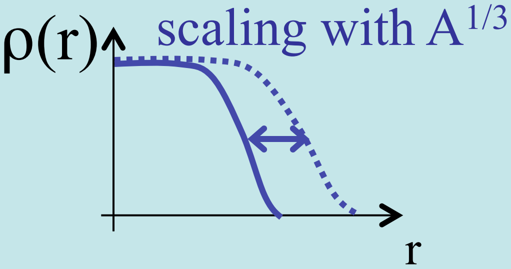
q = transferred momentum

At small **q**

F(q) ~Ze $(1-q^2/6 <r^2>)$

Large **q** : central density distribution



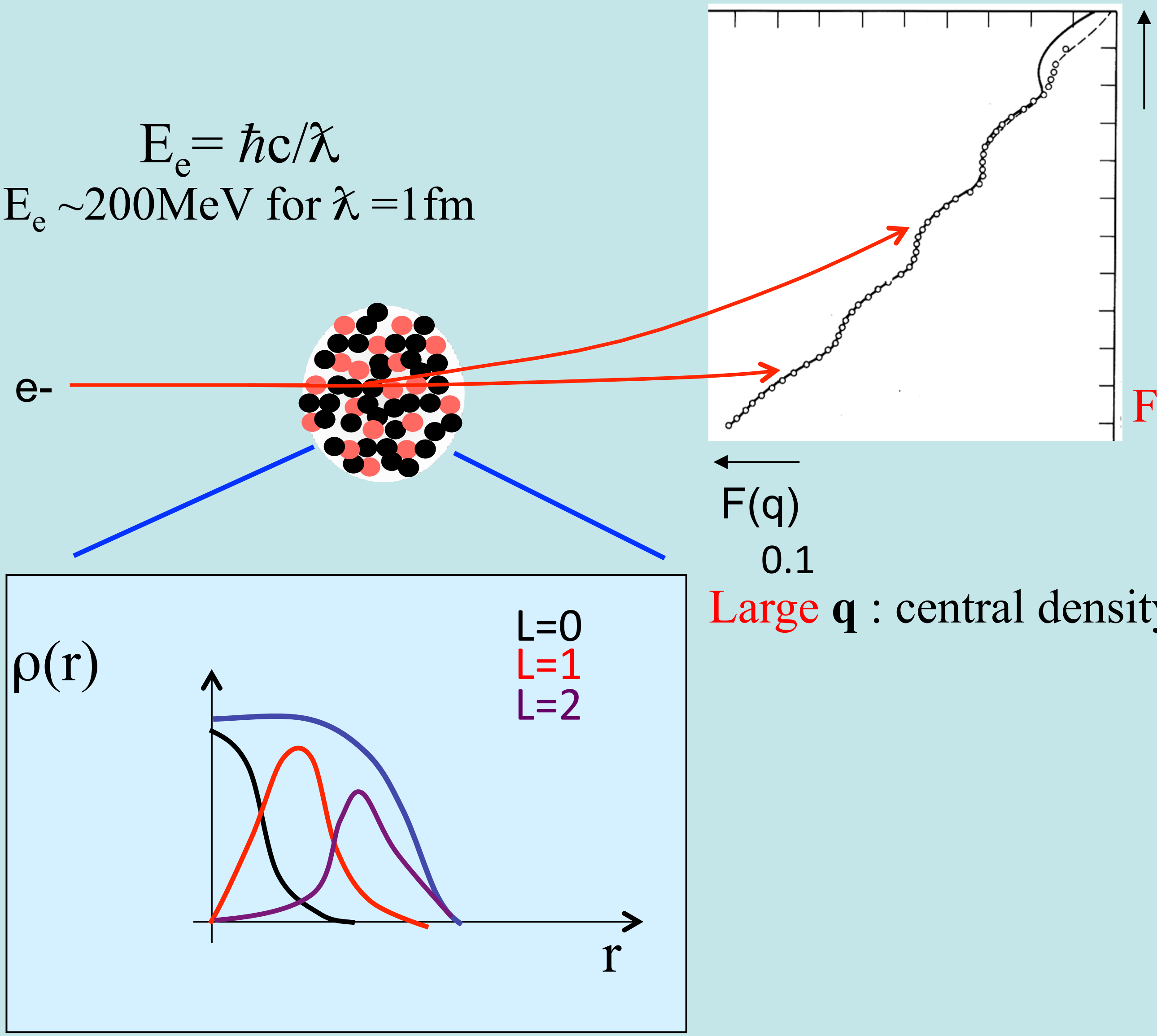


Saturation of nuclear forces

Charge density of the nucleus : ρ(r)

$E_e = \hbar c/\lambdabar$

$E_e \sim 200\text{MeV}$ for $\lambdabar = 1\text{fm}$



q = transferred momentum

At small **q**

$F(q) \sim Ze\,(1-q^2/6\,\langle r^2\rangle)$

Large **q** : central density distribution

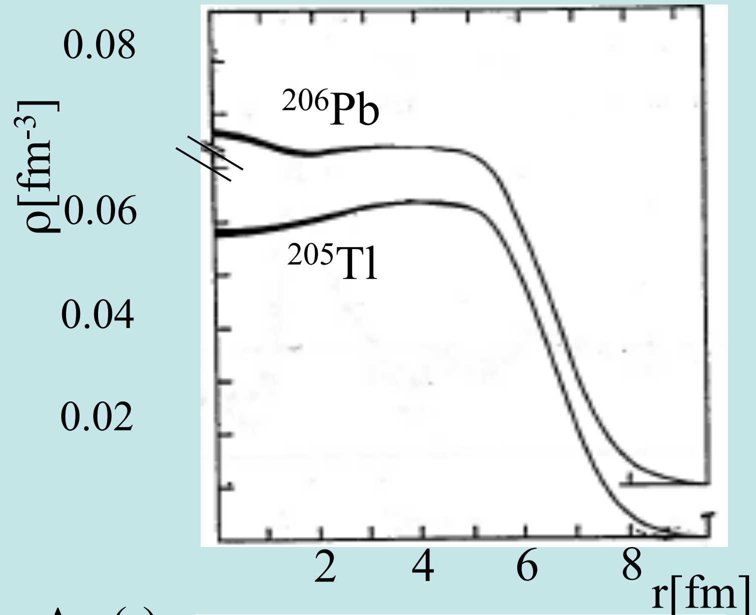
r

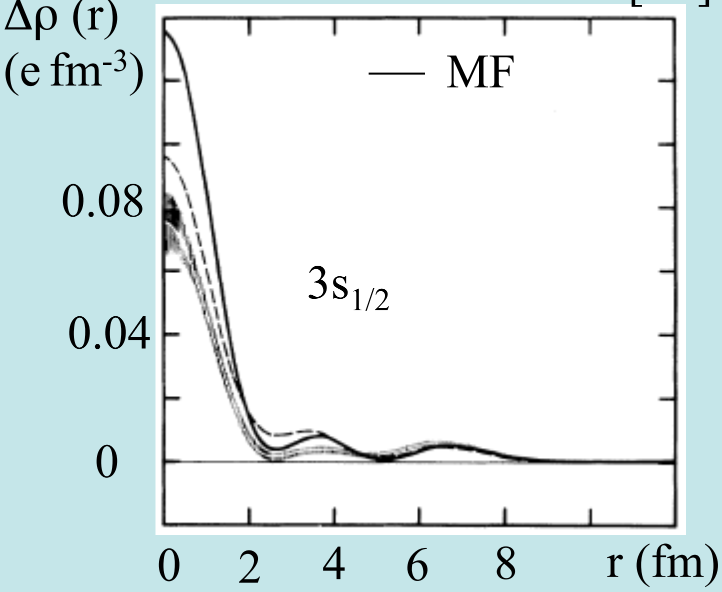
Charge density depletion in the center of the ^{205}Tl nucleus

Cavendon PRL (1982)

Charge density depletion due to
the change in $3s_{1/2}$ occupancy by 0.7 proton

Independent particle model works well
also in the interior of nucleus





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

Orbital labelling

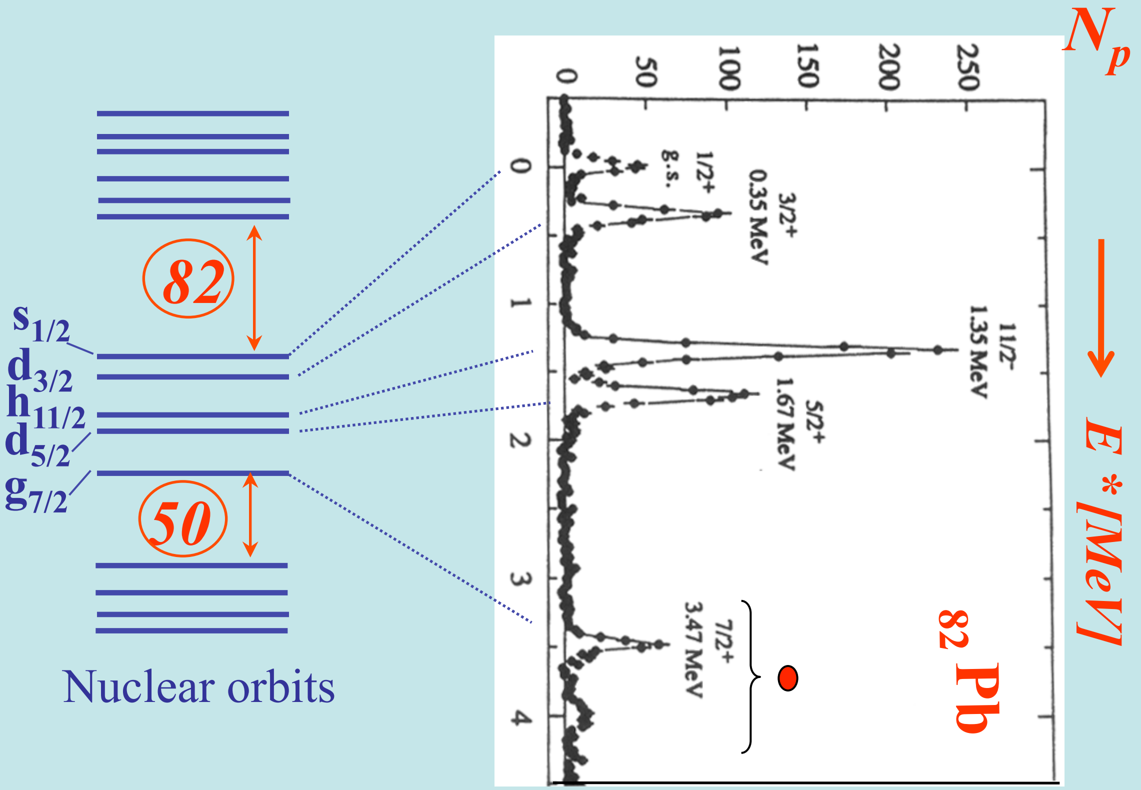
n,L,J

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 scales with orbit occupancy
-> Mixing with collective states at high E* ●
-> Study limited (so far) to STABLE nuclei

