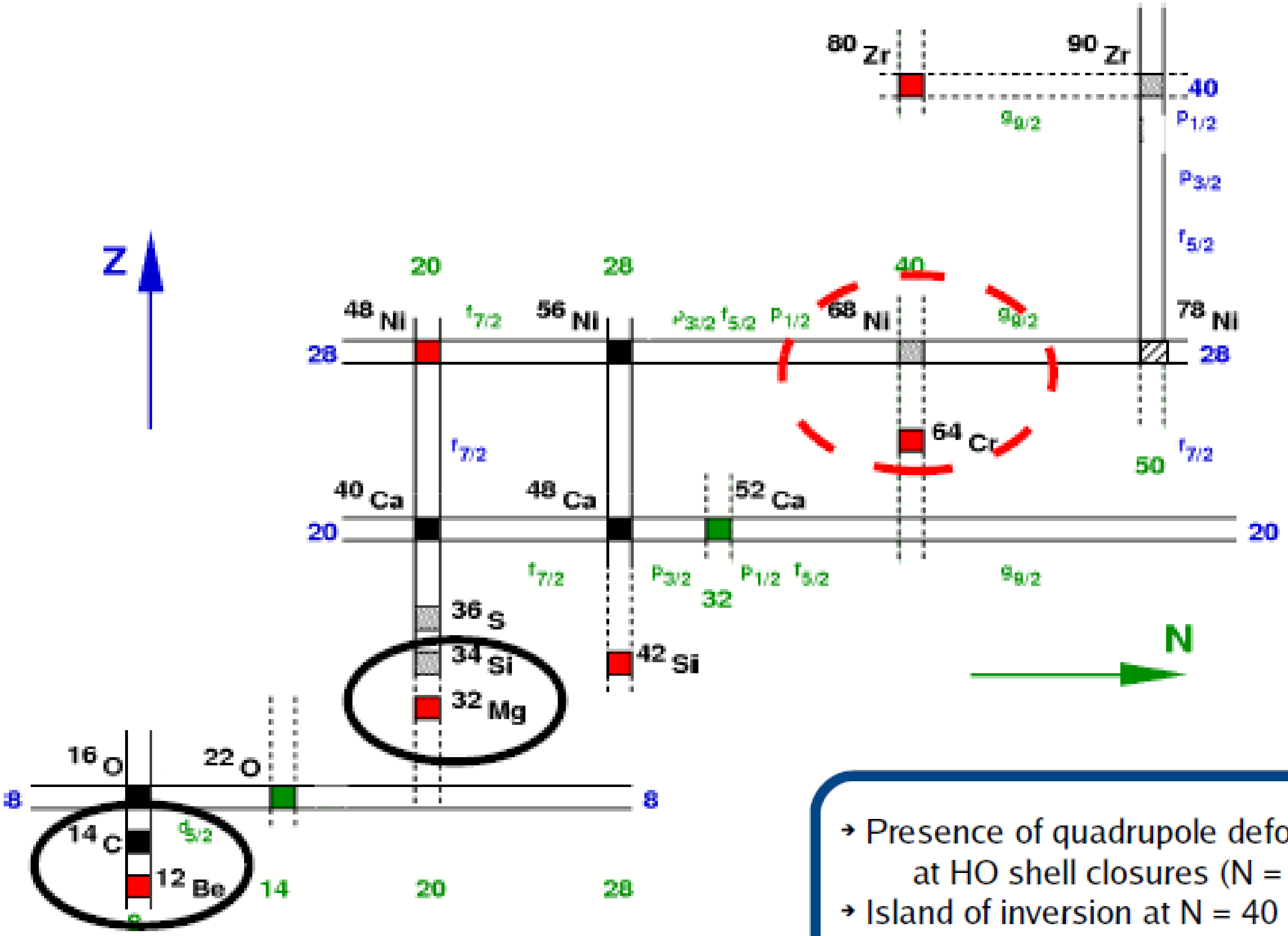
Recent results from single-particle spectroscopy using the (d,p) transfer reaction

D. Beaumel,
IPN Orsay / RIKEN Nishina center

- **Shell evolution at N ~ 40 through ^{68}Ni(d,p)**
- **Properties of the Spin-orbit interaction from ^{34}Si(d,p) study**

Harmonic Oscillator Shell Closures

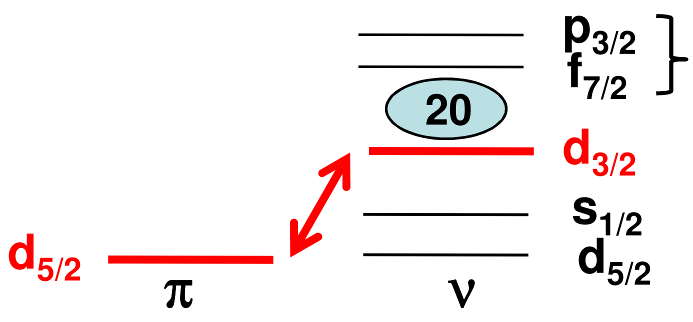


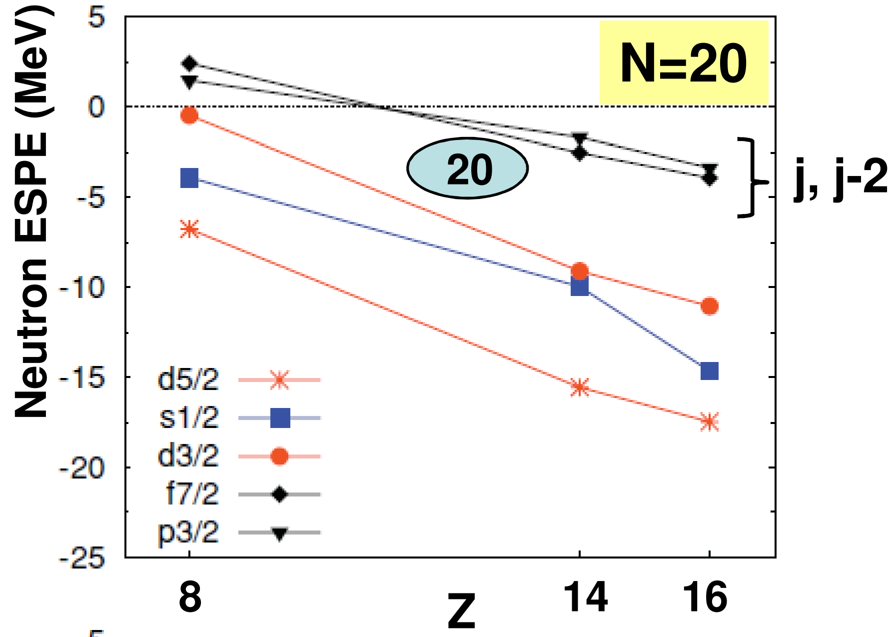
- Presence of quadrupole deformation at HO shell closures (N = 8, 20, 40)
- Island of inversion at N = 40

Caurier et al. EPJ, A, 15, 2002, 145

From M. Moukaddam

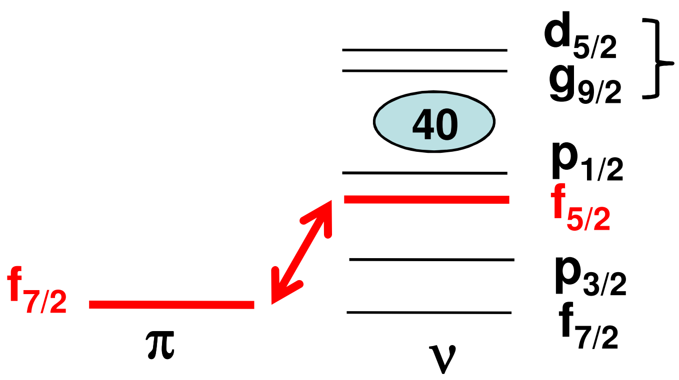
Evolution of Harmonic Oscillator Shell Closures

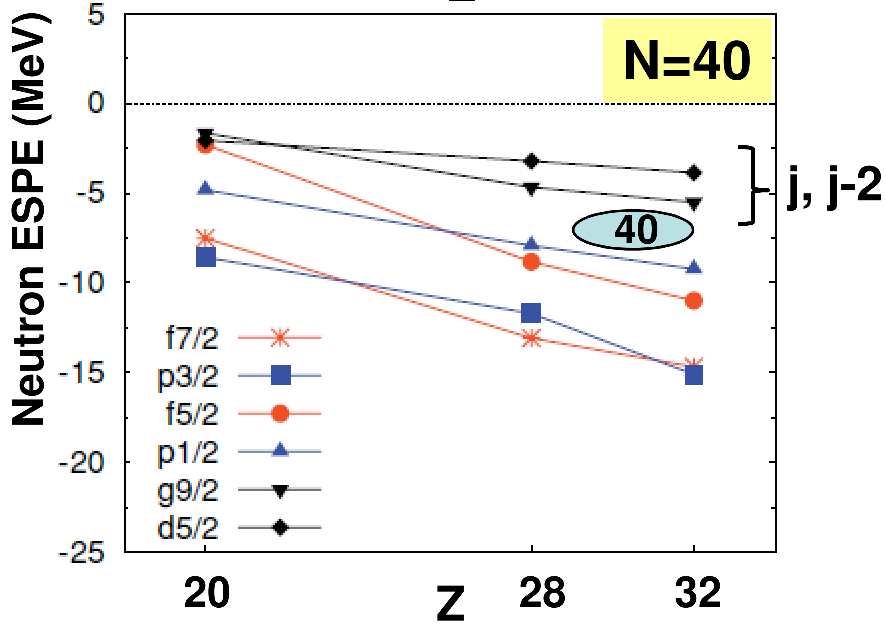




- ***reduction of the gap when Z decreases***
- ***quasi-degeneracy of a j,j-2 sequence above the fermi surface***

