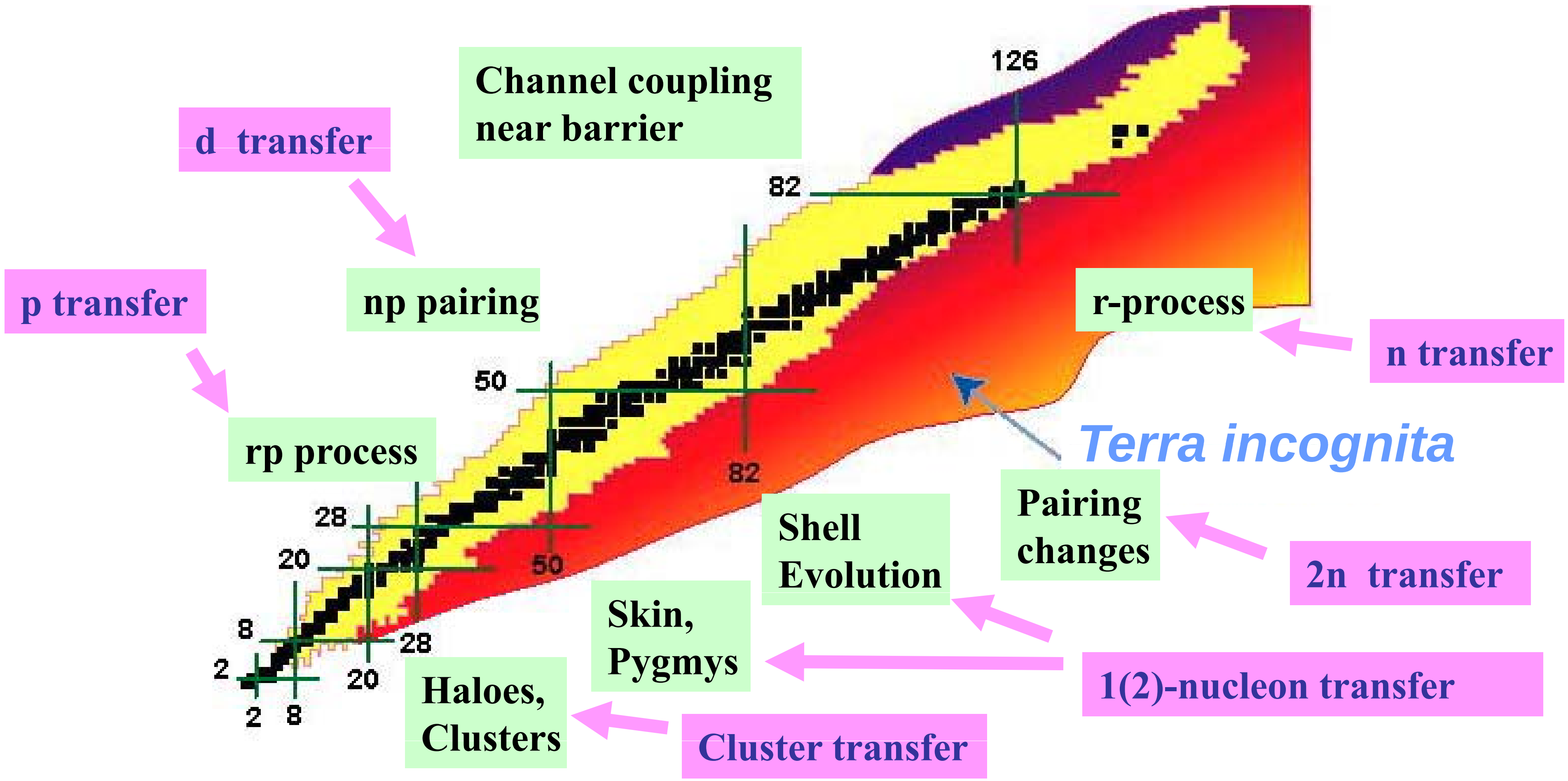
Perspectives in transfer reactions at next generation European RIB facilities

D. Beaumel,
IPN Orsay / RIKEN Nishina center

- **Recent transfer reaction studies**
  Shell evolution at N ~ 40
- **New devices**
  Silicon-based arrays - GASPARD project
- **Pairing studies at future ISOL facilities**