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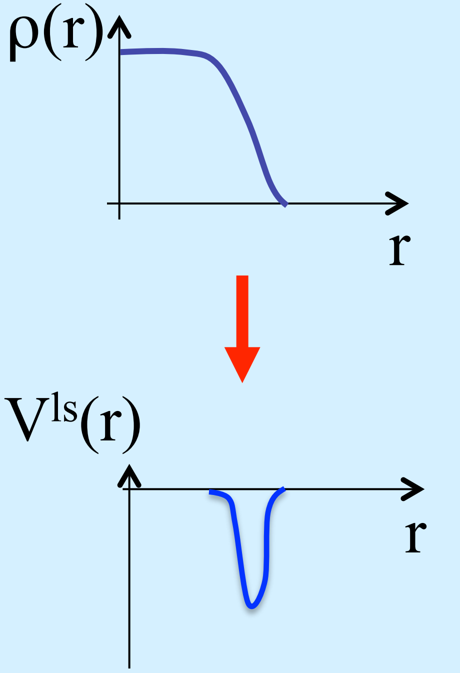
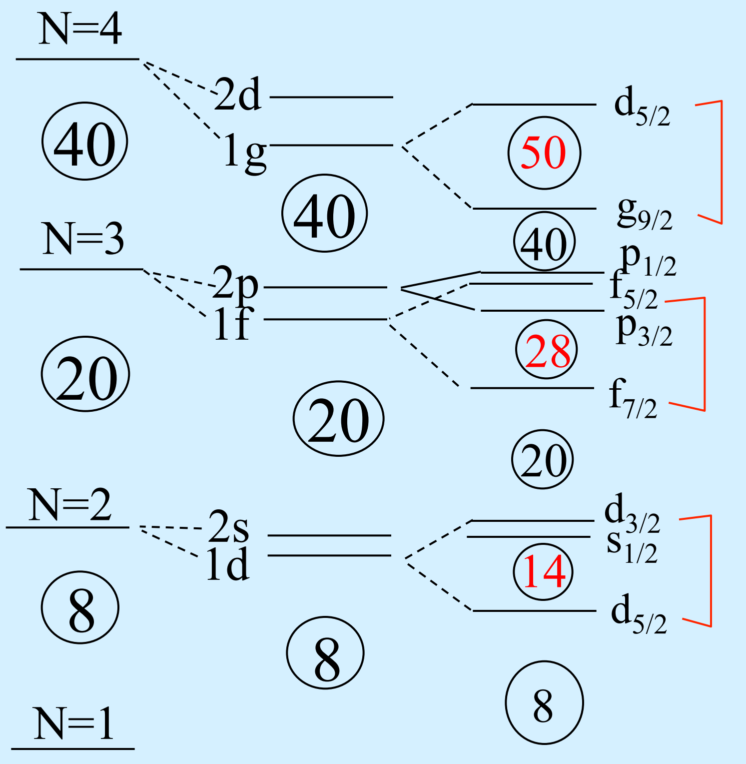
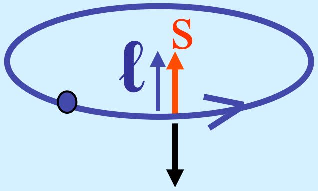
Magic nuclei and the spin-orbit interaction

$$V^{\ell s}(r) = -W \frac{\partial \rho(r)}{\partial r} \vec{\ell}\cdot\vec{s}$$





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

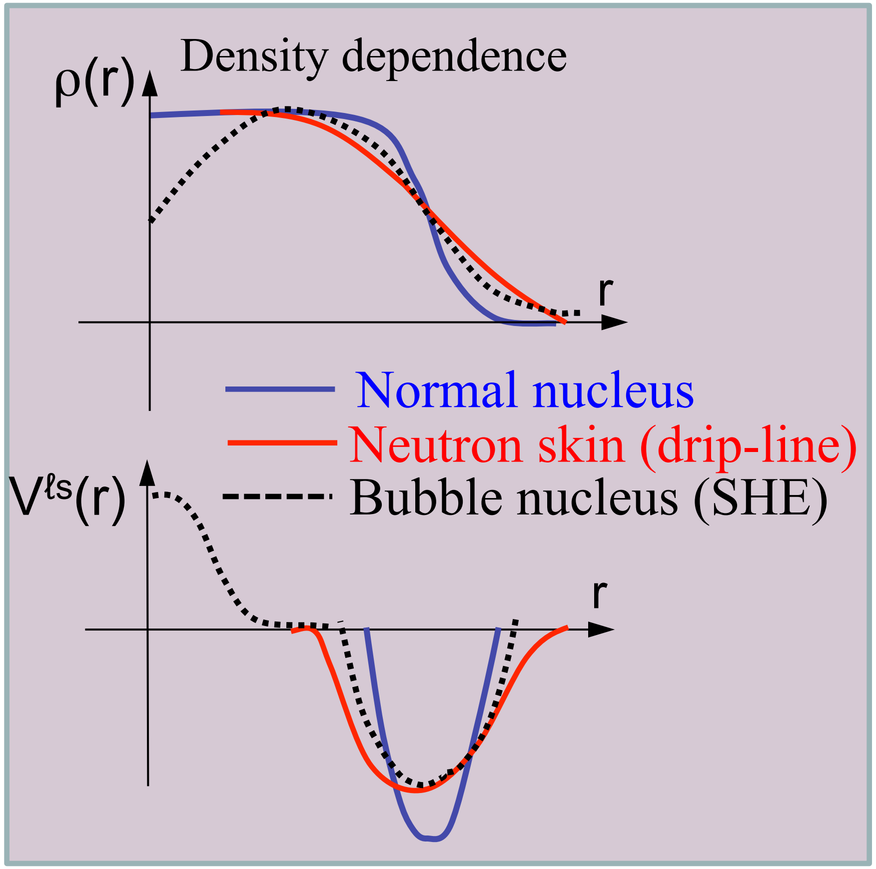


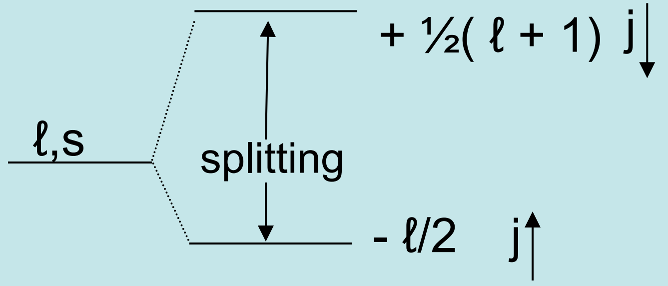
Spin Orbit
6, 14, 28, 50, 82, 126

M. Goppert-Mayer
Nobel prize 1949

The spin orbit (SO) interaction in Mean Field models

$$V_n^{\ell s}(r) = -\left[W_1 \frac{\partial \rho_n(r)}{\partial r} + W_2 \frac{\partial \rho_p(r)}{\partial r}\right] \vec{\ell}\cdot\vec{s}$$





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

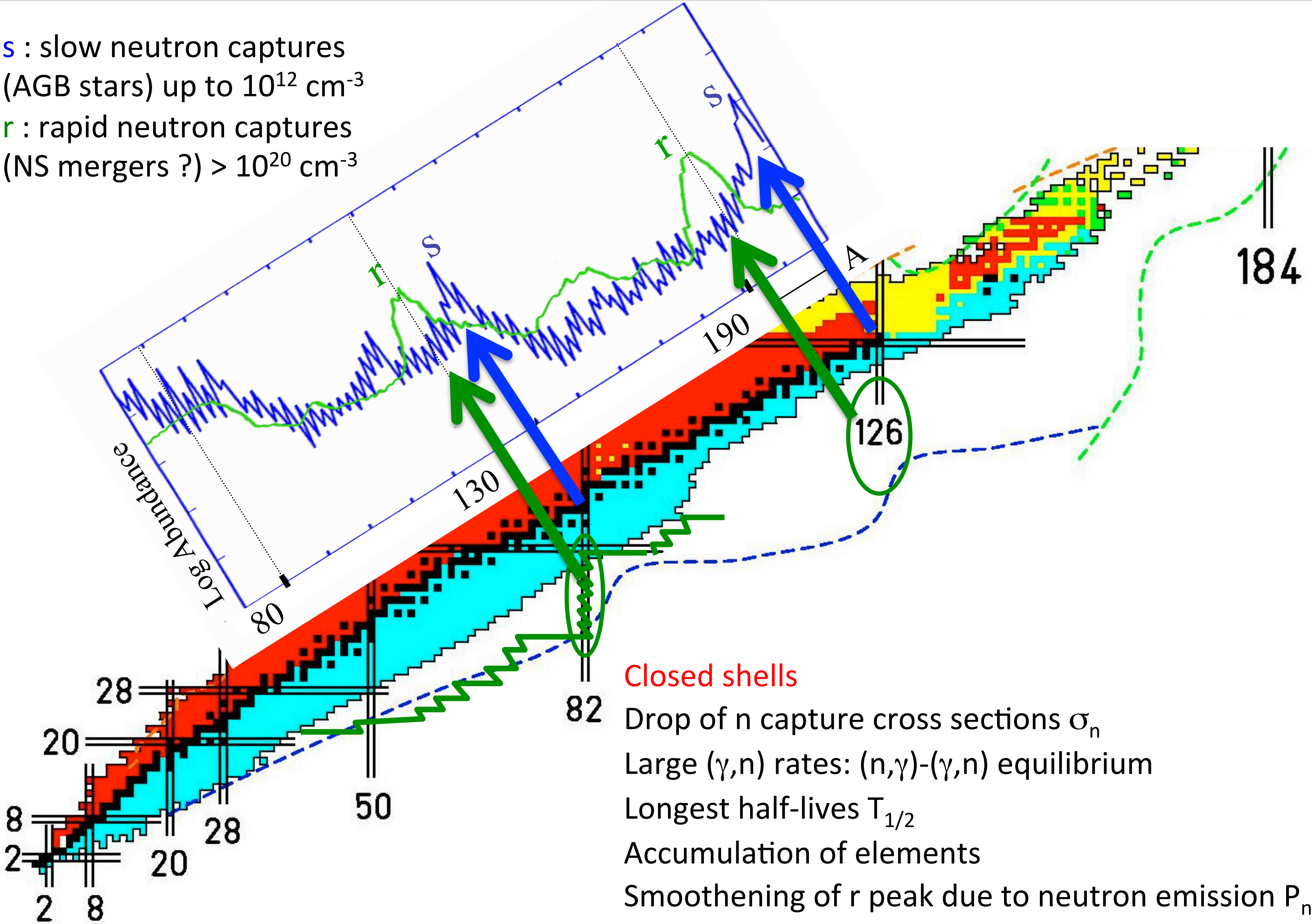
Density and isospin dependence of the SO interaction not yet known/contrained

Important for 1- r process 2- bubble nuclei 3- superheavy nuclei

Shell closures and neutron captures nucleosynthesis

s : slow neutron captures (AGB stars) up to 10^{12} cm^{-3}

r : rapid neutron captures (NS mergers ?) > 10^{20} cm^{-3}



Closed shells

Drop of n capture cross sections σ_n

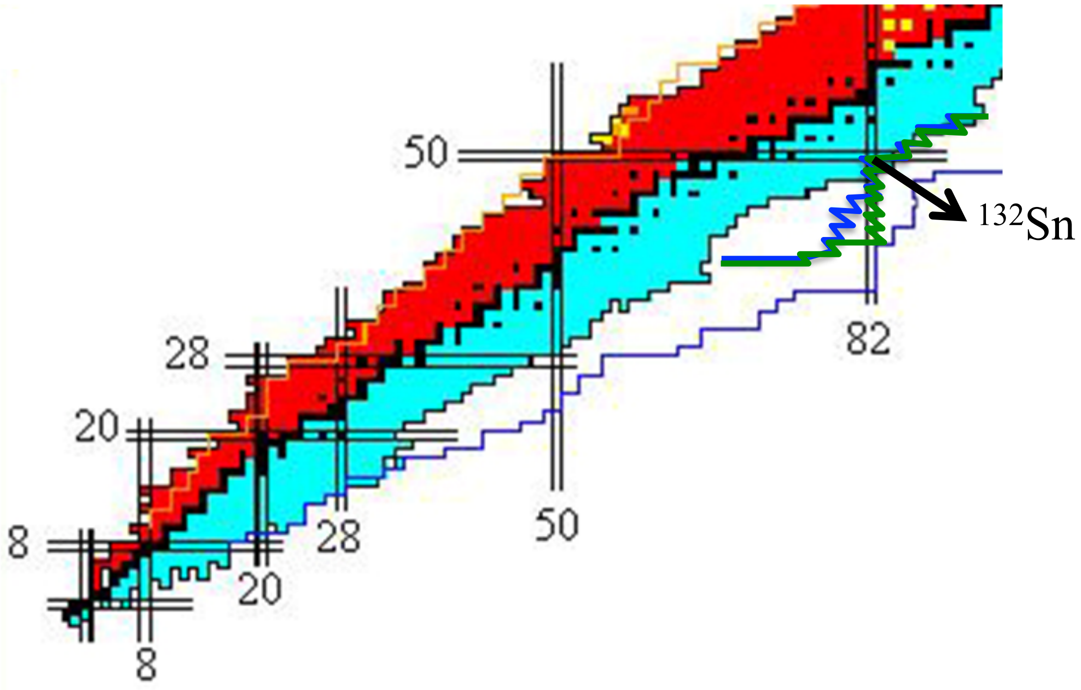
Large (γ,n) rates: (n,γ)-(γ,n) equilibrium