Similar situation for N=40

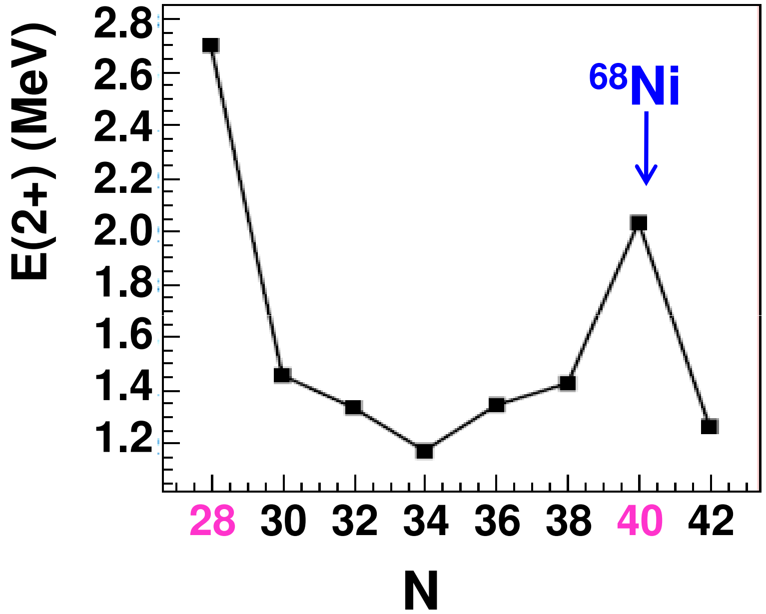


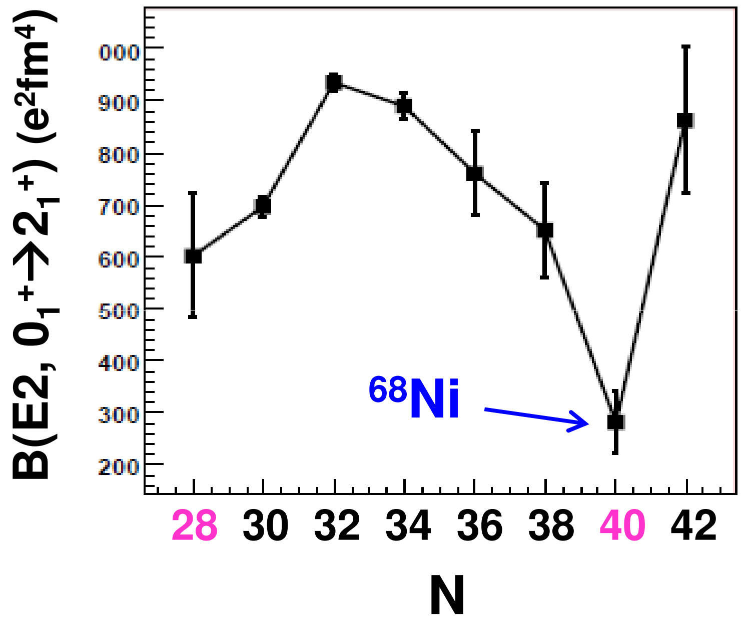


From S.M. Lenzi et al., PRC 82 (2010)

(and also at N=8)

The Nickel isotopes

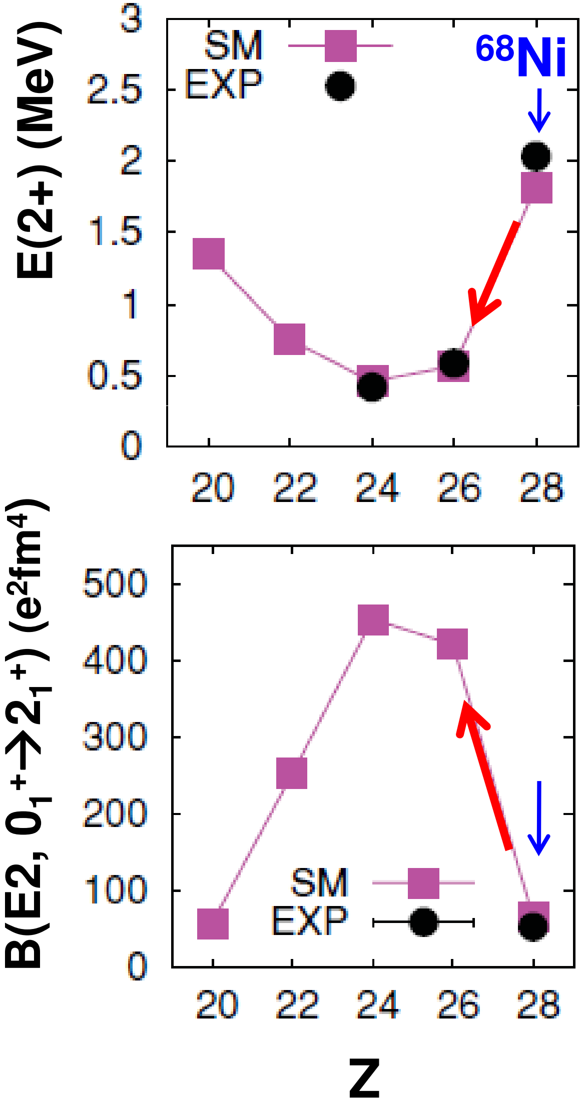




For ^{68}Ni :
- Doubly magic character of E(2+)/B(E2)
- No sign of shell closure in neutron separation energy

Southwest of Nickel's

N = 40



Large valence space SM calculations

S.M. Lenzi, F.Nowacki, A. Poves, and K. Sieja, PRC 82 (2010)

LPNS interaction

fp shell + $1g_{9/2}$ + $2d_{5/2}$

Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	0p0h	2p2h	4p4h	6p6h	E_{corr}
^{68}Ni	0.98	0.10	55.5	35.5	8.5	0.5	−9.03
^{66}Fe	3.17	0.46	1	19	72	8	−23.96
^{64}Cr	3.41	0.76	0	9	73	18	−24.83
^{62}Ti	3.17	1.09	1	14	63	22	−19.62
^{60}Ca	2.55	1.52	1	18	59	22	−12.09

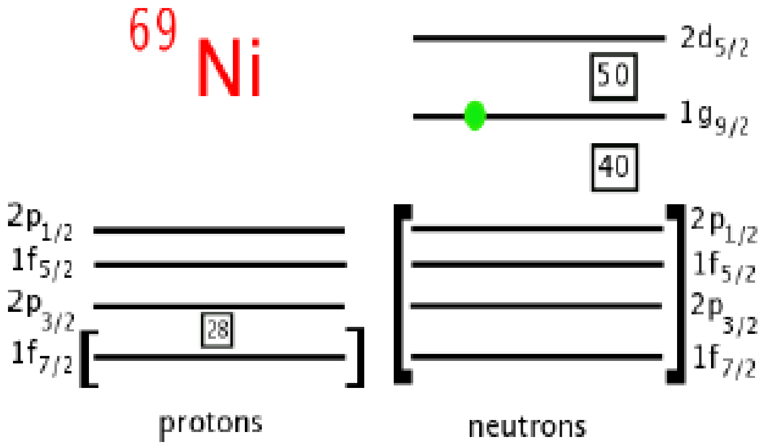
- **Drastic change with only 2 protons removed**
- **Strong gain in correlation energy**

similar to ^{34}Si / ^{32}Mg

New island of inversion

$2d_{5/2}$ plays a major role in the deformation mechanism at N = 40 *Caurier et al. EPJ, A, 15, 2002, 145*

Our approach : the ^{68}Ni(d,p) reaction



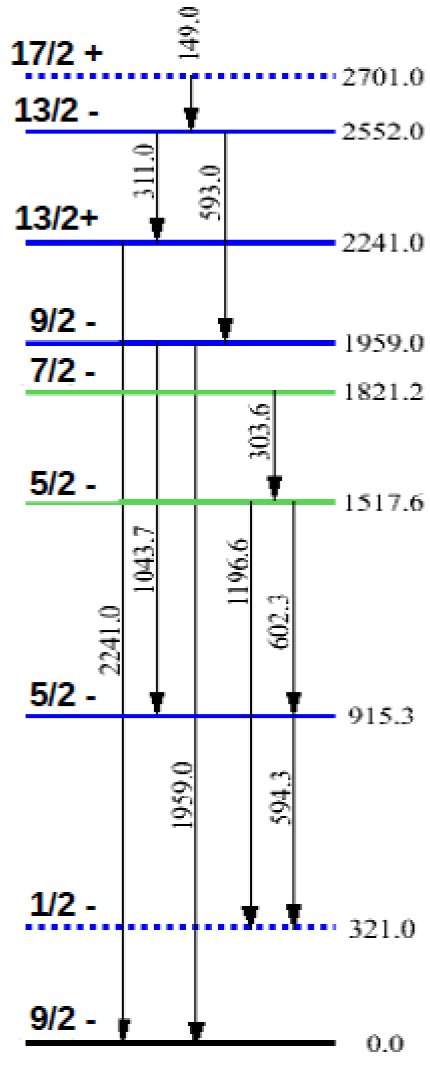
<u>**Previous experiments**</u>:

- **Isomer-state decay**
  (Grzywacz et al., PRL 81 (1998))
- **β-decay**
  (Mueller et al., PRL83 (1999))
  $2d_{5/2}$ (5/2+) was not observed

We proposed to measure ^{68}Ni(d,p)

- **Selective of single-particle state**
- Promotion of the single neutron from g9/2 g.s. to d5/2

  g9/2 – d5/2 gap



^{69}Ni

Collaboration

M. Moukaddam, G. Duchêne, D. Curien, F. Didierjean, Ch. Finck, A. Goasduff, F. Haas, F. Nowacki, J. Piot, K. Sieja
IPHC - Strasbourg, France

D. Beaumel, N. de Séréville, S. Franchoo, S. Giron, J. Guillot, F. Hammache,Y. Matea, A. Matta, L. Perrot, E. Pllumbi, J. A. Scarpaci, I. Stefan
IPN - Orsay, France

J. Burgunder, L. Caceres, E. Clement, B. Fernandez, S. Grevy, J. Pancin, R. Raabe, O. Sorlin, C. Stoedel, J.C. Thomas
GANIL - Caen, France