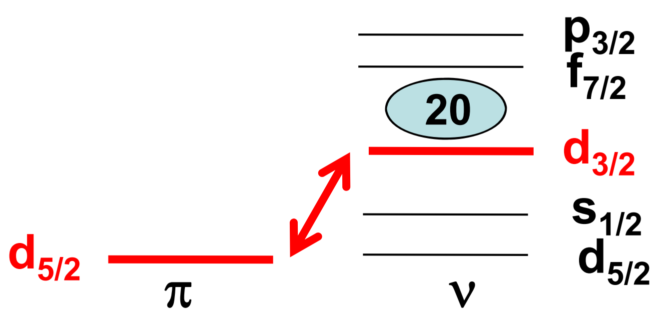
Transfer reactions

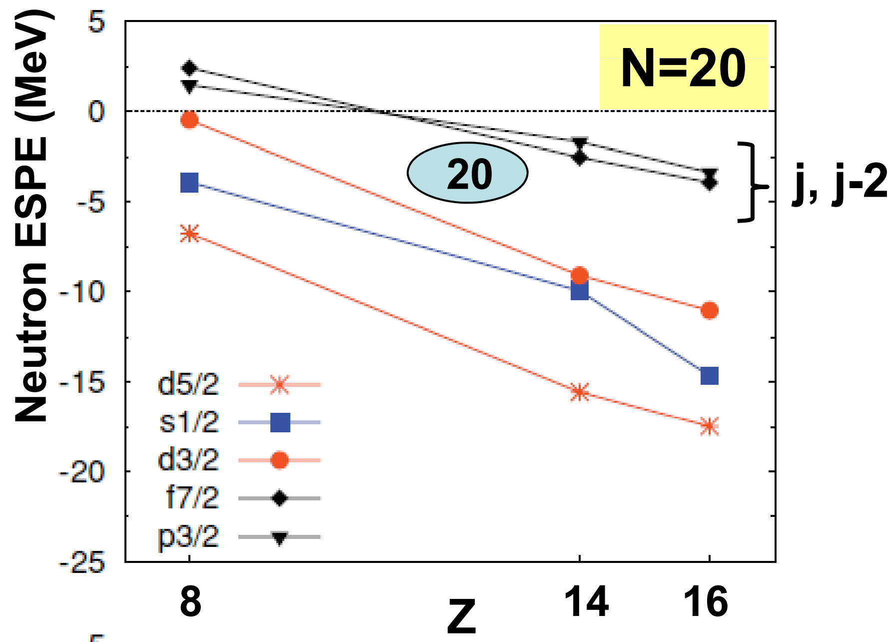
A great tool to investigate Exotic Nuclei and astrophysics processes



Good energy regime : few MeV/u → few tenths of MeV/u

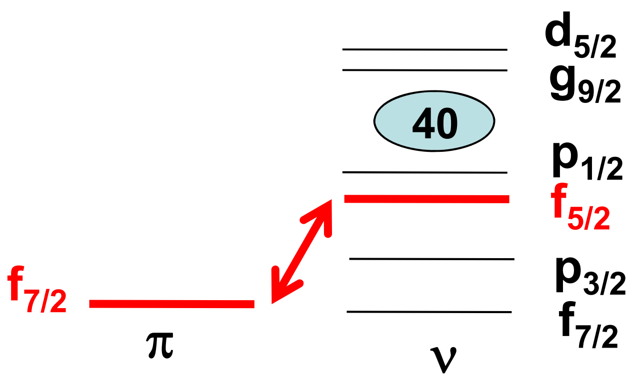
Evolution of Harmonic Oscillator Shell Closures

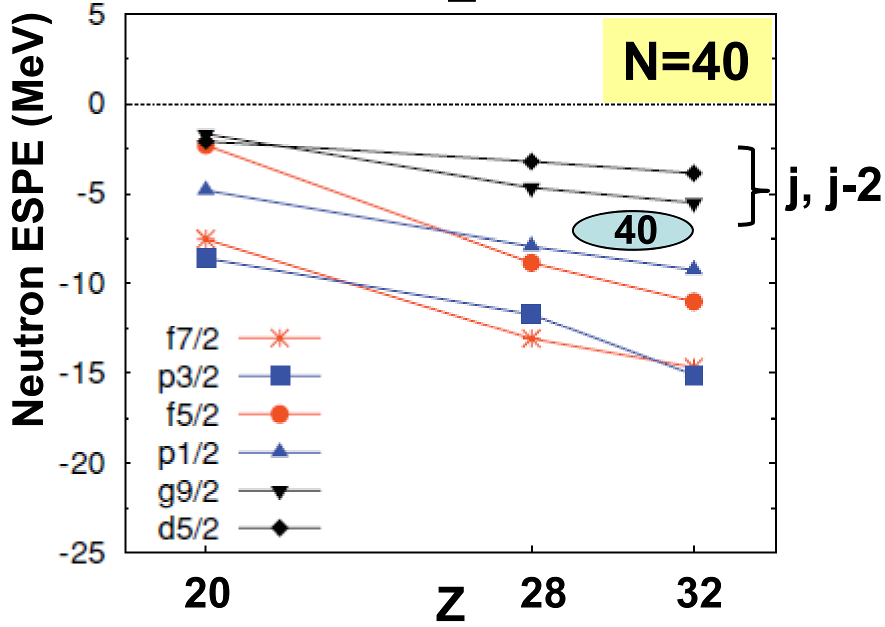




- ***reduction of the gap when Z decreases***
- ***quasi-degeneracy of a j,j-2 sequence above the fermi surface***