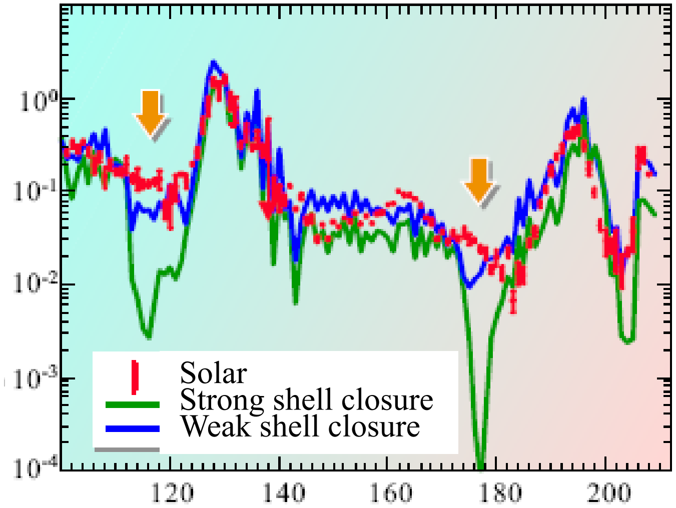
Longest half-lives $T_{1/2}$

Accumulation of elements

Smoothening of r peak due to neutron emission P_n

Influence of nuclear structure on the abundance of elements



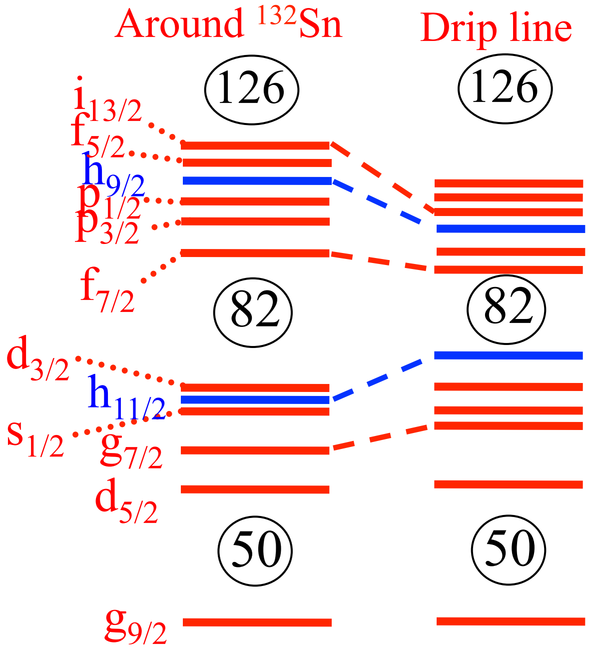


Adapted from Pfeiffer, Kratz et al.

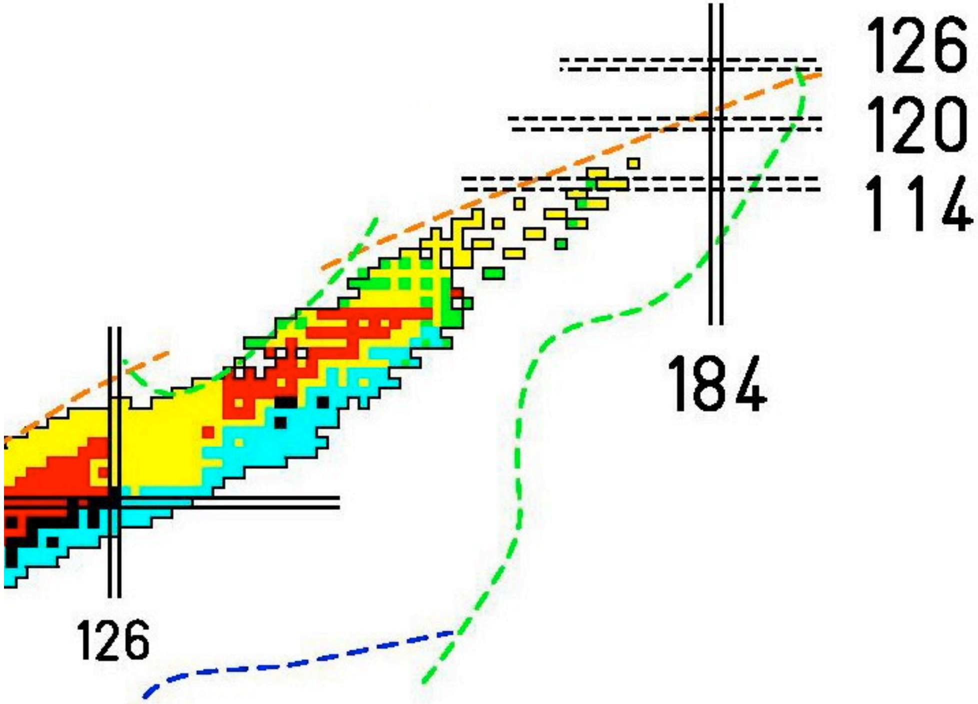
Location and shape of r process peaks does depend on the evolution of shell gaps (but not only !)

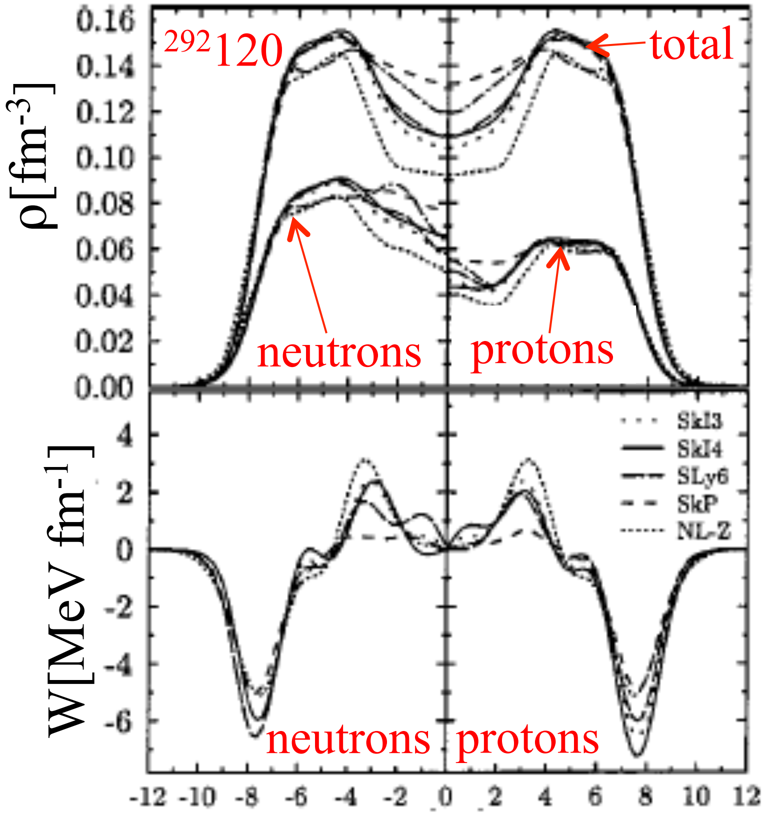
Need new accelerators to produce/study nuclei further from stability

Probe the spin-orbit interaction using other data



Quest for superheavy elements





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

SHE display central density depletions at certain proton and neutron numbers

Reduction of the SO splittings depends on isospin dependance of SO

Location of ‘island of stability’ depends on models

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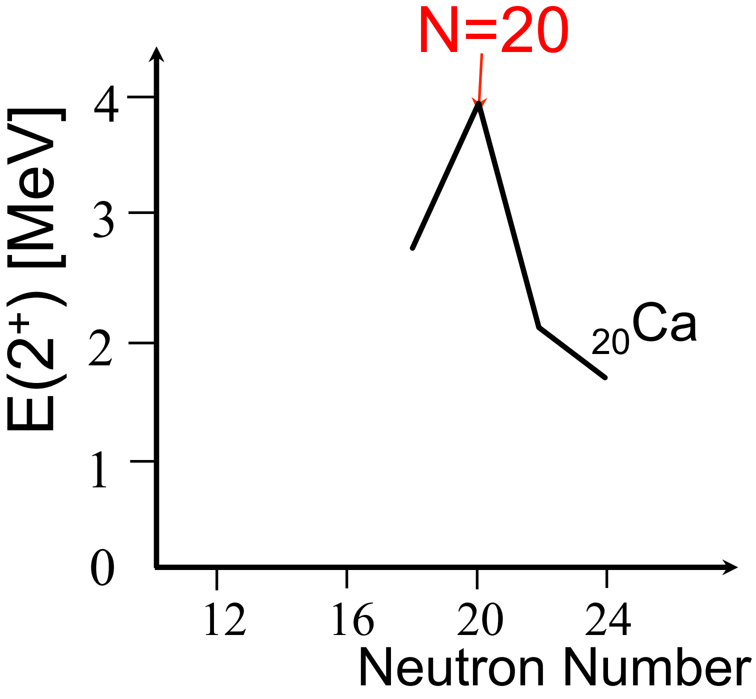
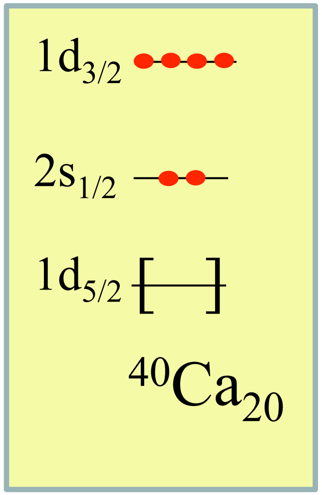
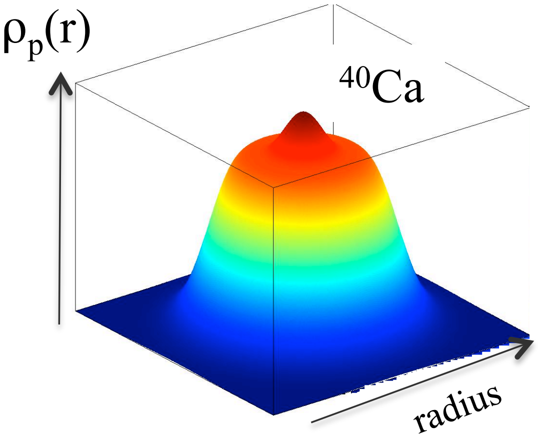
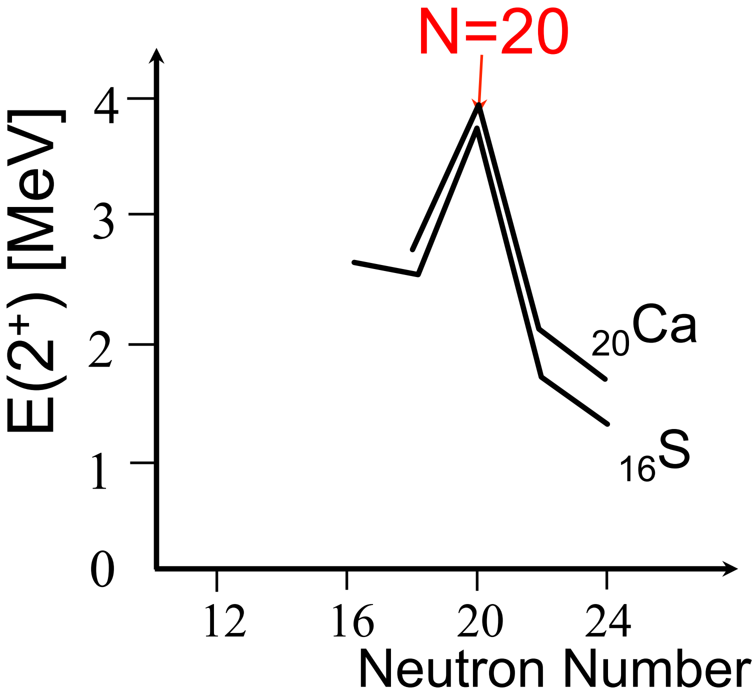
Finding a bubble nucleus in nature ….