F. Flavigny, A. Gillibert, V. Lapoux, L. Nalpas, A. Obertelli
SPhN - Saclay, France

M. N. Harakeh
GSI - Darmstadt, Germany

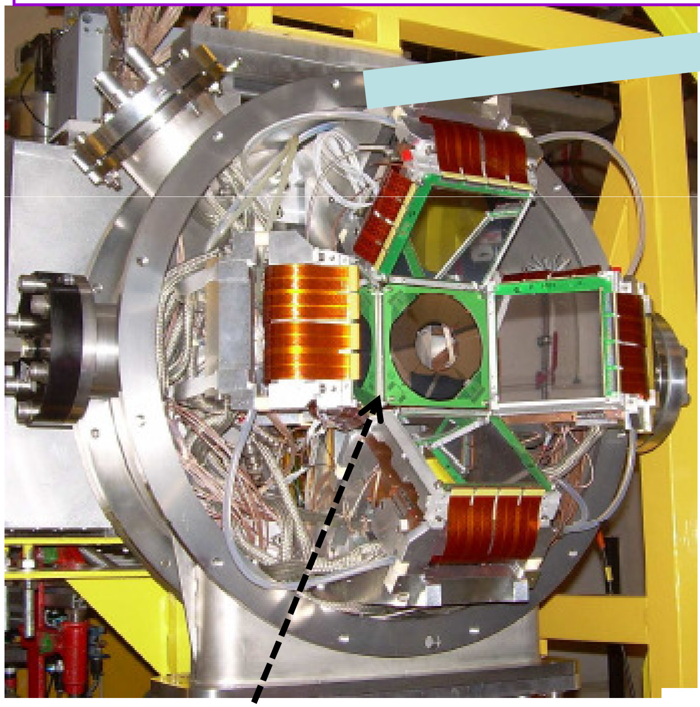
J. Gibelin
LPC - Caen, France

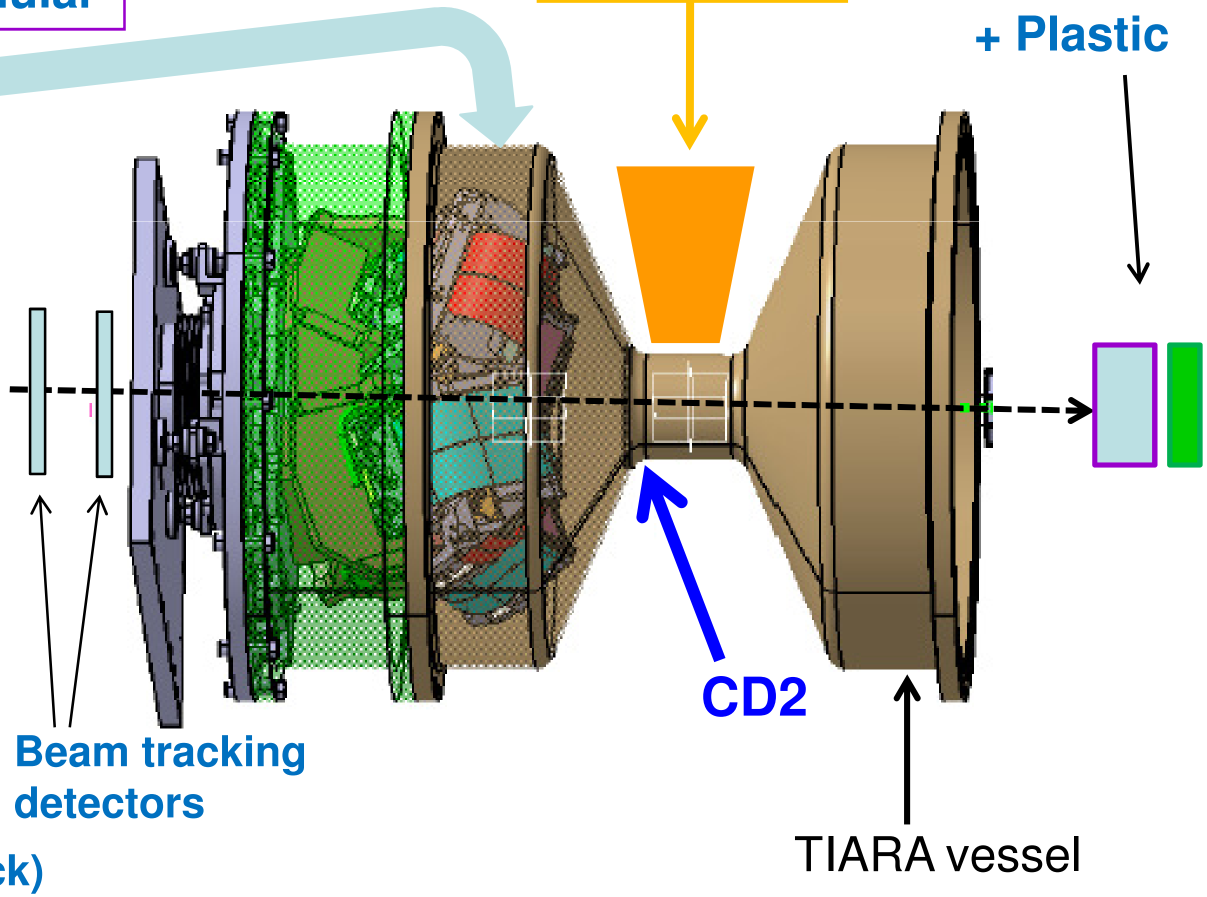
K. Kemper
Florida State University, USA

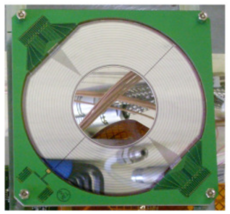
Experimental setup

Primary beam: ^{70}Zn
^{68}Ni @ 25 MeV/u, rate: ~8.10^{4} pps
Purity : 86%

4 MUST2 telescopes + S1 annular



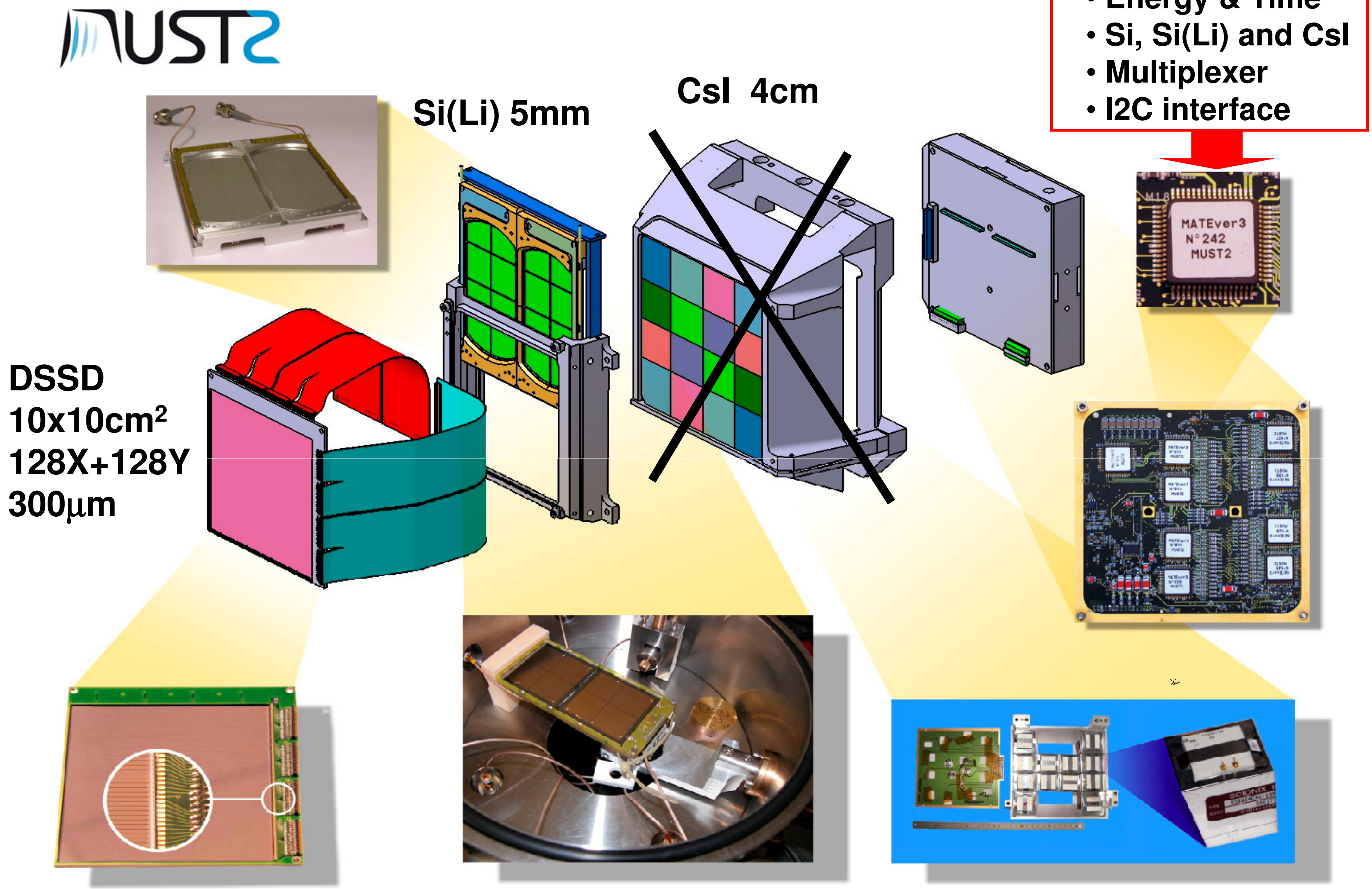




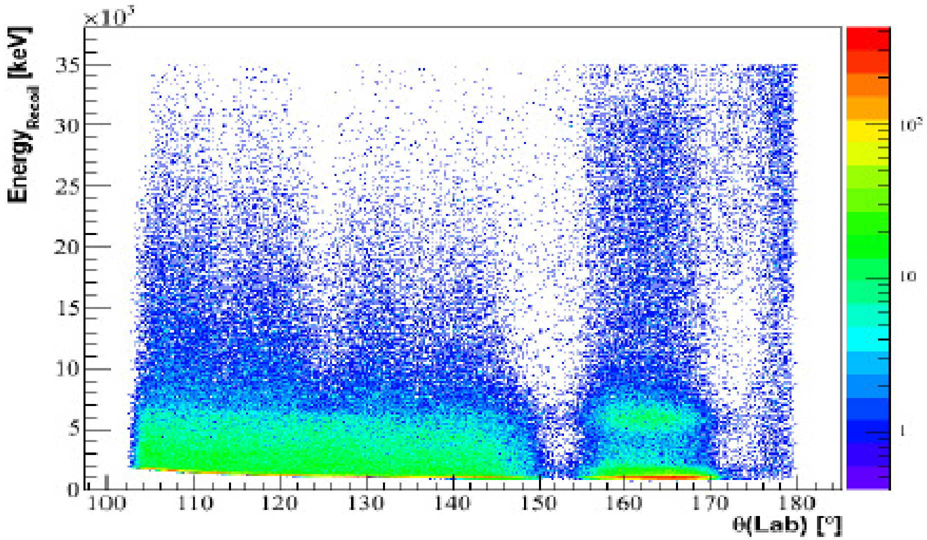
Annular Si (500μm thick)
MICRON SC, S1 design