Similar situation for N=40

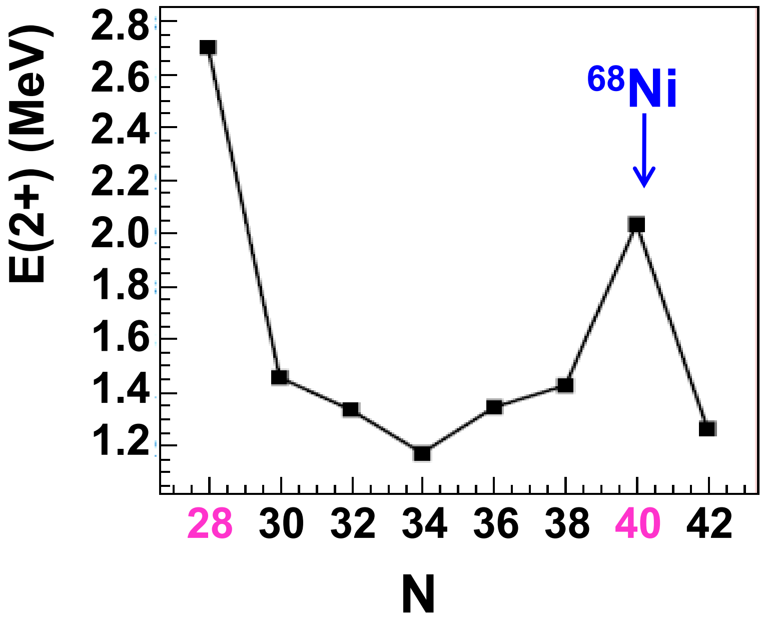


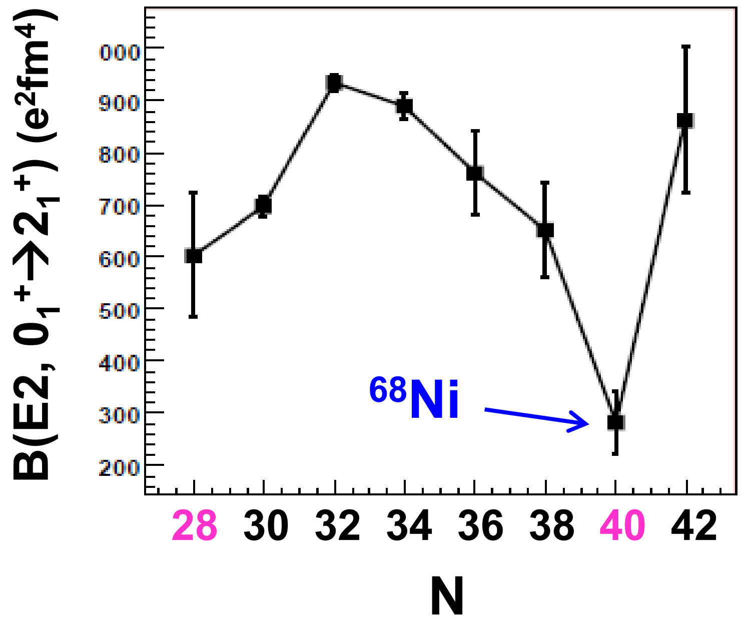


(and also at N=8)