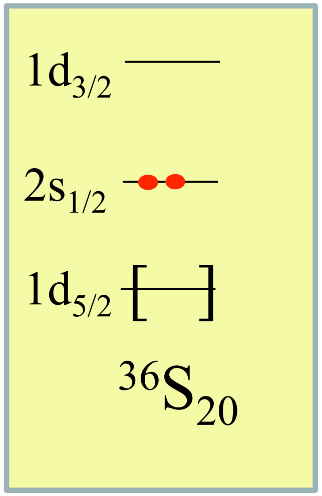


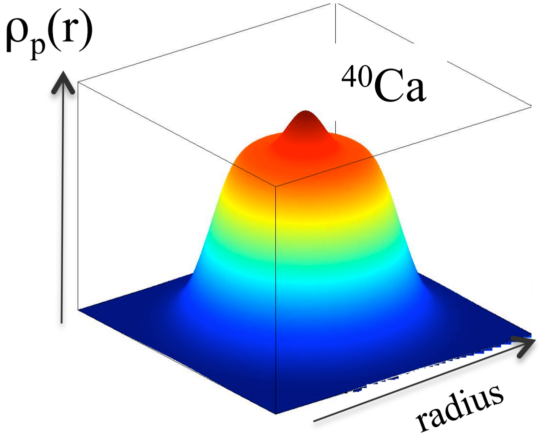


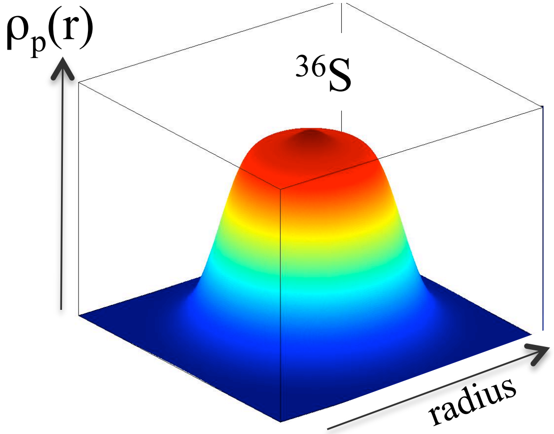


Finding a bubble nucleus in nature ….









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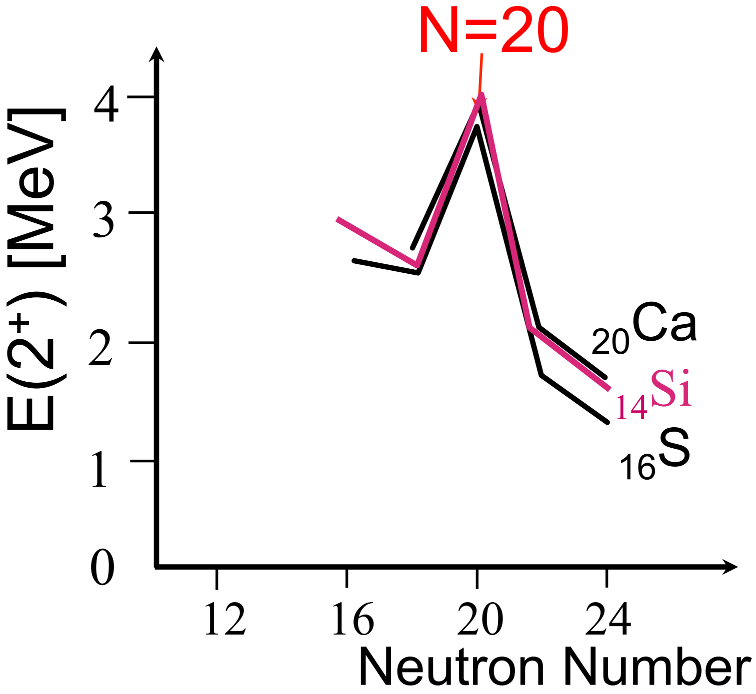
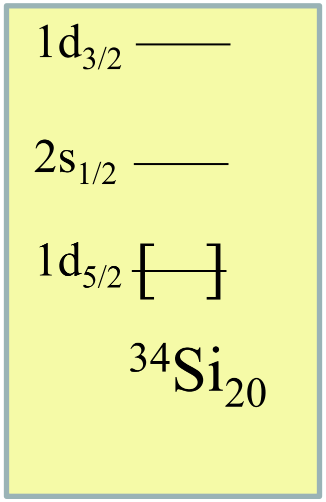
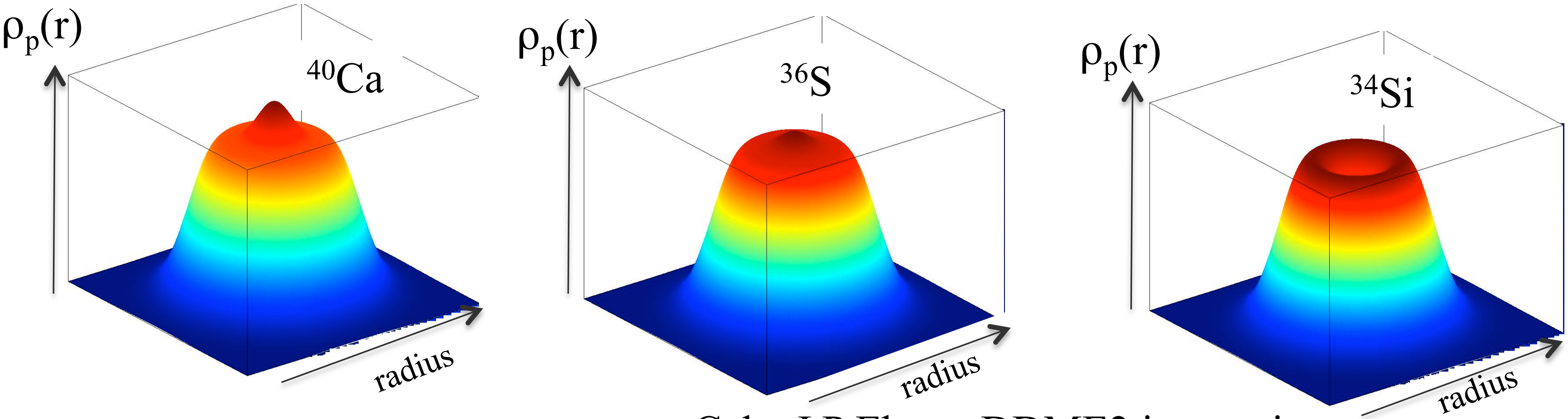
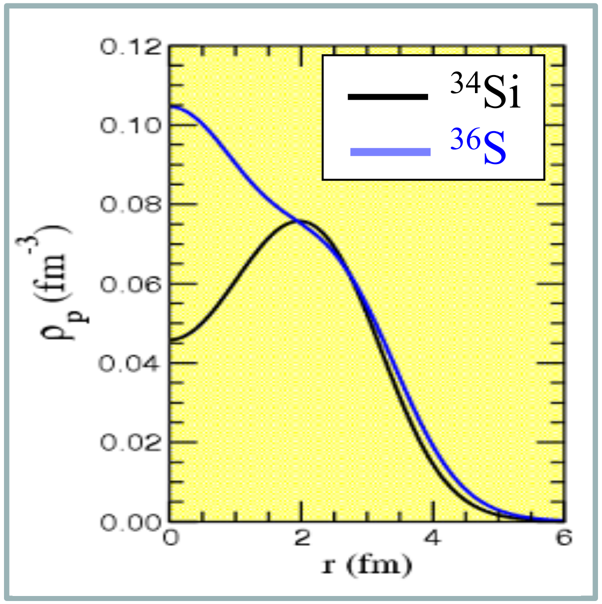




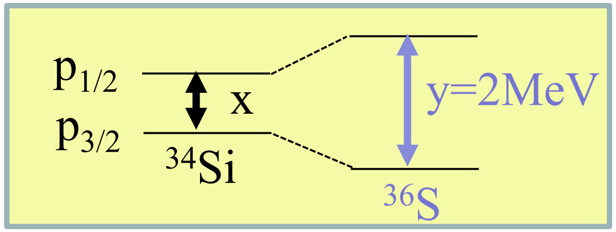


Calc. J.P Ebran, DDME2 interaction

PROBING THE SO INTERACTION WITH A BUBBLE NUCLEUS



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



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

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

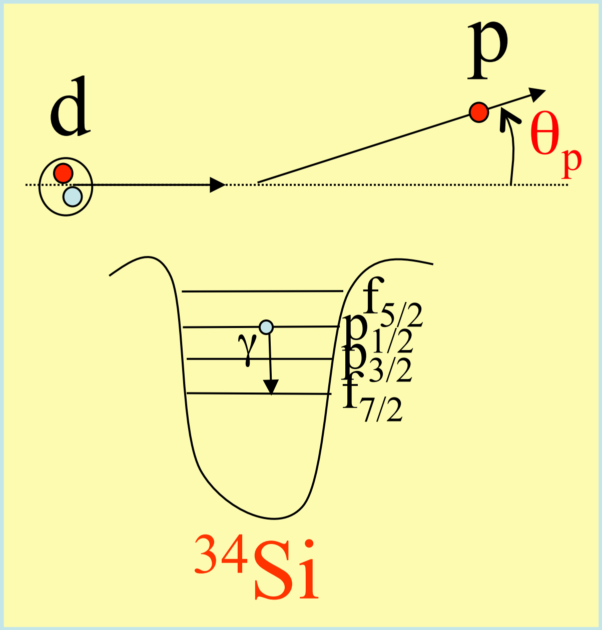
Predictions	Δ_nSO/SO (%)
RMF/ NL3	95
MF Skyrme	10 - 40
Shell Model	33

HF/Skyrme $$V^{\enclose{circle}{n}}_{\ell s}\,\alpha\,\frac{1}{r}\frac{\partial}{\partial r}\left[\enclose{circle}{2}\rho_n(r)+\rho_p(r)\right]\vec{\ell}\cdot\vec{s}$$

RMF $$V^{n}_{\ell s}\,\alpha\,\frac{1}{r}\frac{\partial}{\partial r}\left[\rho_n(r)+\rho_p(r)\right]\vec{\ell}\cdot\vec{s}$$

Isospin dependence differs HF/ Skyrme and RMF models

Probing the neutron orbits in ^{34}Si via transfer reaction in inverse kinematics