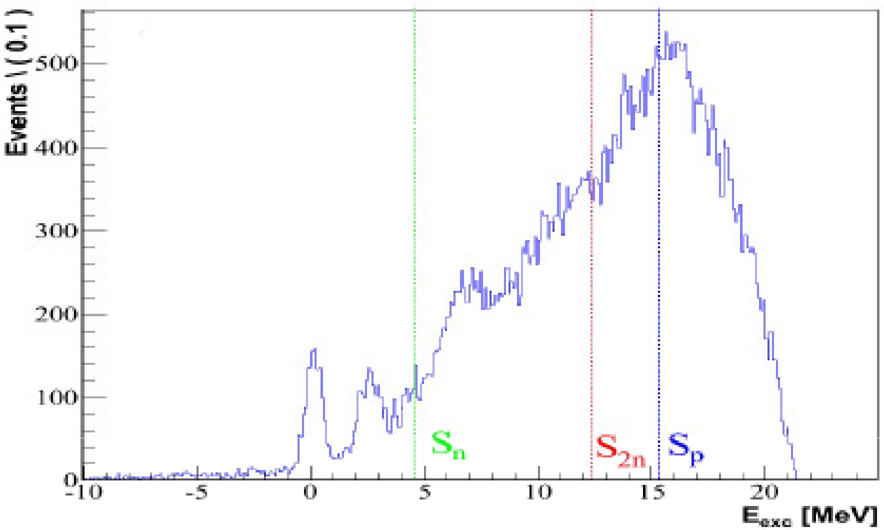
Collaboration: IPN Orsay/Saclay/GANIL

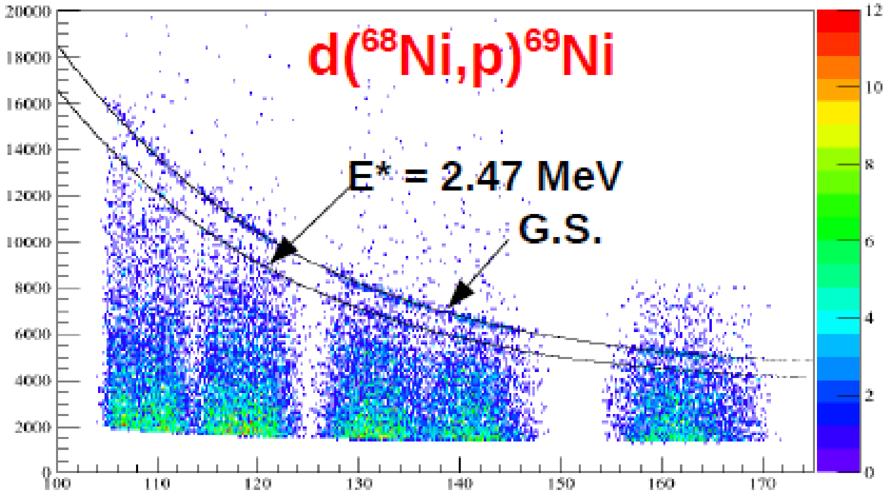
- 16 channels
- Energy & Time
- Si, Si(Li) and CsI
- Multiplexer
- I2C interface



Kinematical plots and E spectrum*



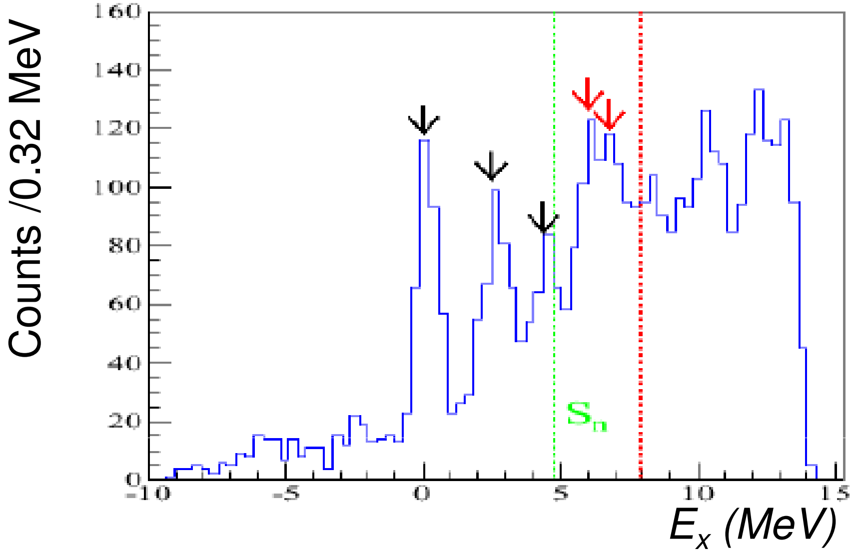


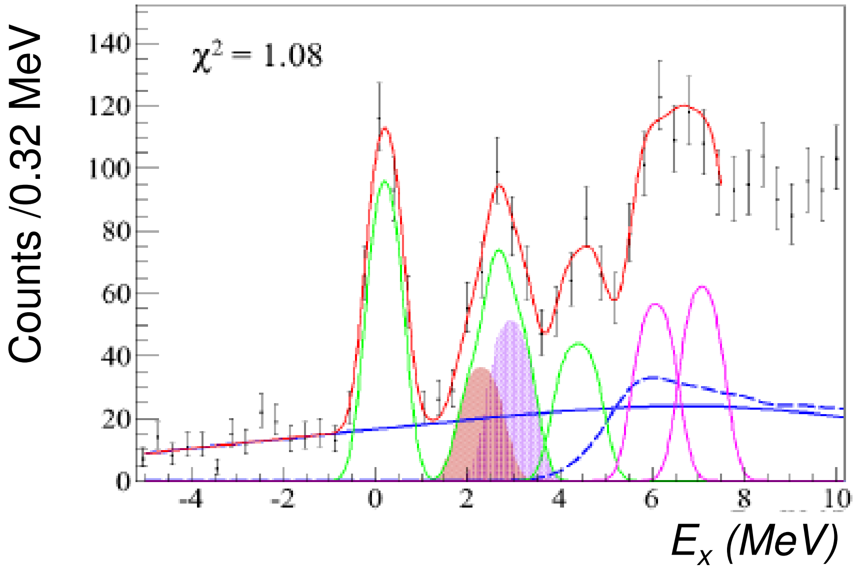


- Pronounced G.S.
- 1st excited state at ~ 2.5 MeV
- Structures ~ 4 MeV
  and 6−7 MeV (> S_n)

Excitation energy spectrum

Backward (fwd) Lab(CM) angles



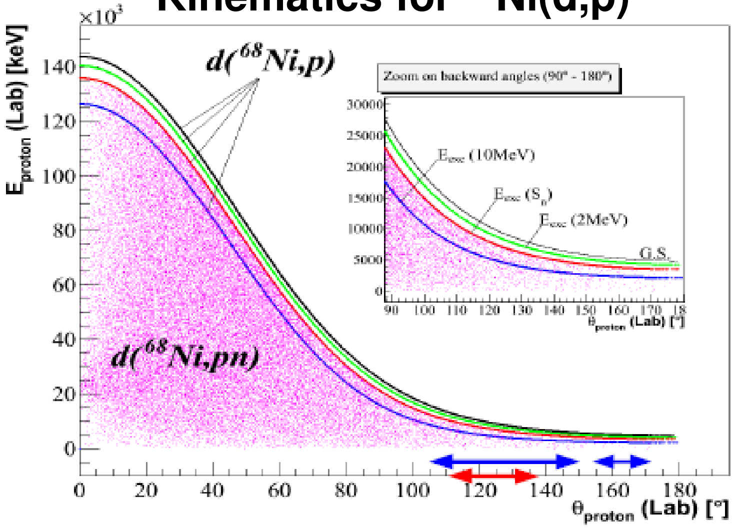


- 3 bound states
- 2 resonances above S_n
- Background reactions (2 different ways)

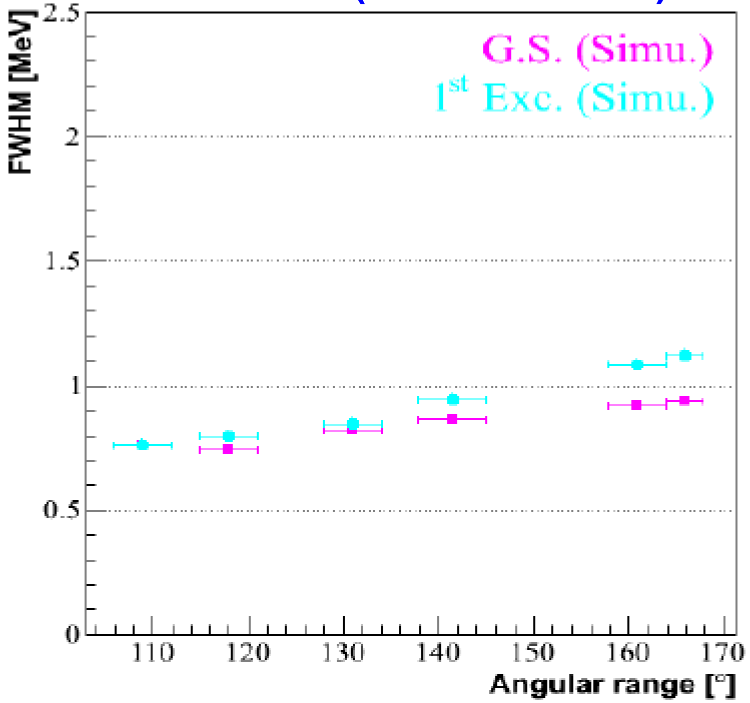
Pic #	Energy [MeV]	FWHM [MeV]
G.S	0.00	1.04
1	2.47	<u>**1.43**</u>
2	4.19	1.27
3	5.88	1.39
4	6.89	1.39

Evidence for a doublet state at E~2.5MeV*

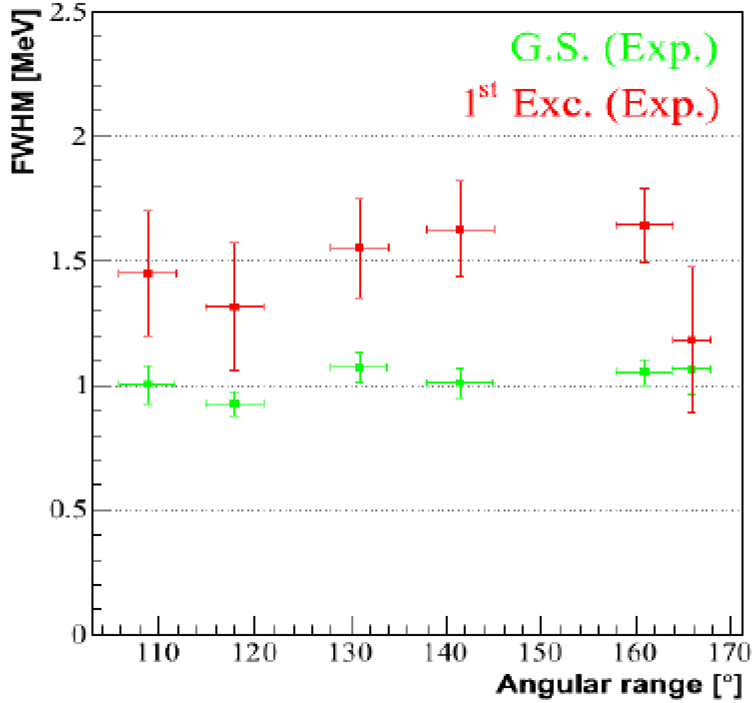
Kinematics for ^{68}Ni(d,p)