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

The Nickel isotopes



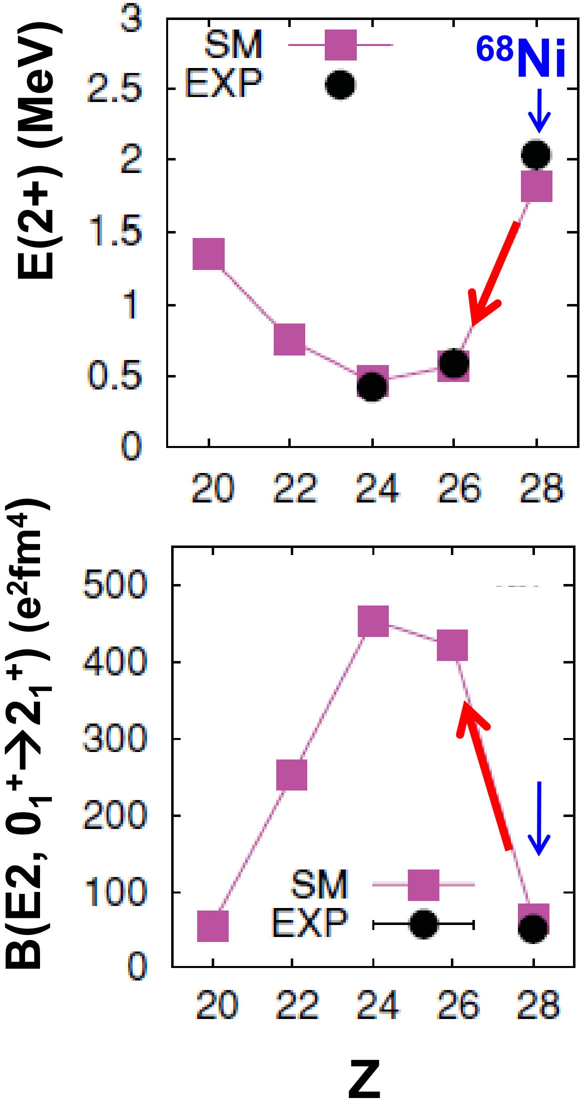


For ^{68}Ni :

- ➢ **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

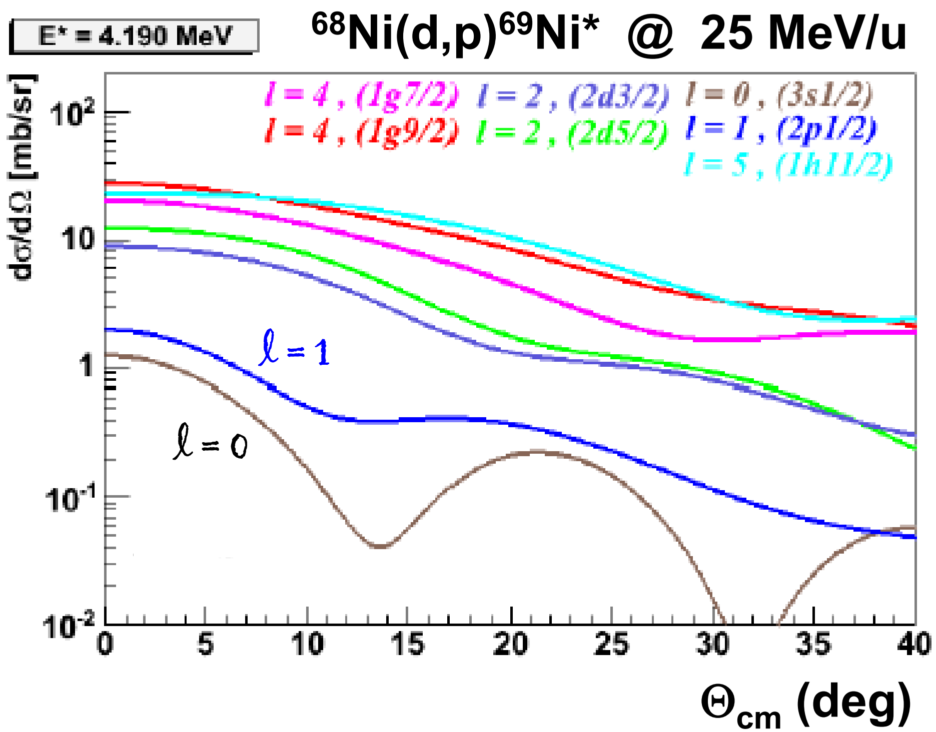
New island of inversion

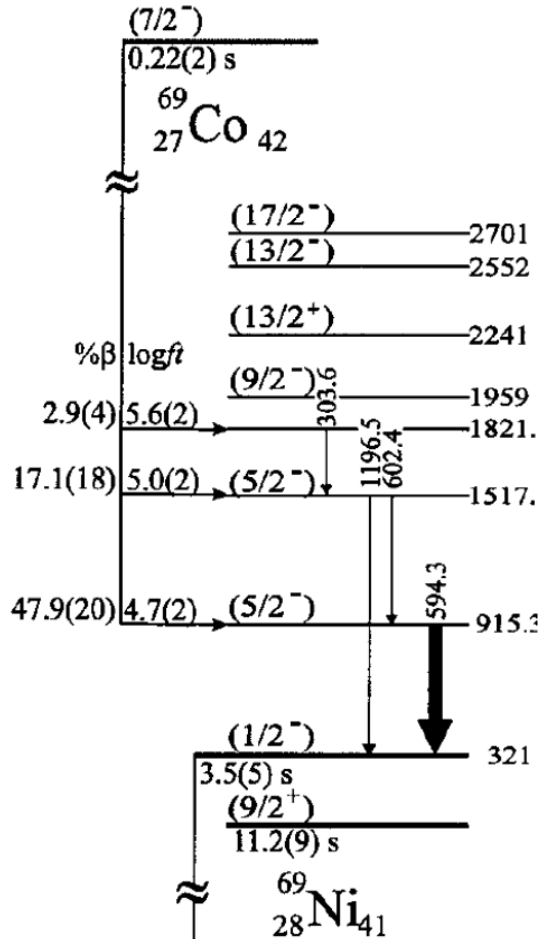
$2d_{5/2}$ plays a major role in the deformation mechanism at N = 40 *Caurier et al. EPJ, A, 15, 2002, 145*