E_p -> binding energy

θ_p -> orbital momentum L

Probability of transfer-> vacancy

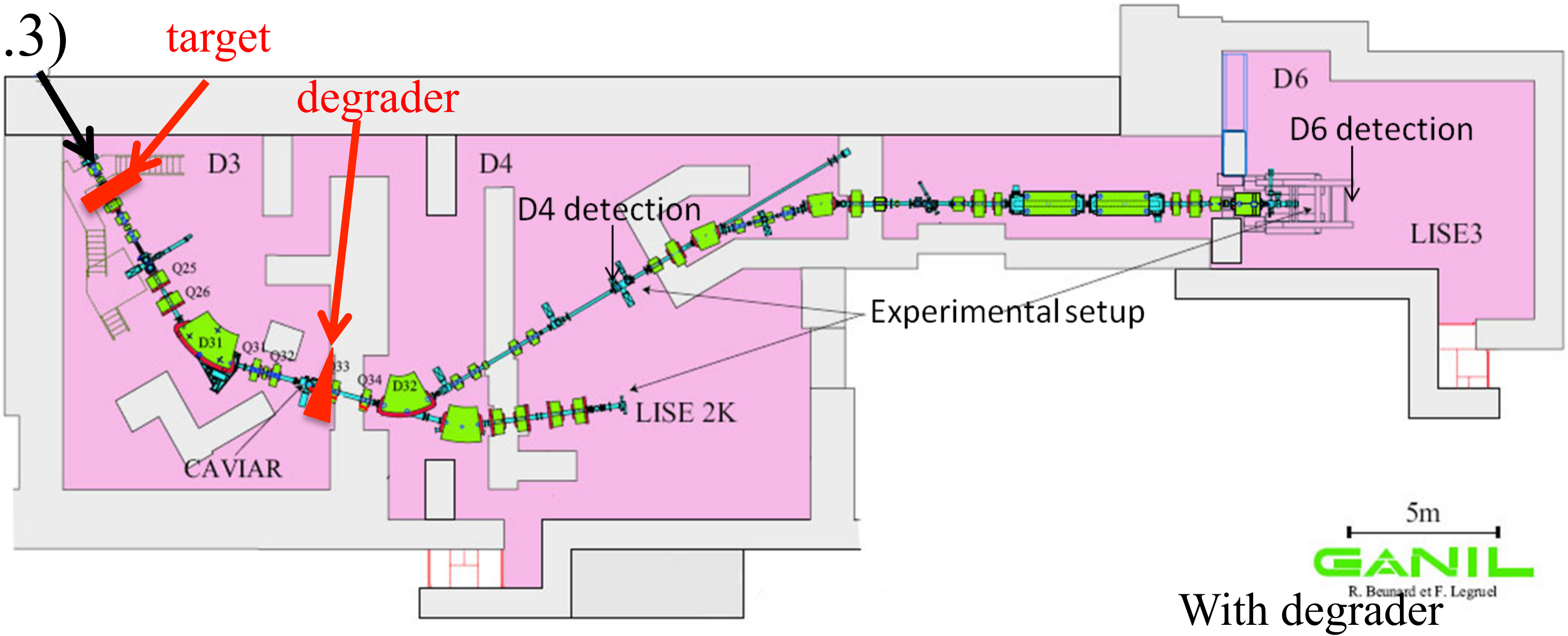
If excited state, decays by γ–ray emmission

Production and selection of ^{34}Si at GANIL

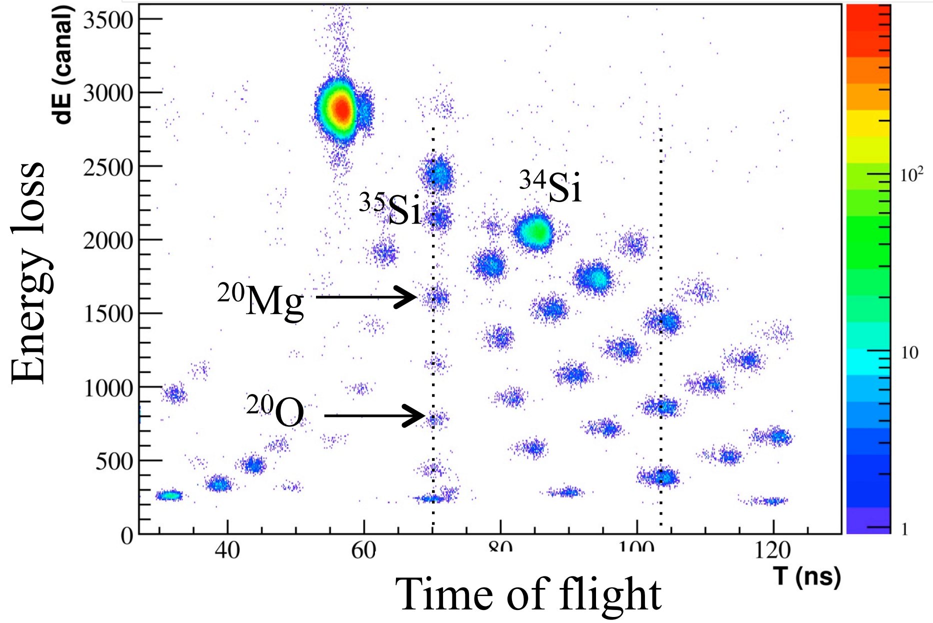
^{36}S ($v/c \approx 0.3$)