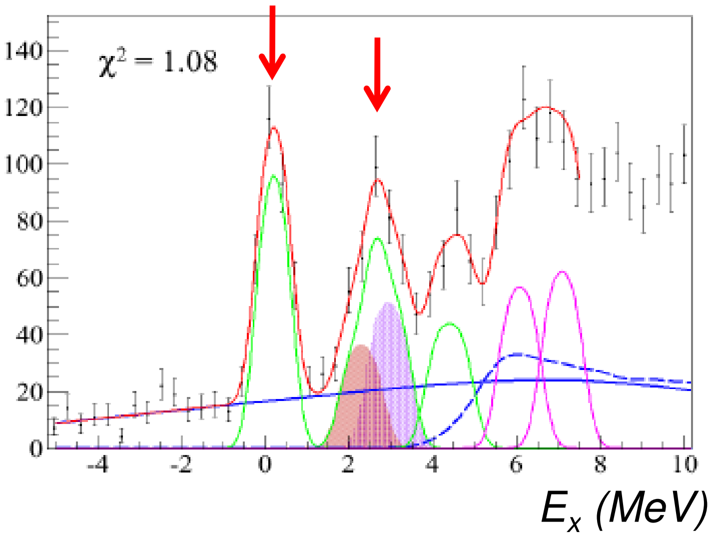
resolution (full simulation)



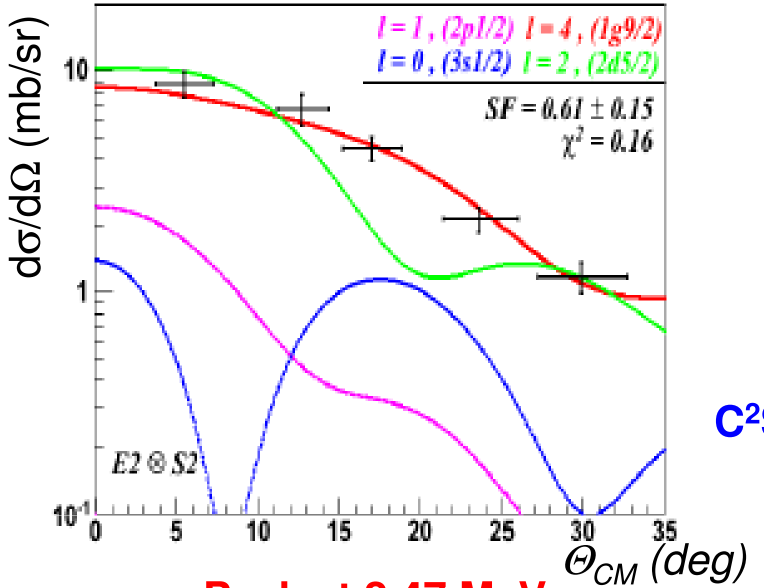
Experimental resolution (data)



Differential cross-sections

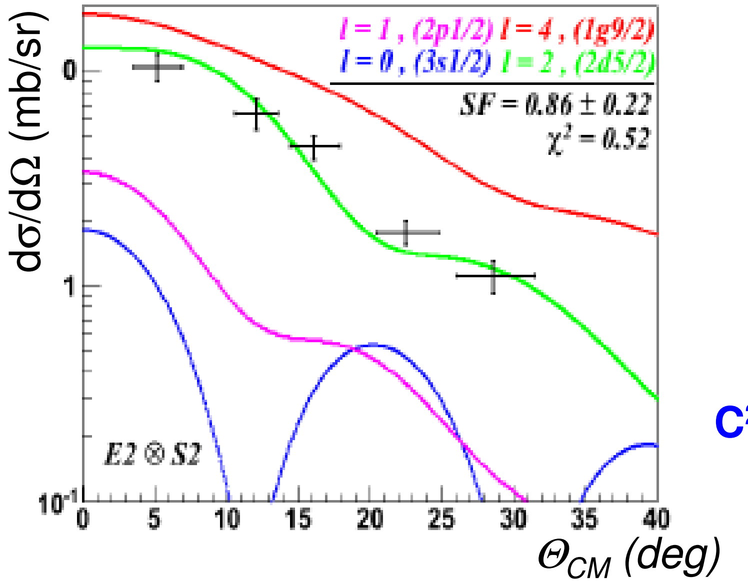


Ground-state



$C^2S = 0.61 \pm 0.15$

Peak at 2.47 MeV



$C^2S = 0.86 \pm 0.22$

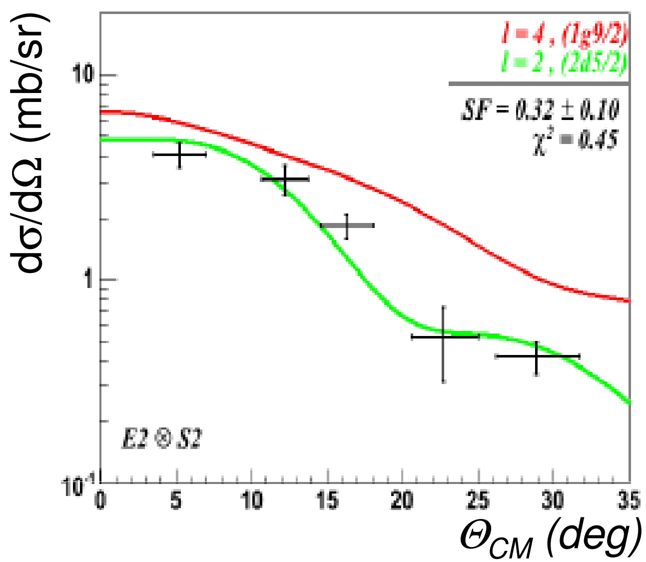
ZR code DWUCK
L = 0,1,2,4

- **Weak dependence on the exit channel pot.**
- **Significant dependence on the entrance pot.**

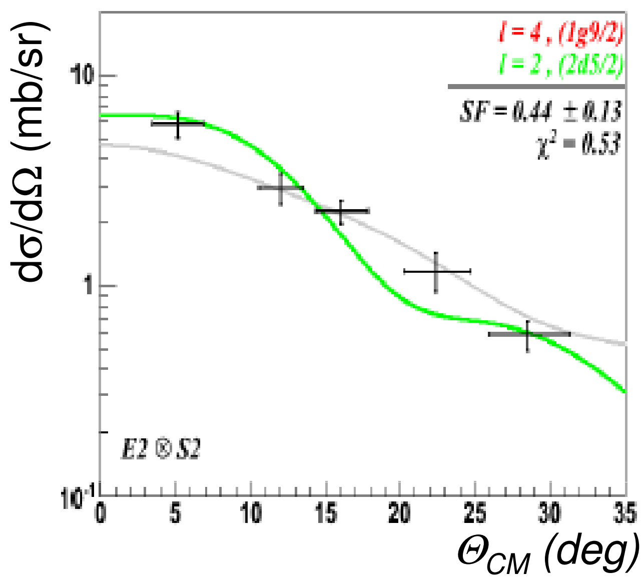
Adiabatic channel (ADWA) provides better agreement