Study of the ^{68}Ni(d,p) reaction

- **Selective of single-particle state**
- $9/2^+$ ground state
- Promotion of the single neutron from g9/2 g.s. to d5/2

  g9/2 – d5/2 gap
- Search for l=2 υ states in excitation energy range 0.5 to 4 MeV





Collaboration

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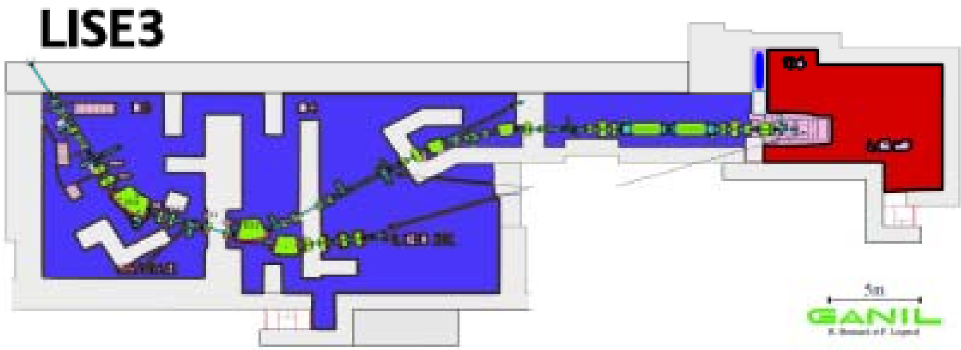
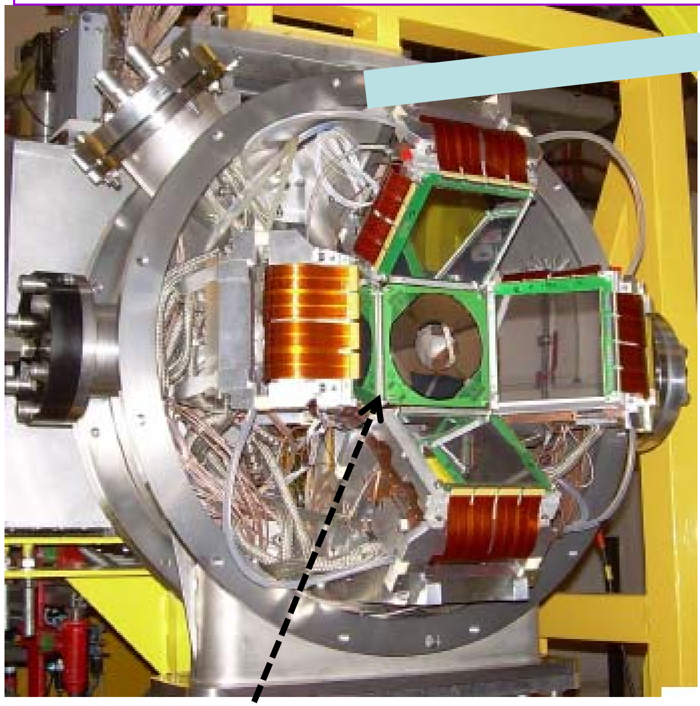
Experimental setup



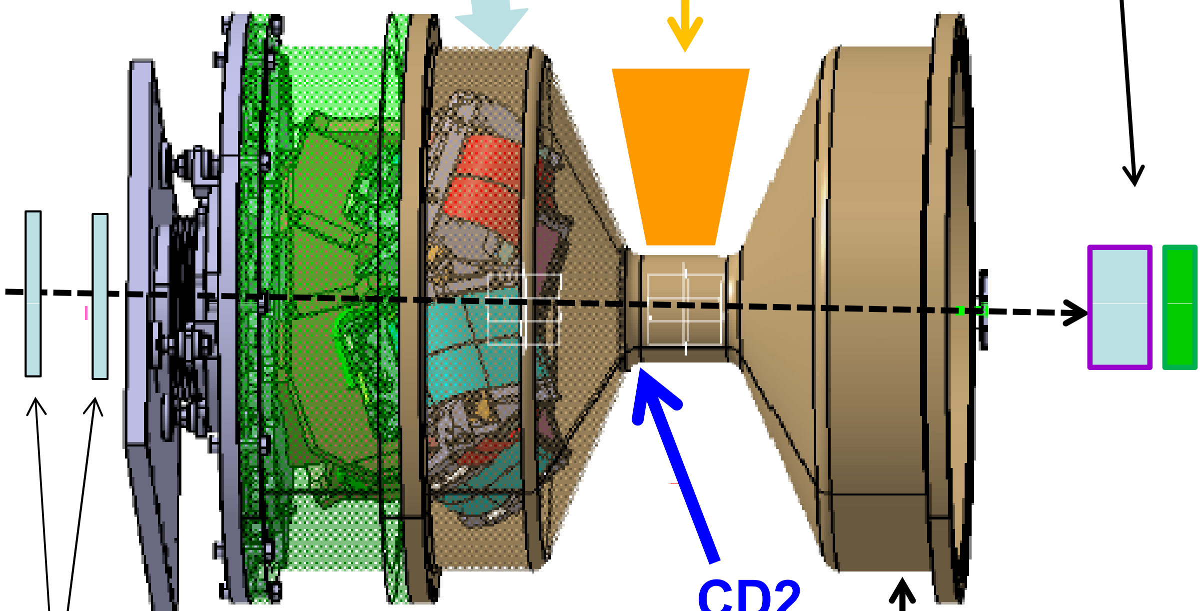
Primary beam: ^{70}Zn
^{68}Ni @ 25 MeV/u, rate: ~8.10^4 pps
Purity : 86%