target

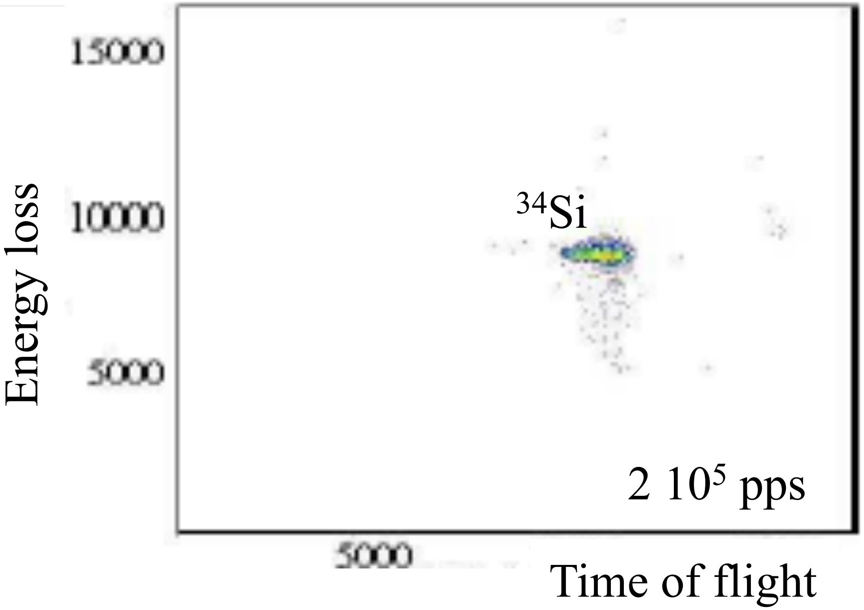
degrader



Av/Z selection

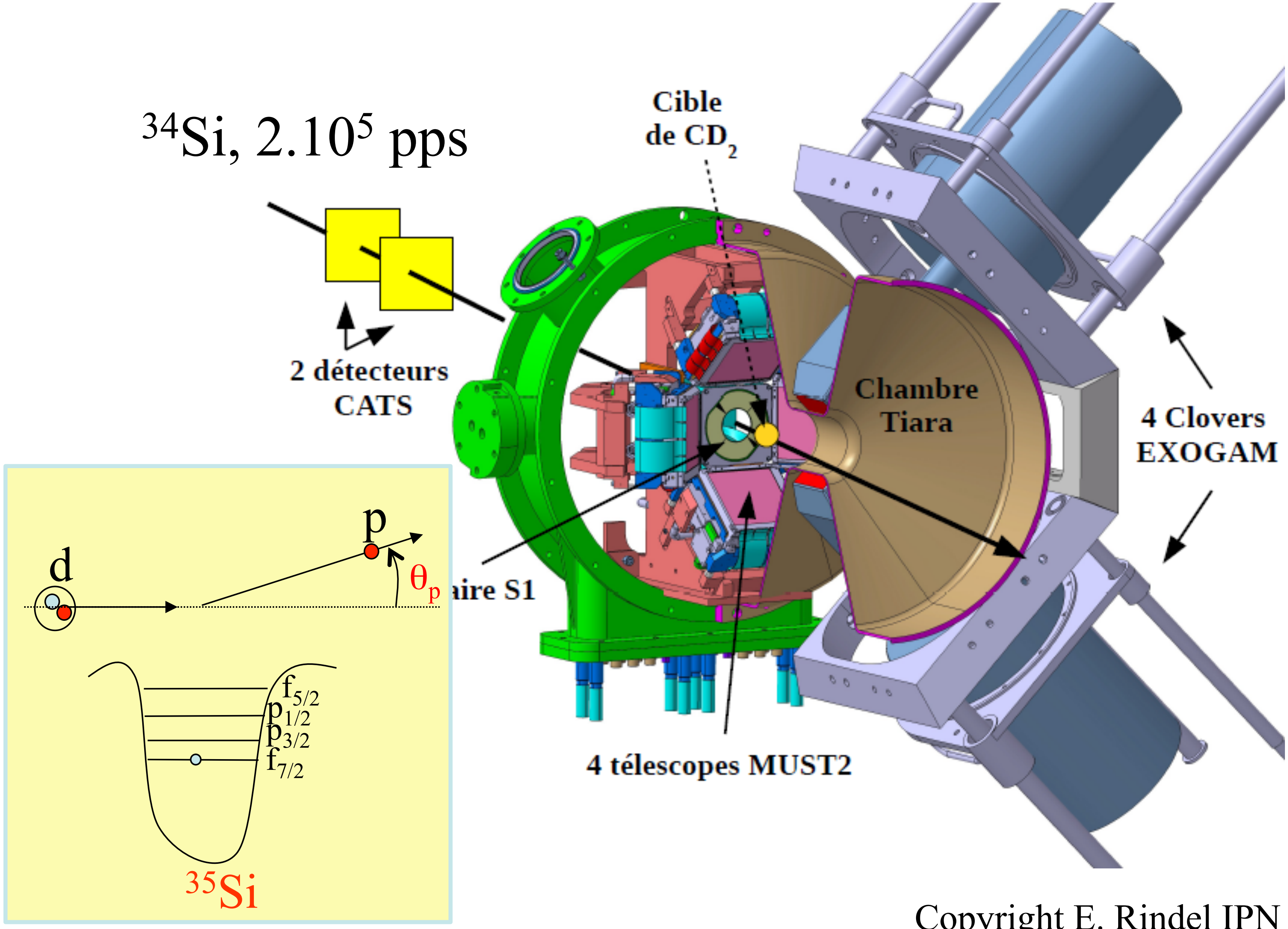


With degrader
A^3/Z^2 selection



$2\ 10^5$ pps

Experimental setup for the $^{34}Si(d,p)^{35}Si$ reaction



Reaction in inverse kinematics

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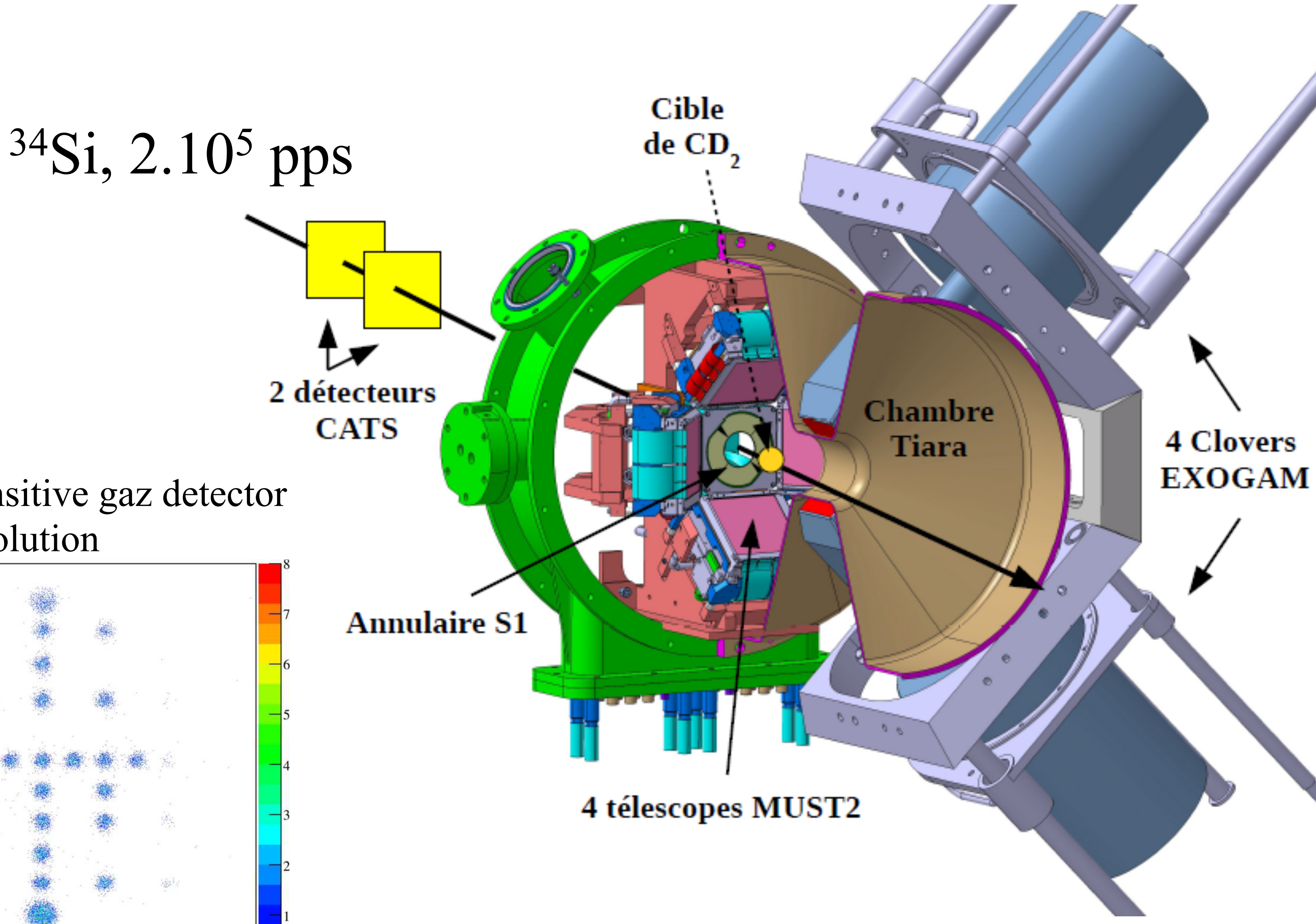
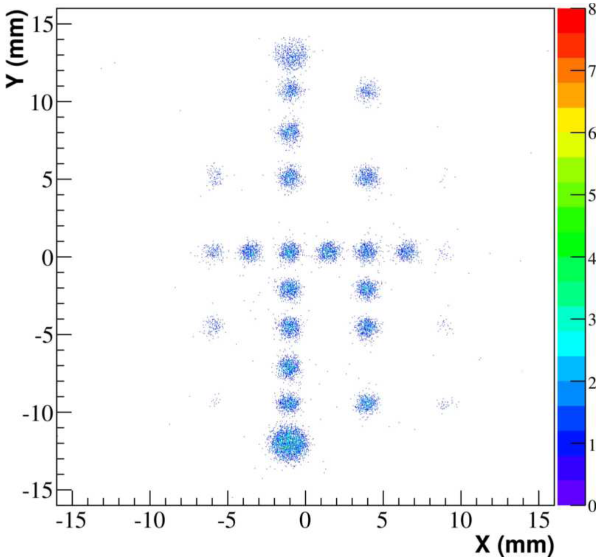


Position sensitive gaz detector
0.2 mm resolution



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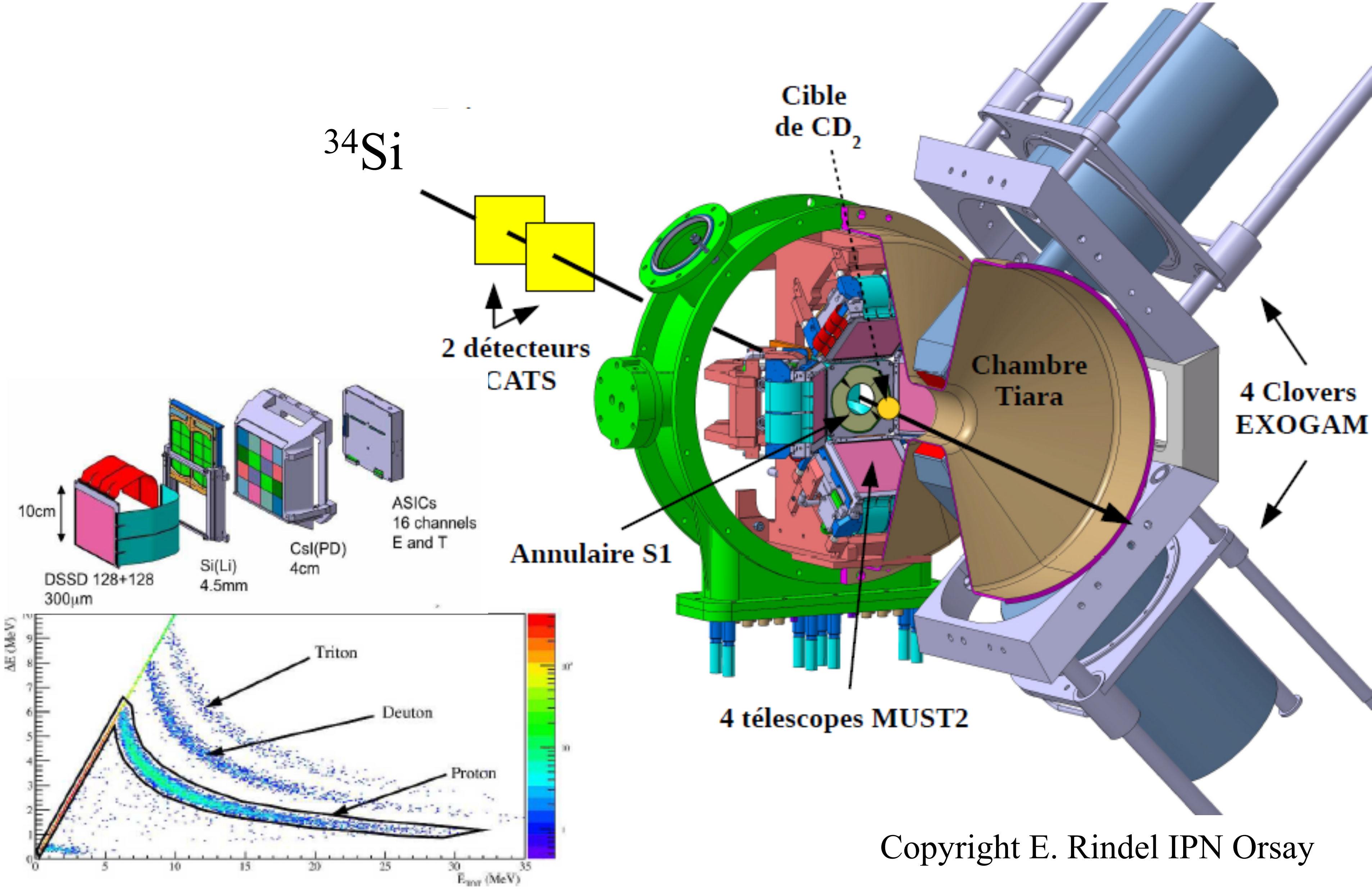

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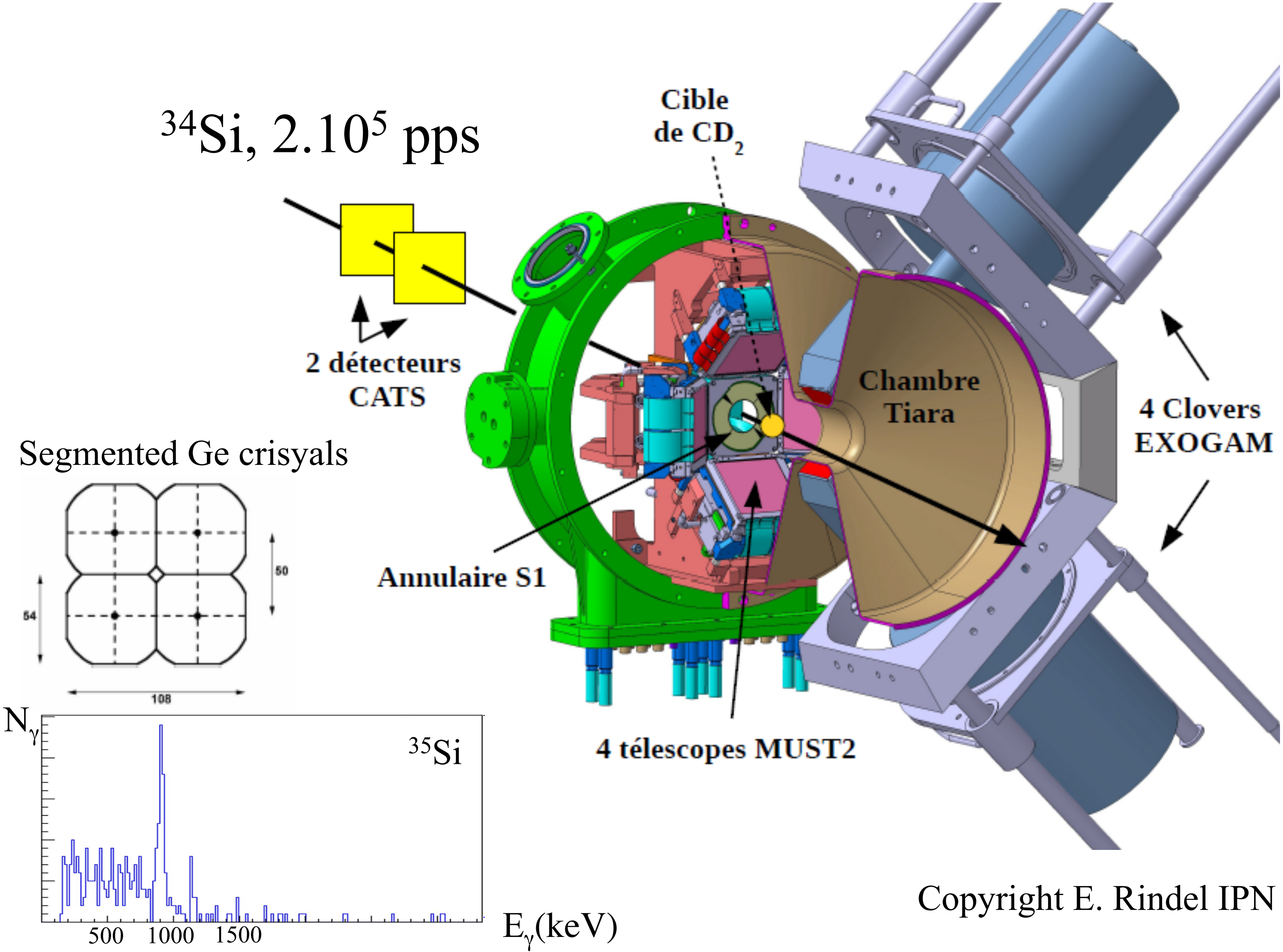