Differential cross-sections: 1st excited peak

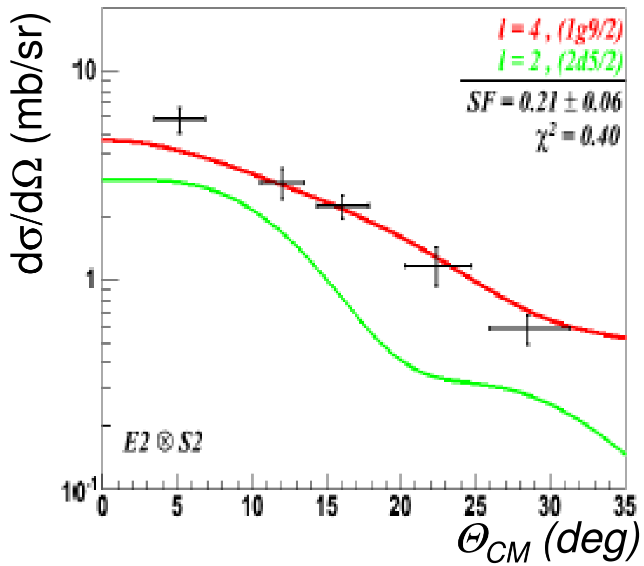
E_x = 2.05 MeV



E_x = 2.74 MeV



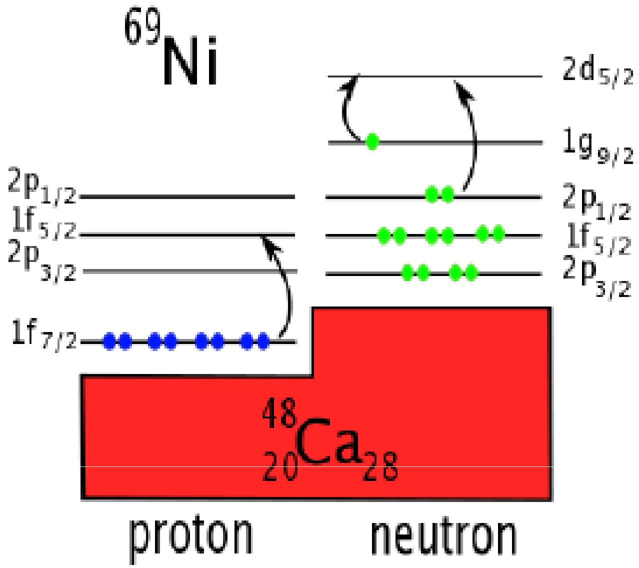
L=2
C^2S = 0.44 ± 0.13



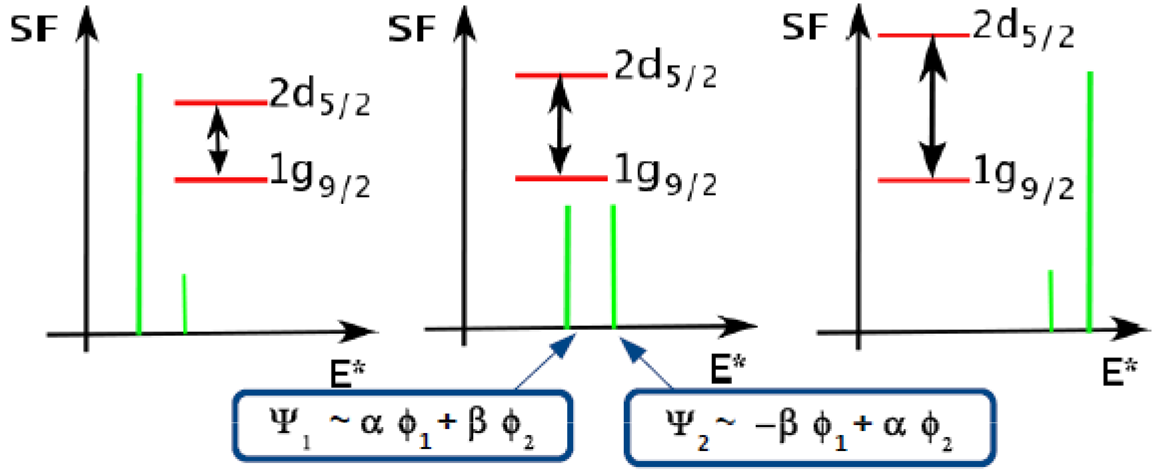
L=4
C^2S = 0.21 ± 0.06

We favor the interpretation in terms of two l=2 fragments

Comparison with Shell model calculations

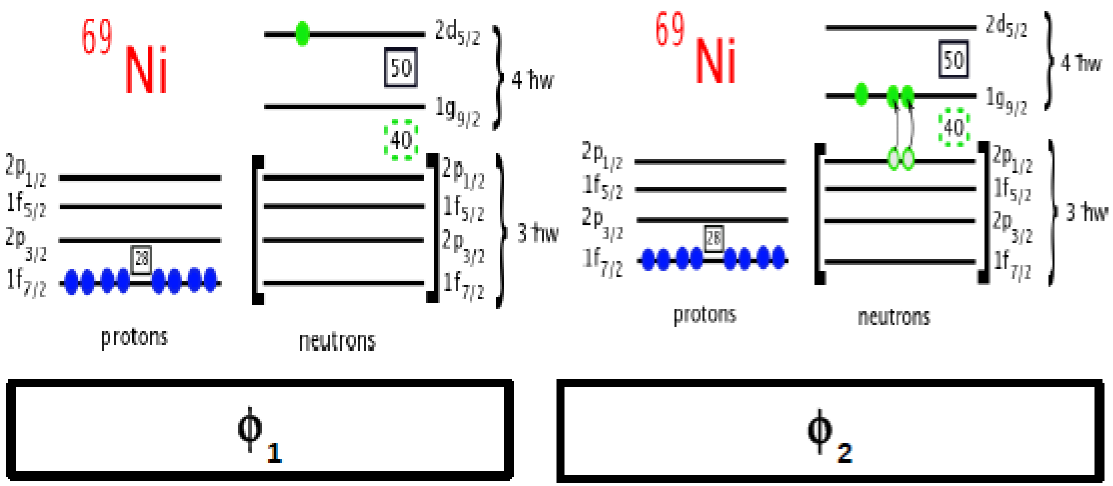


Doublet of 5/2+ states predicted

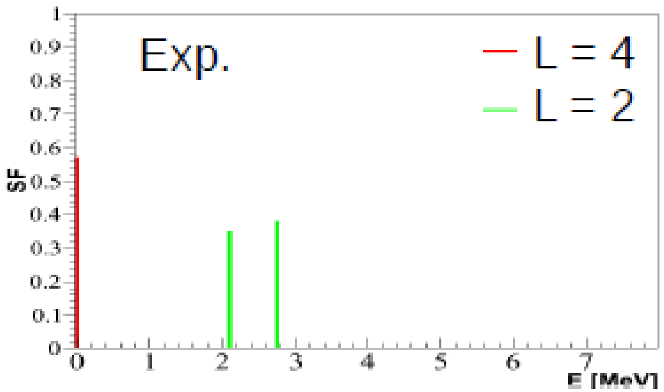


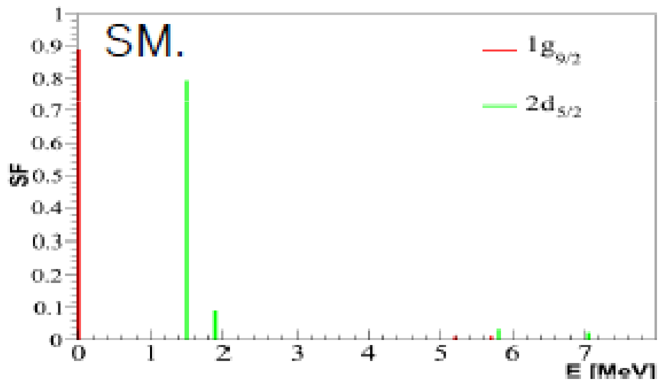
- **LPNS interaction**
- **fp shell + $1g_{9/2}$, $2d_{5/2}$ $3s_{1/2}$**

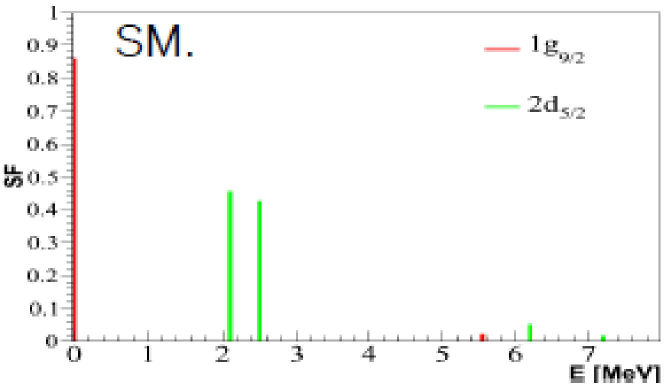
S.Lenzi et al., PRC82 (2010)
Sieja and Nowacki, submitted



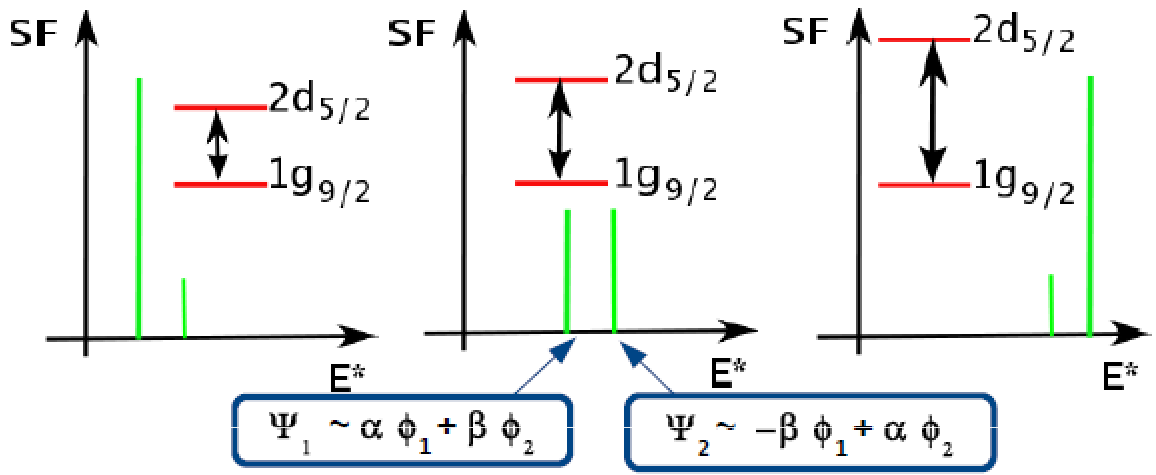
Comparison with Shell model calculations

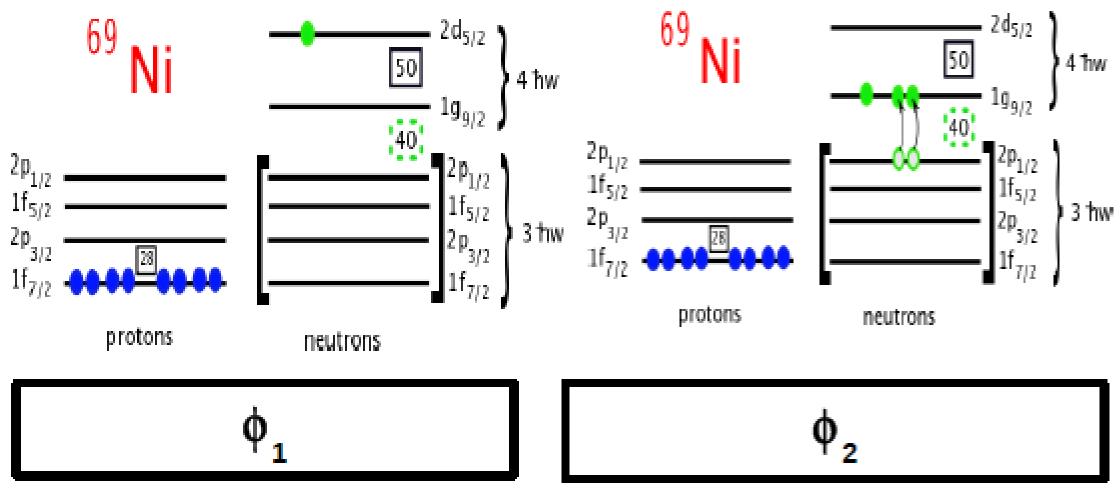






Doublet of 5/2+ states predicted





Conclusions

- $^{68}Ni(d,p)$ @ 25 MeV suitable for study of ($L \geq 2$) shell structure of ^{69}Ni
- Spin and parity assignement for the G.S. (9/2+) and for the doublet at 2.47 MeV with sizeable spectroscopic factors

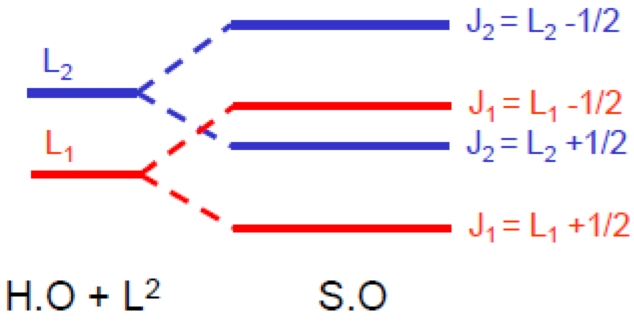
Energy [MeV]	L	Jπ	SF
0.00	4	9/2+	0.61±0.15
2.05 2.74	2 2	5/2+ 5/2+	0.32±0.10 0.44±0.13

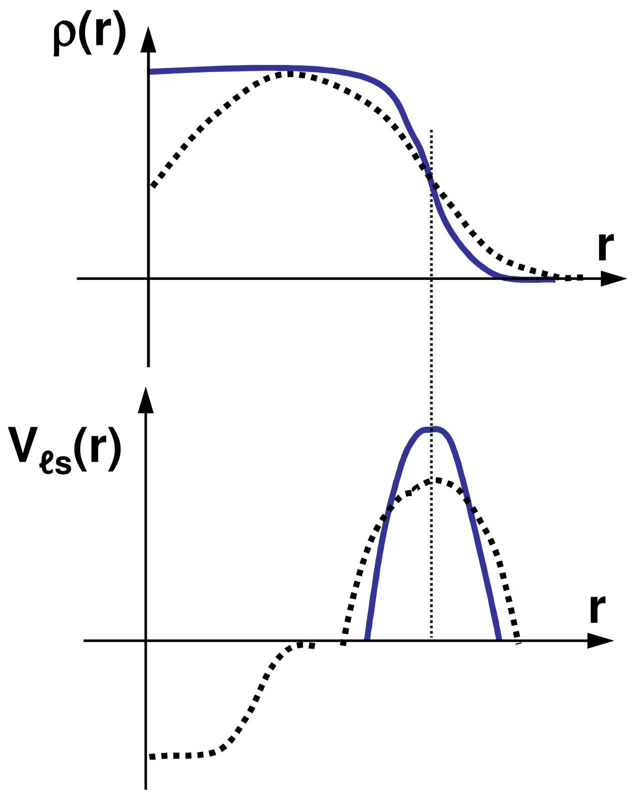
- Good agreement with Shell Model calculations
  Validation of the hypothesis postulated by the Strasbourg group on the small energy gap between $1g_{9/2}$ and $2d_{5/2}$
  (Caurier et al., EPJA 15, 145 (2002))
- identification of a neutron state at 4.2 MeV and two resonances at ~5.9 and ~6.9 MeV