4 MUST2 telescopes + S1 annular



4 EXOGAM Clovers

Ionization Chamber + Plastic



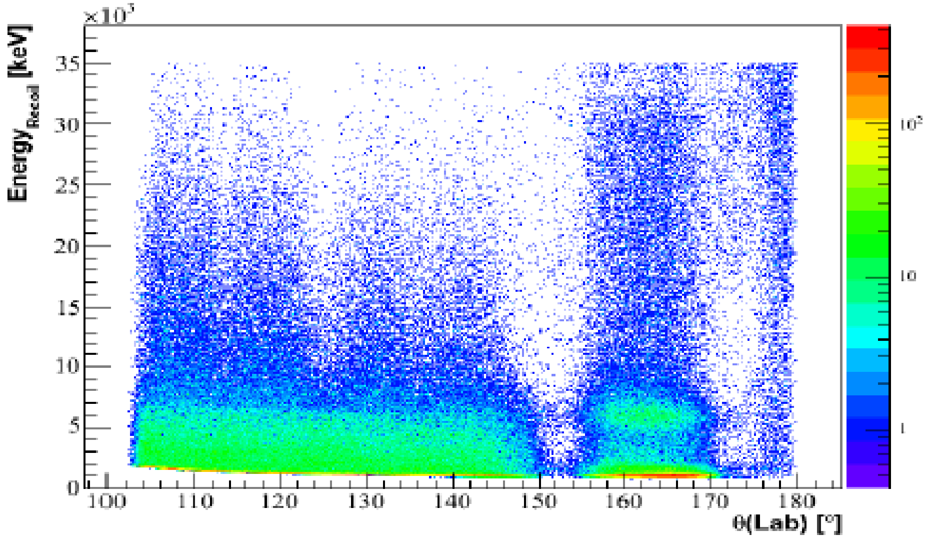
Beam tracking detectors

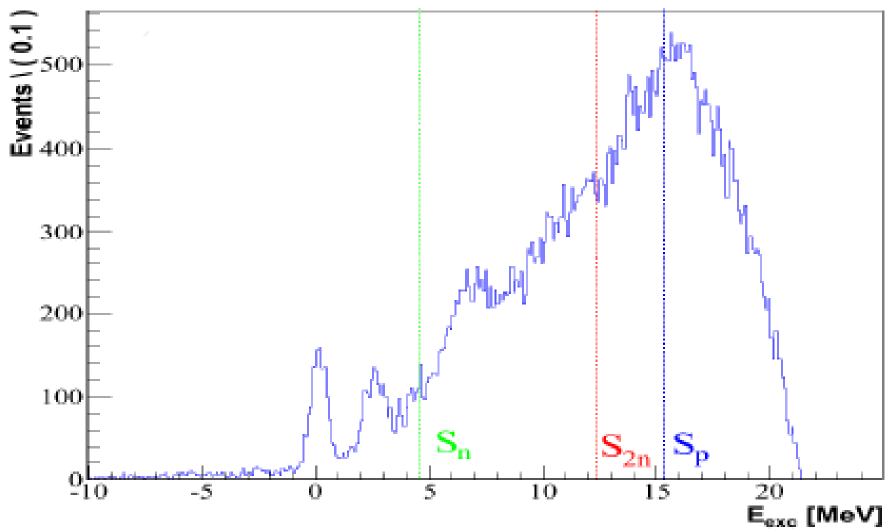
CD2

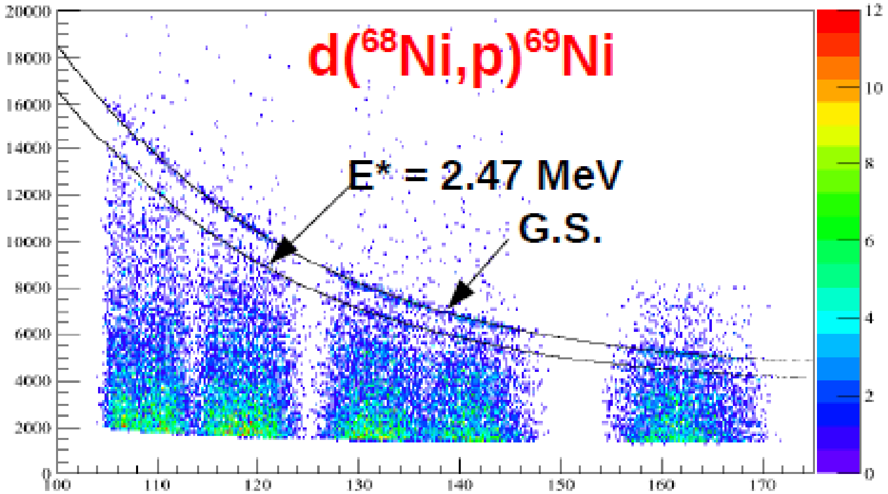
TIARA vessel

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

Kinematical plots and E spectrum*