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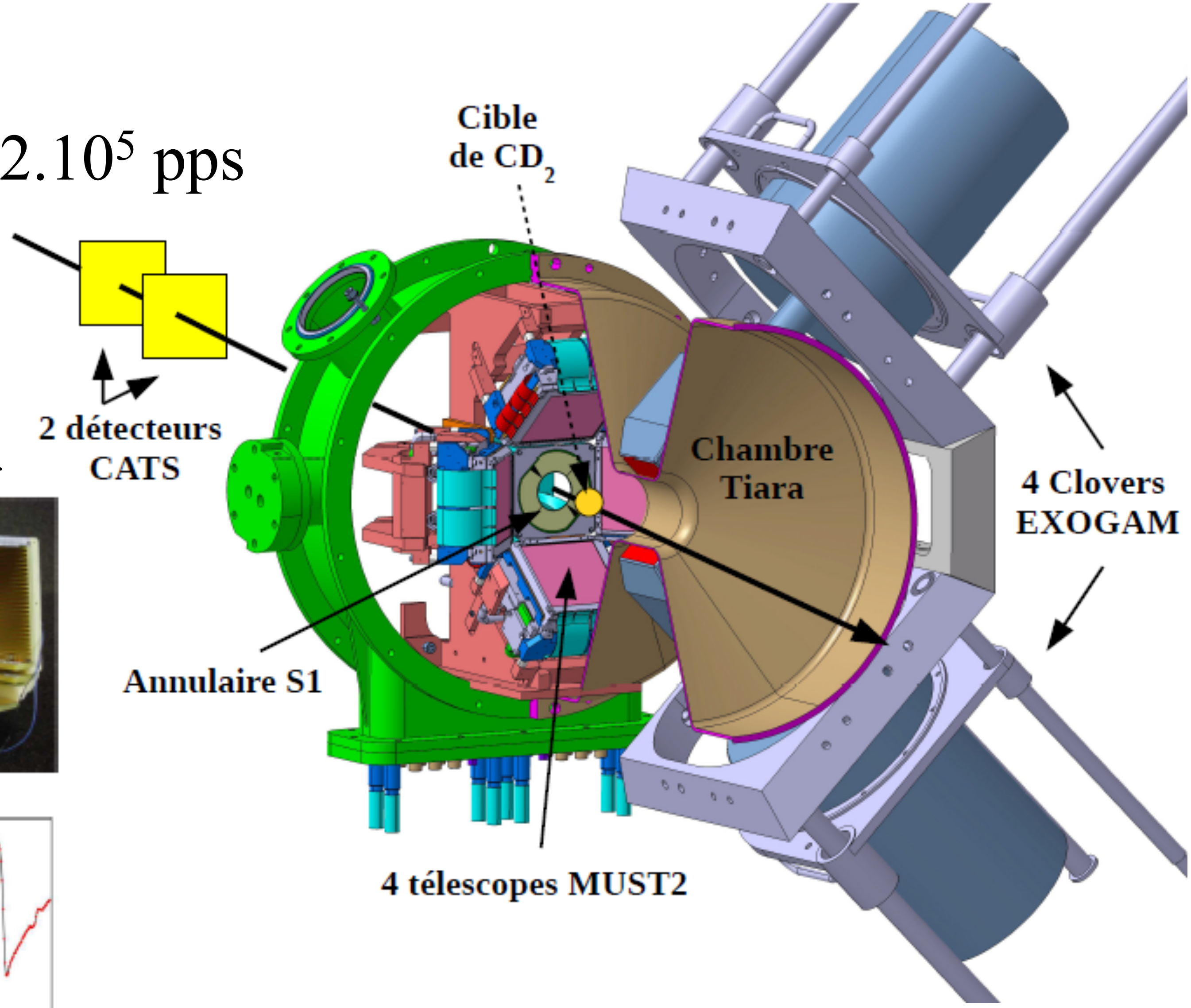
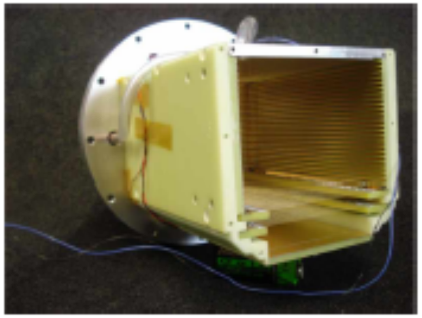
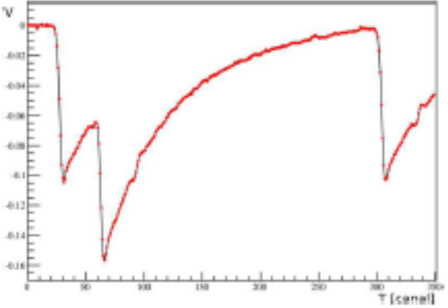


Ionisation chamber



Digitized signal



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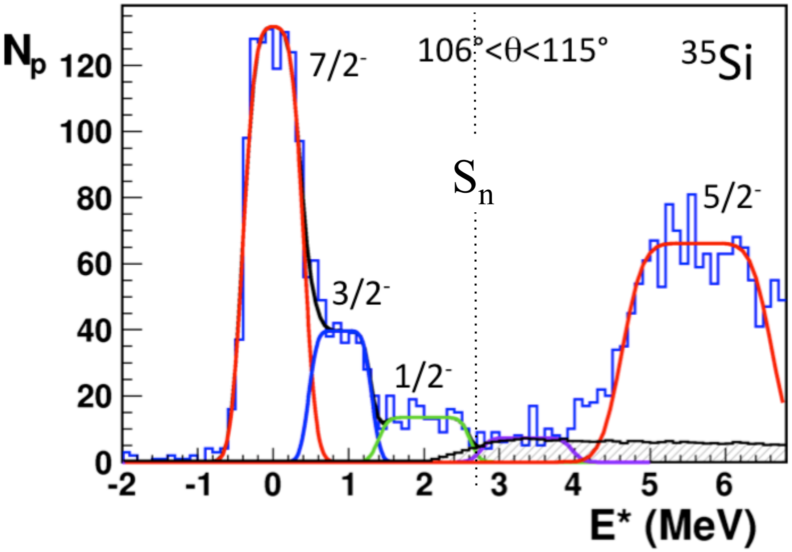
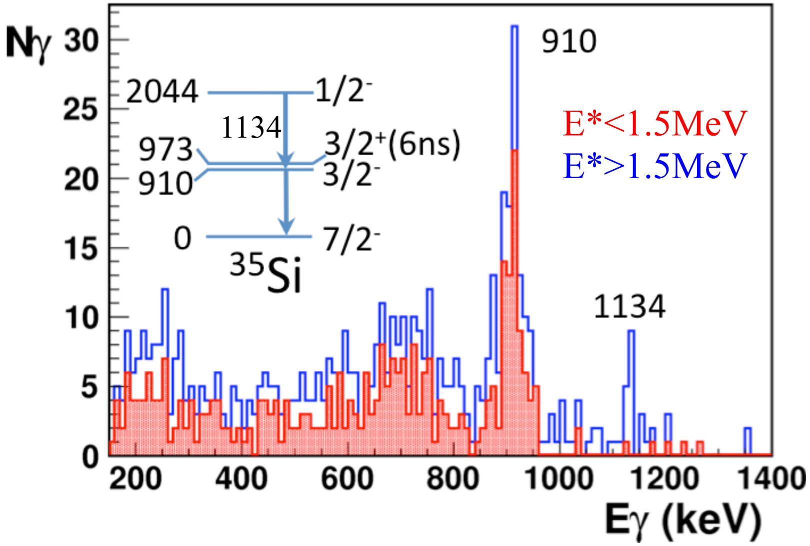
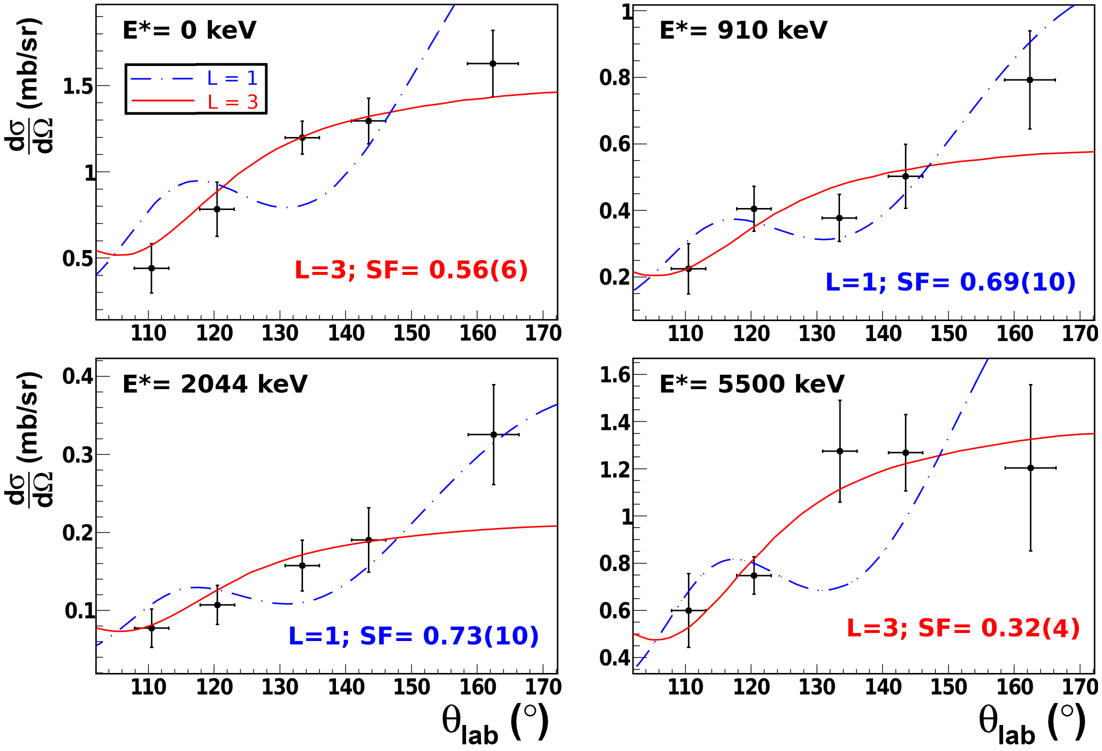
EXPERIMENTAL RESULTS ^{34}Si(d,p)^{35}Si