<u>Outlook</u>: Data analysis of γ-rays (EXOGAM) for more accurate determination of excitation energies

How to probe the properties of the spin-orbit interaction

$$V_{ls}(r) \propto \frac{1}{r}\frac{d}{dr}\left[A\rho_n(r) + B\rho_p(r)\right]\cdot\left(\vec{l}\cdot\vec{s}\right)$$





normal mean field

.... central depletion

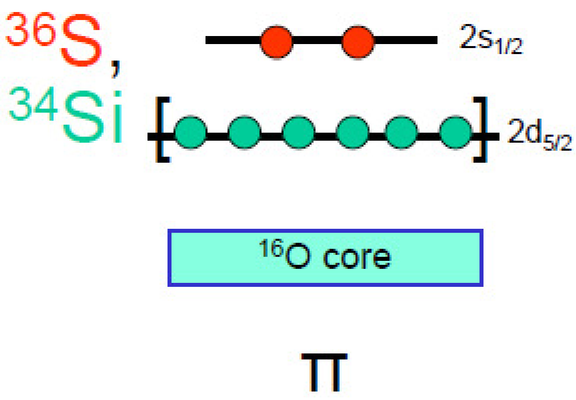
Density and Isospin dependence of SO interaction not firmly established

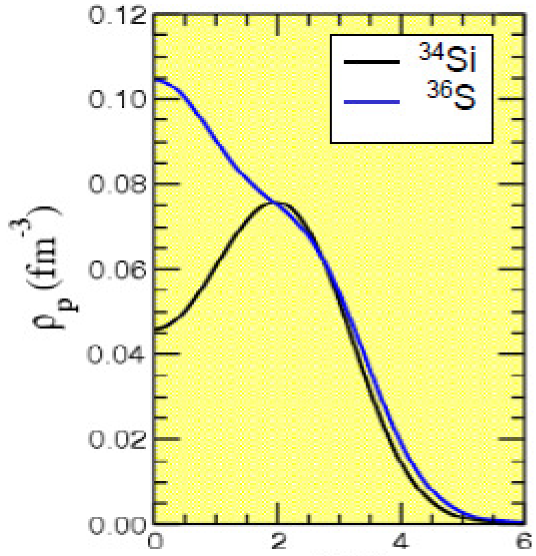
Bubble nuclei ⟷ Probe of the SO density dependence

Optimum experimental candidate : ^{34}Si

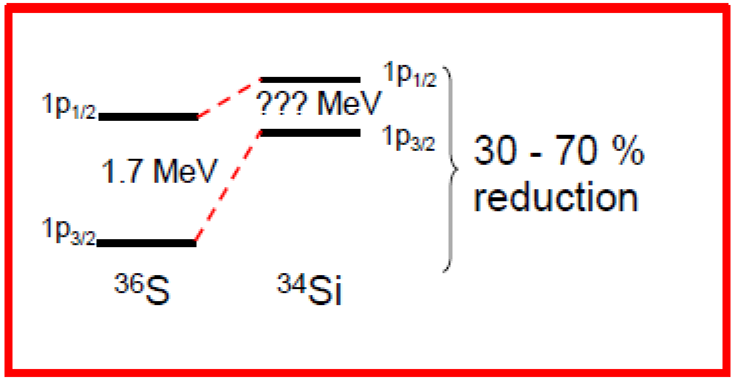
From G.Burgunder

How to probe the properties of the spin-orbit interaction



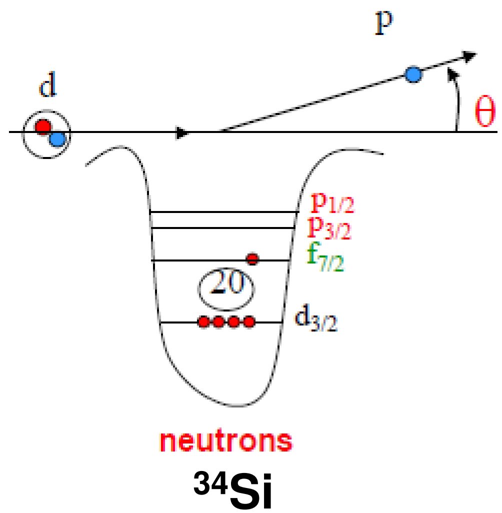


What impact on the neutron orbits ?



EXPERIMENT NEEDED

Use ^{34}Si(d,p) and ^{36}S(d,p)



NB : no contribution from tensor term

From G.Burgunder

Collaboration

G. Burgunder, O. Sorlin, L. Caceres, E. Clement, G. De France, B. Fernandez,
S. Grevy, R. Raabe, C. Stoedel, J.C. Thomas
(GANIL-Caen)

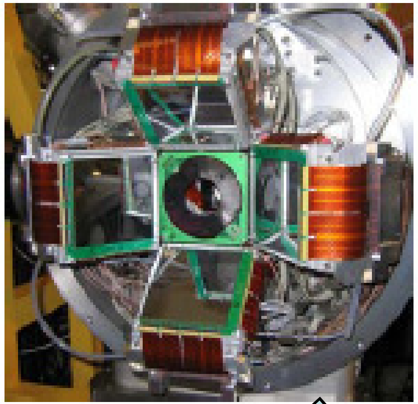
S. Giron, F. Hammache, N. de Séréville, D. Beaumel, S. Franchoo, J. Guillot,
F. Maréchal, A. Matta, Y. Matea, L. Perrot,
J. A. Scarpaci, I. Stefan
(IPN-Orsay)

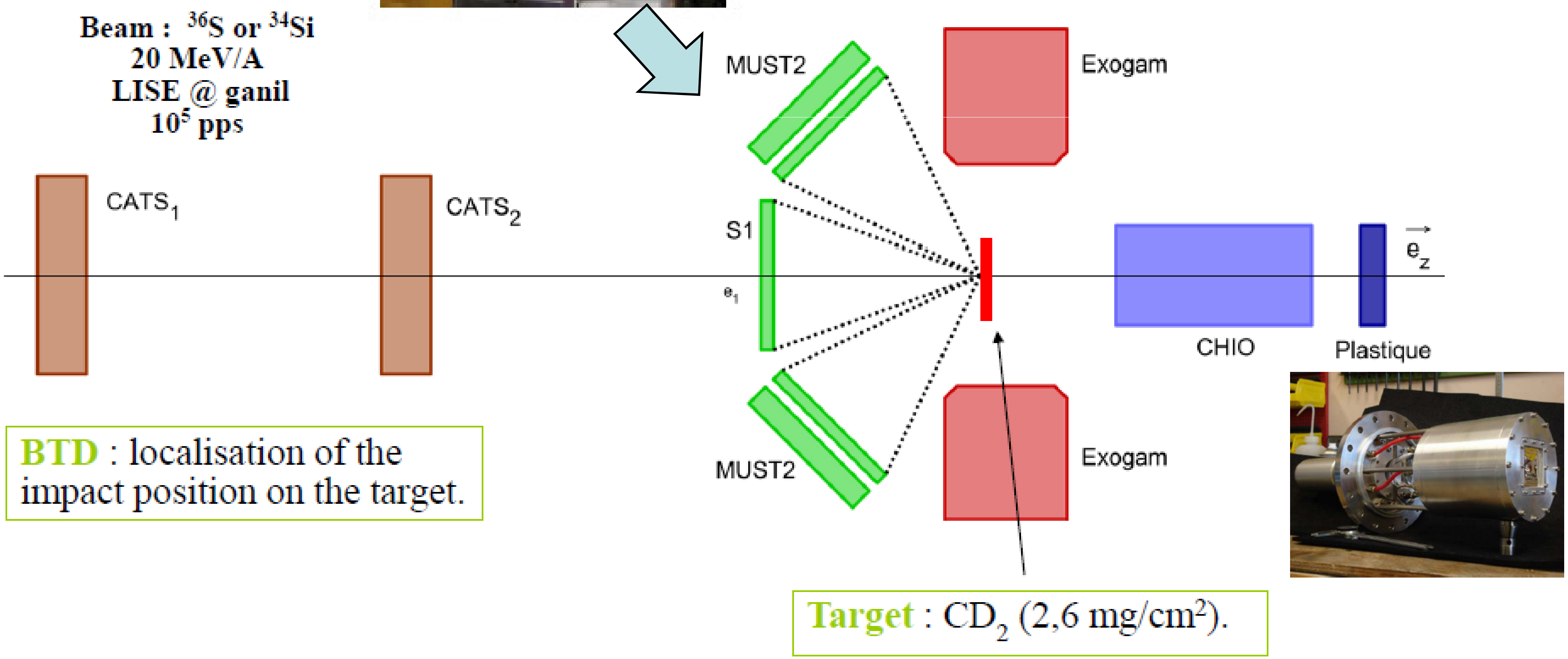
F. Flavigny, A. Gillibert, V. Lapoux, L. Nalpas, A. Obertelli
(SPhN Saclay)