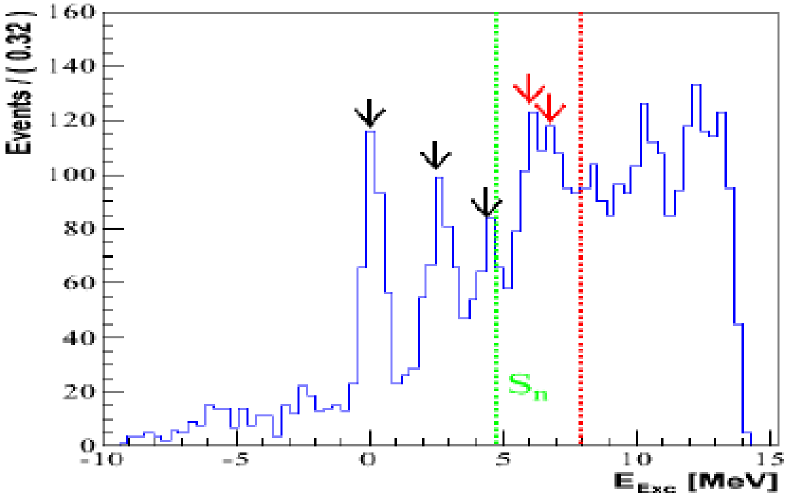






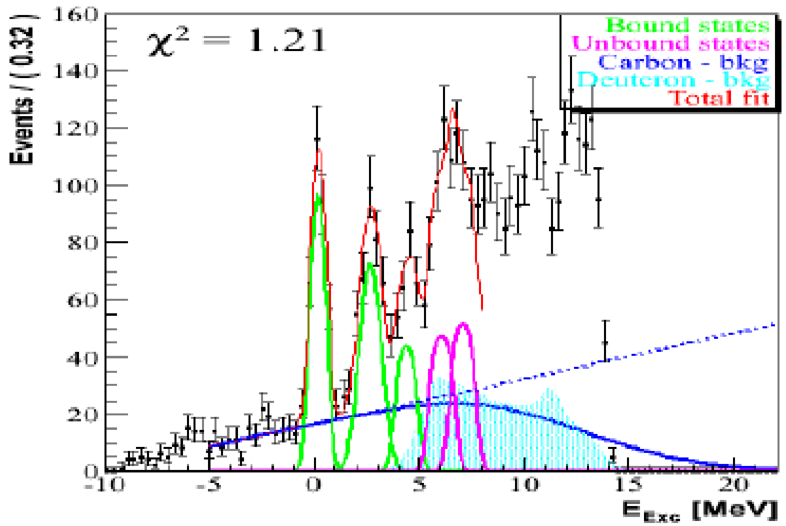
- Pronounced G.S.
- 1st excited state at ~ 2.5 MeV
- Structures ~ 4 MeV
  and 6−7 MeV (> S_n)

Excitation energy spectrum



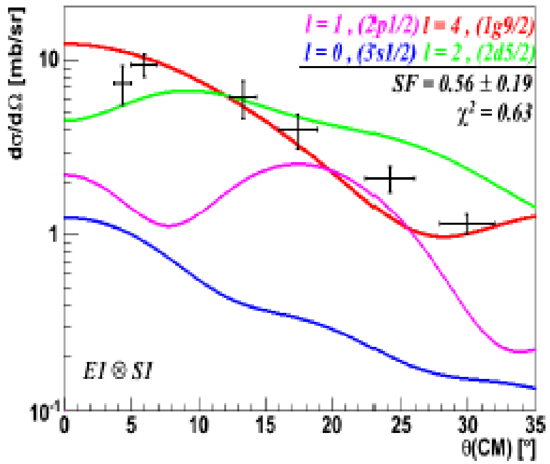
- 3 bound states
- 2 resonances above S_n
- Background reactions