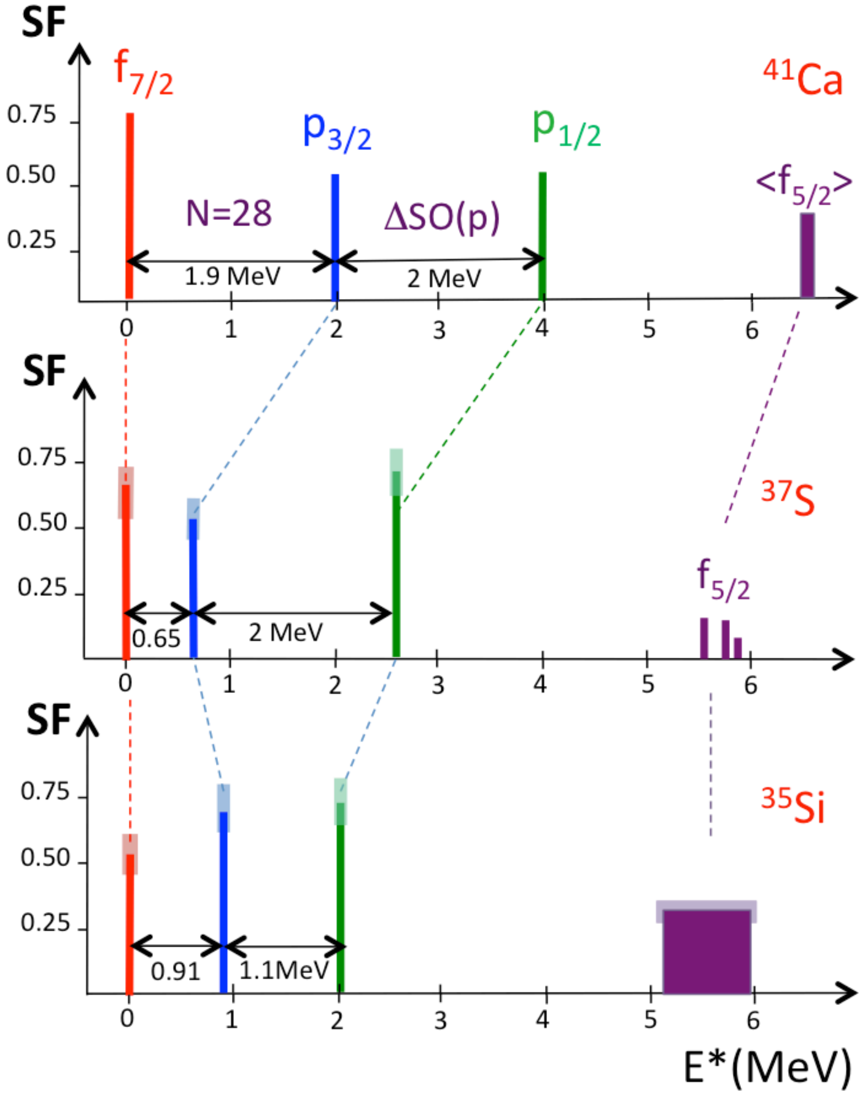


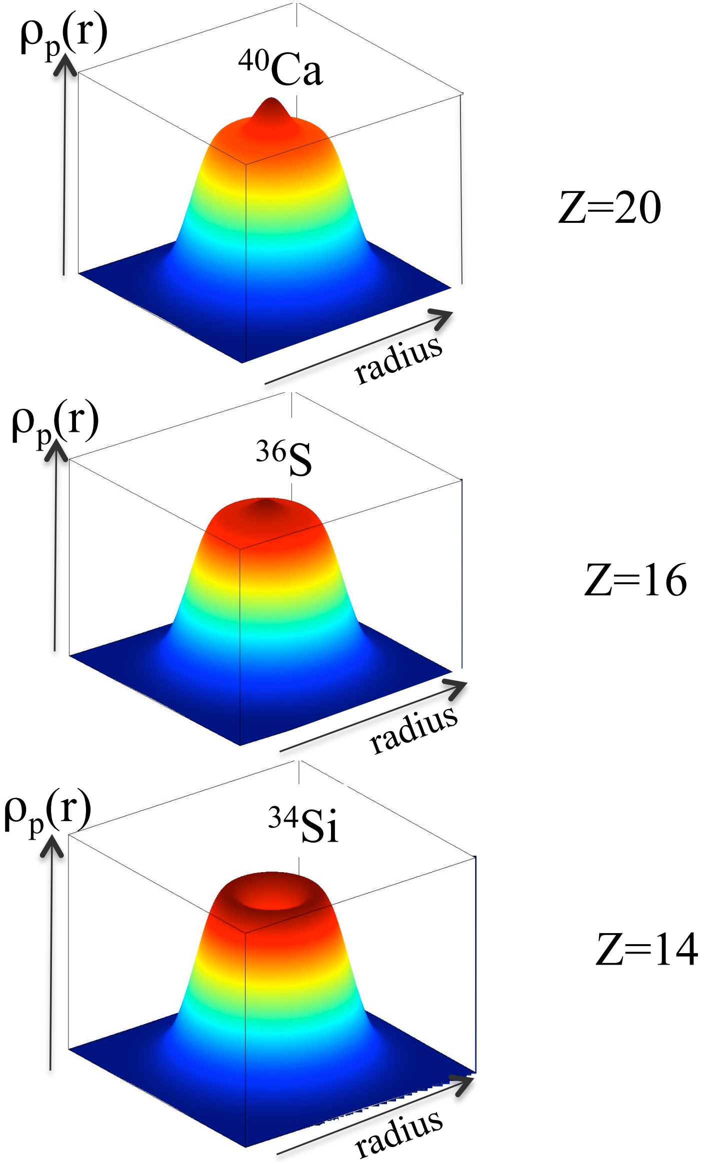


L assignments from proton angular distributions
Accurate energy of states with γ-ray detection

J. Burgunder et al., Phys. Rev. Letters 2014

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

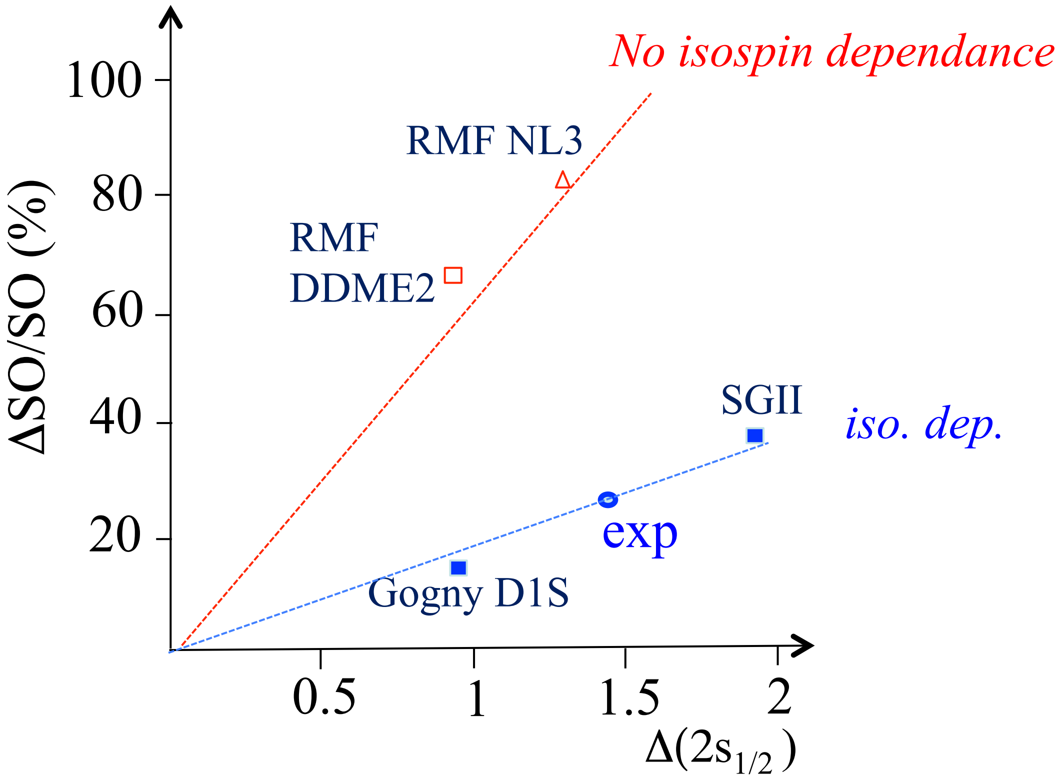




The $p_{3/2}$-$p_{1/2}$ splitting changes by almost a factor of 2 between ^{37}S and ^{35}Si

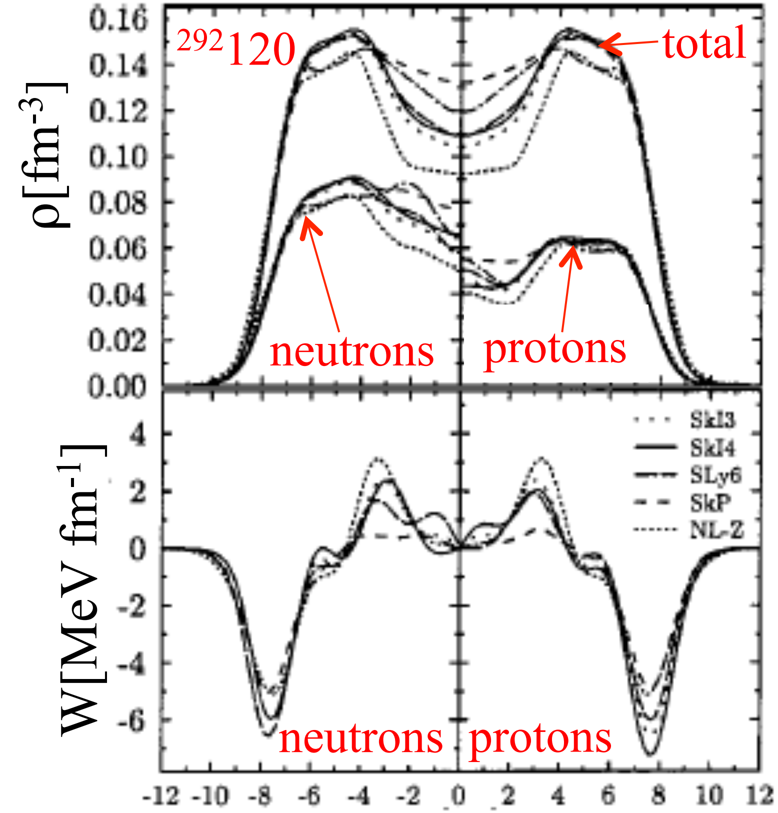
Density dependence of the SO interaction proven – Isospin dependance constrained

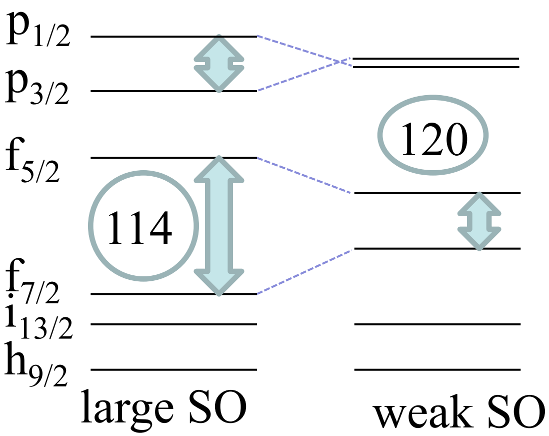
Modification of the SO splitting in a bubble nucleus



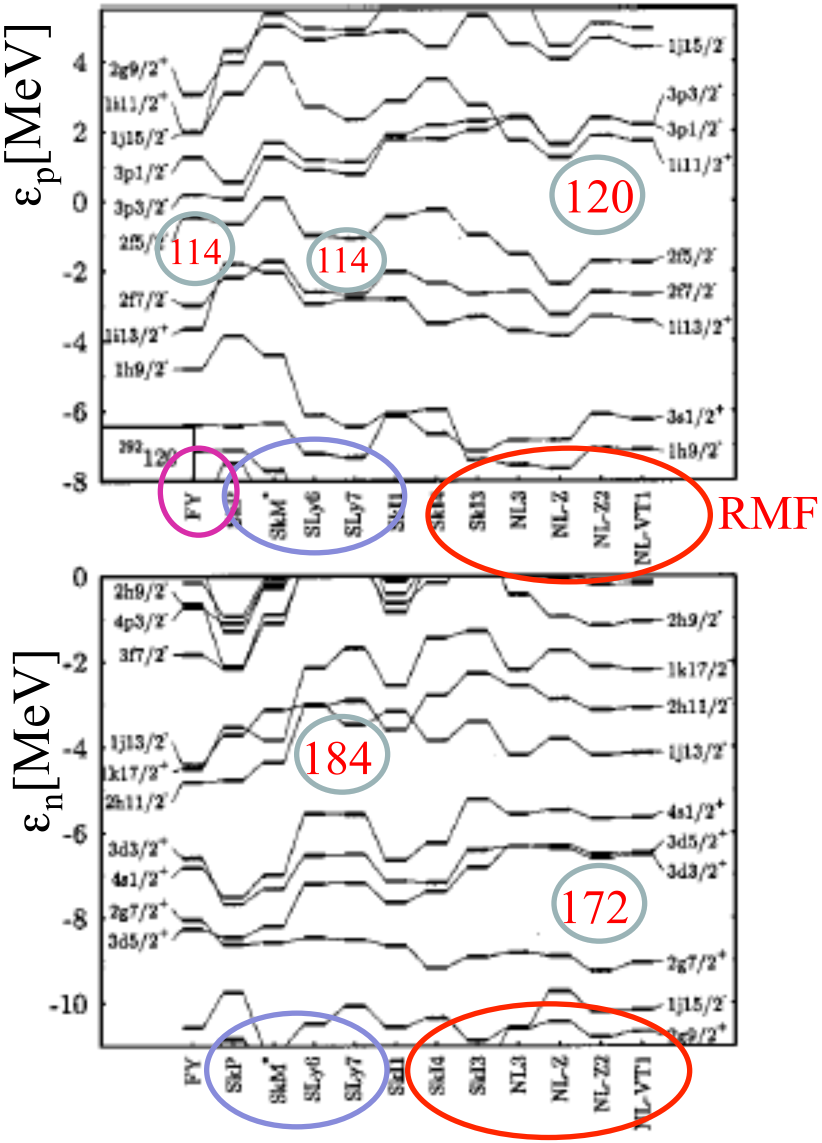
Exp. favors density AND isospin dep. of SO interaction
Anticipate consequences for drip line and SHE nuclei …

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

Conclusions & Perspectives

^{34}Si Bubble nucleus to probe density and isospin dependence of the SO interaction

Change of the neutron $p_{3/2}$-$p_{1/2}$ splitting by ~33%

➔ Density dependance of the SO interaction established

➔ isospin dependence of the SO interaction

➔ Conseq. on shell gaps far from stability and explosive nucleosynthesis

➔ Conseq. on the Location/existence of island of stability SHE

➔ Determine the amplitude of the density depletion (in progress @ NSCL/MSU with Gretina)