G. Duchene, M. Moukaddam (IRES-Strasbourg)

J. Gibelin (LPC-Caen)

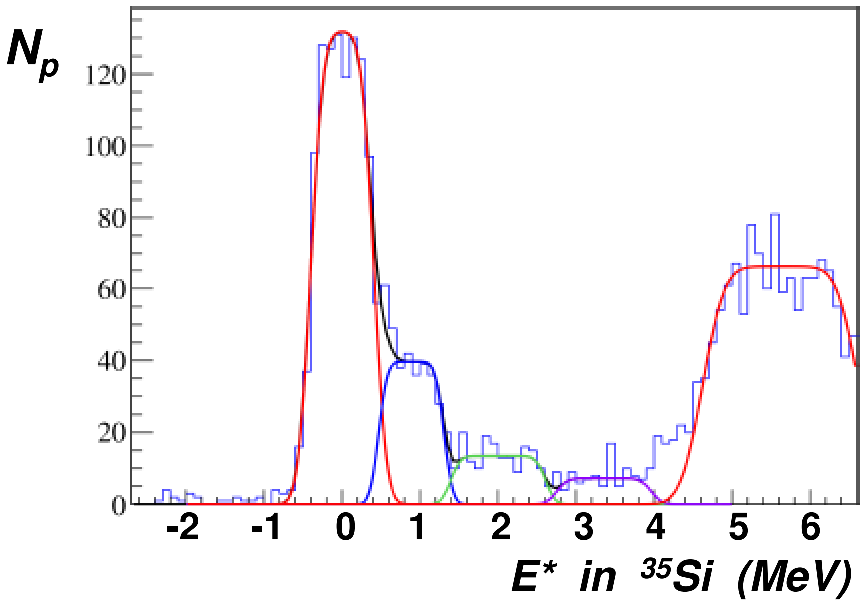
Experimental setup



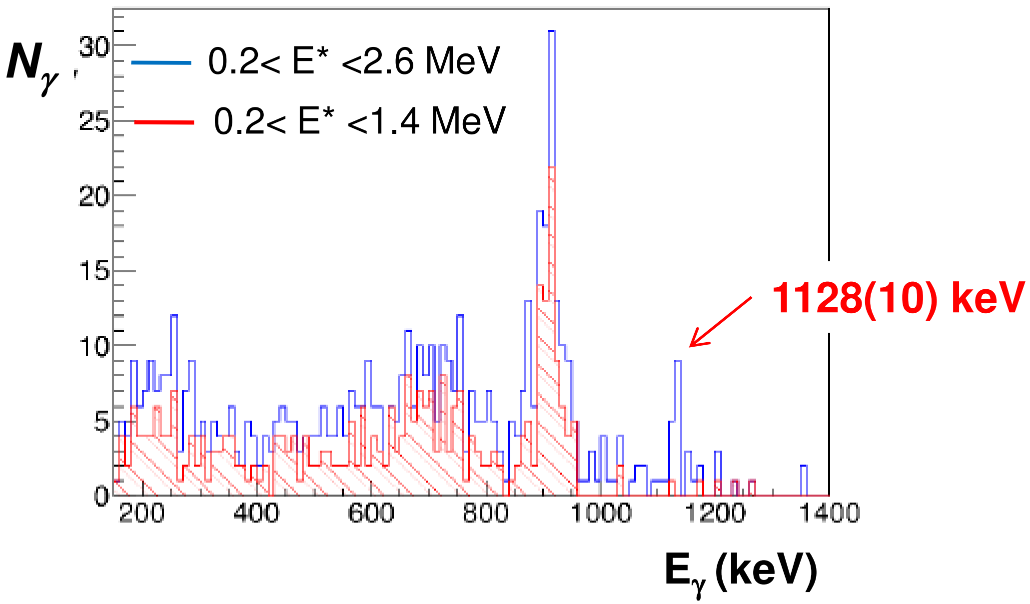


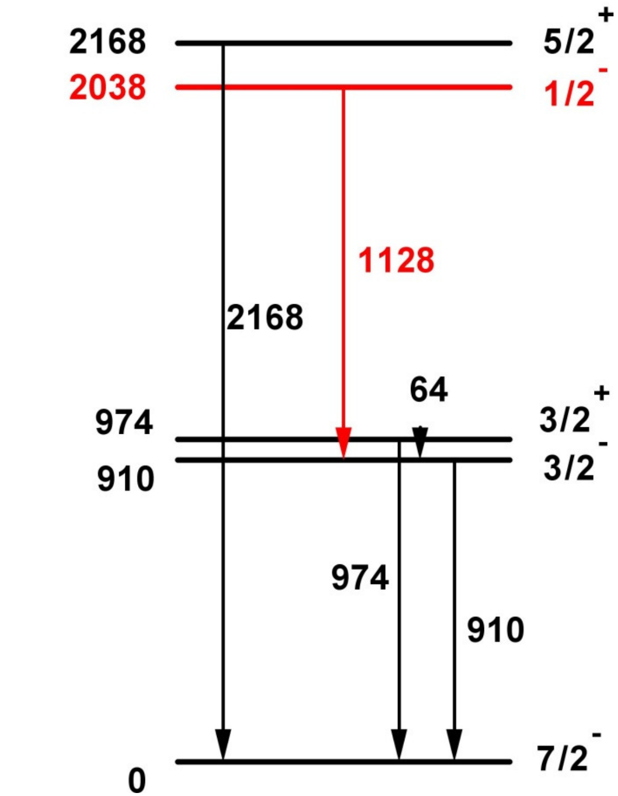
From G.Burgunder

Results for $^{34}Si(d,p)^{35}Si$

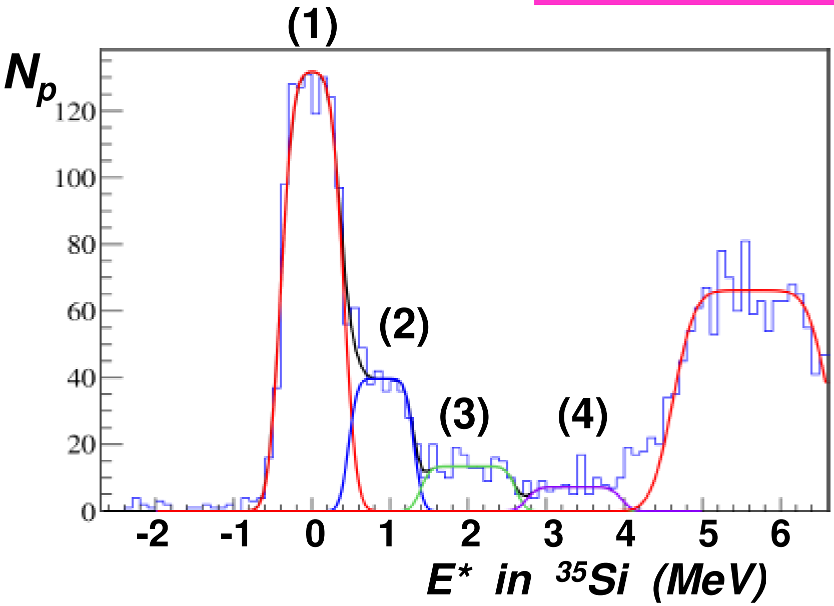


Spectrum is decomposed in 5 peaks



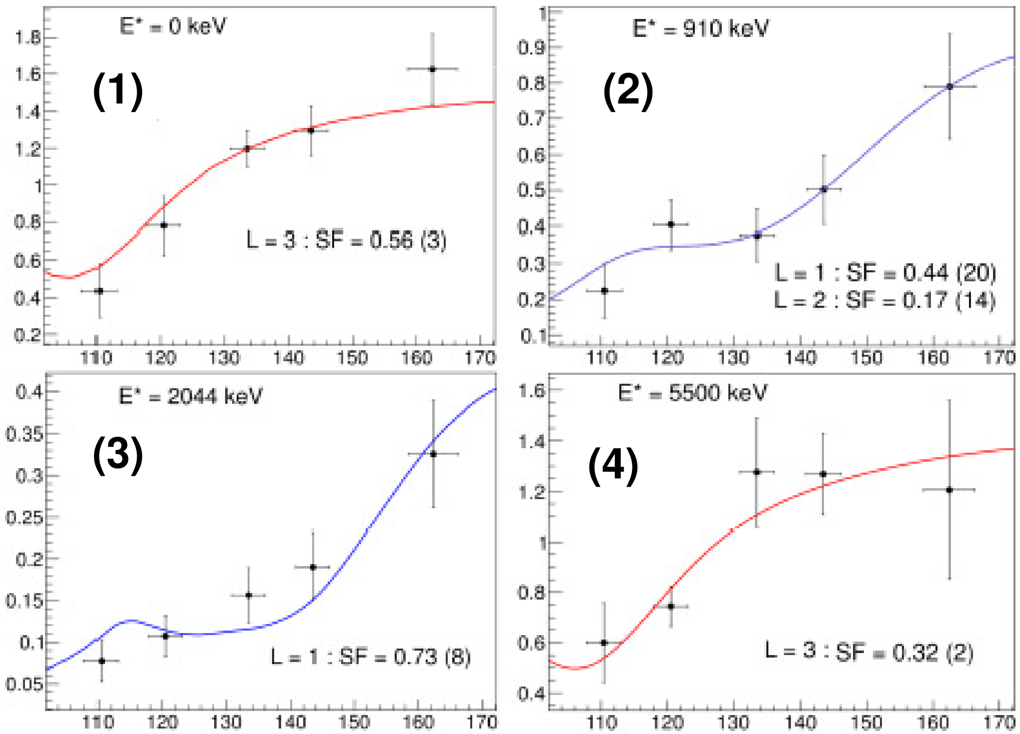


Results for $^{34}Si(d,p)^{35}Si$



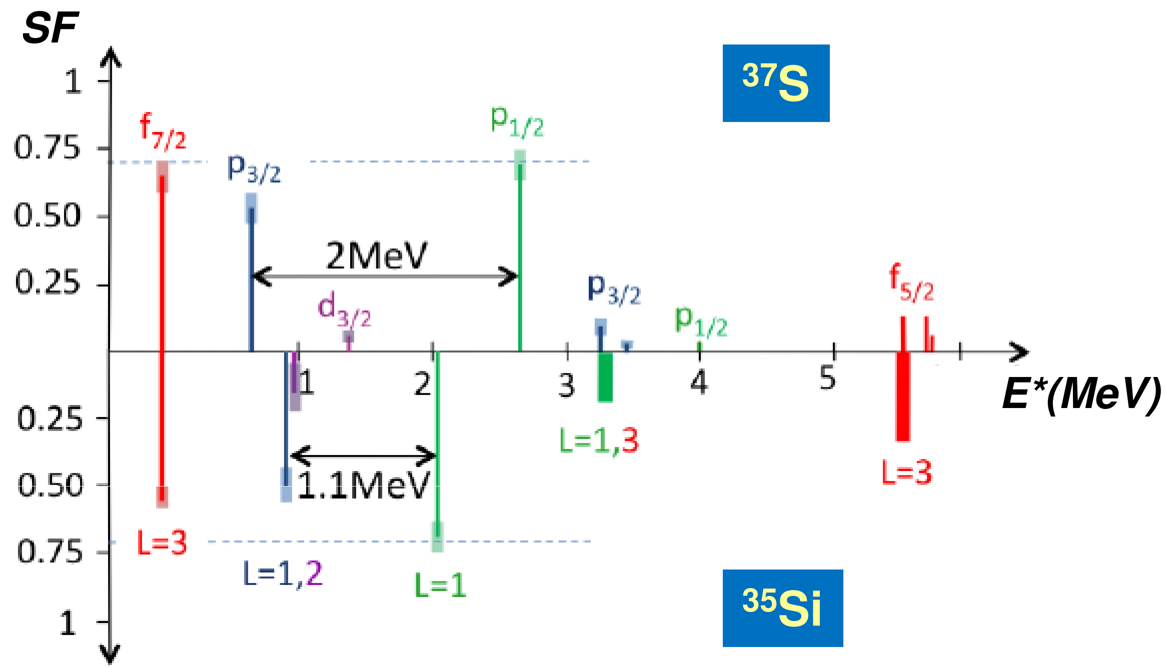
ADWA calculations

ANGULAR DISTRIBUTIONS



Comparison ^{35}Si vs ^{37}S

Experimental single-particle strength distribution (preliminary)



- Need include contribution of all fragments
- Use all available data for ^{36}S and SM for ^{34}Si

A change by 25% in the SO splitting is derived between ^{37}S and ^{35}Si

- Not observed between ^{41}Ca and ^{37}S
- Being compared with model predictions
  RMF models seem predict bigger change (~70%)