Energy reference : S1 [156°-170°]

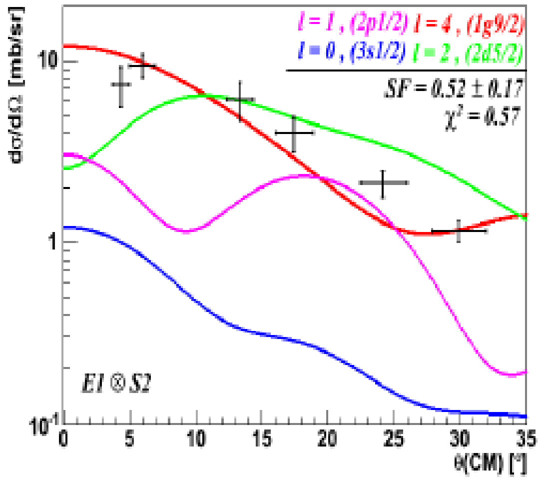


Pic #	Energy [MeV]	FWHM [MeV]
G.S	0.00	1.04
1	2.47	**1.43**
2	4.19	1.27
3	5.88	1.39
4	6.89	1.39

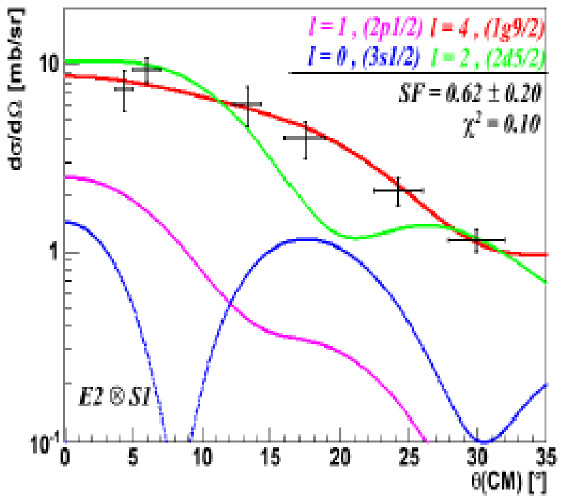
Angular distribution for ^{69}Ni ground-state



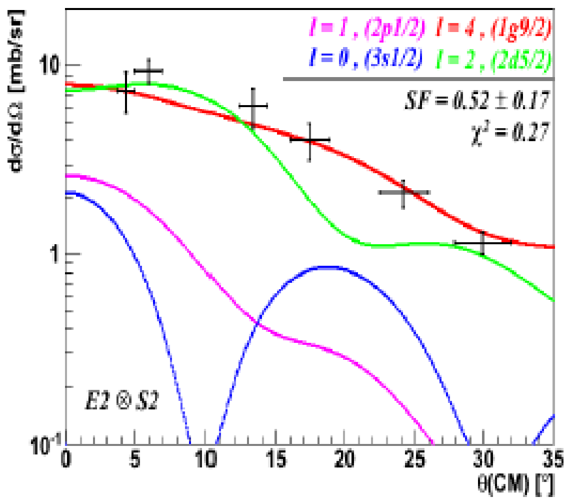
E1 ⊗ S1



E1 ⊗ S2



E2 ⊗ S1



E2 ⊗ S2

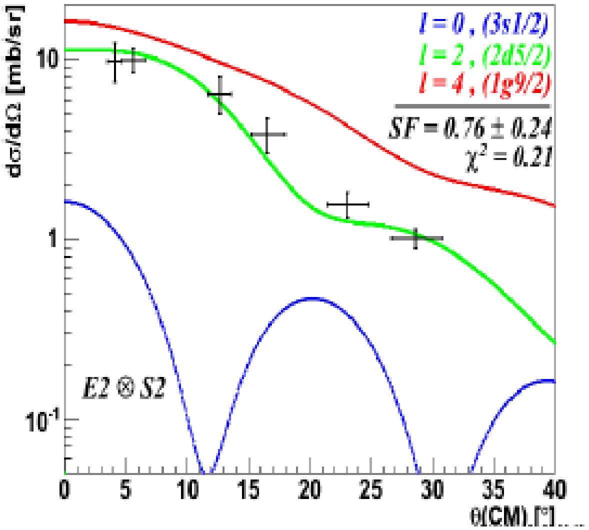
ZR code DWUCK4
4 sets of opt. potentials
L = 0,2,4

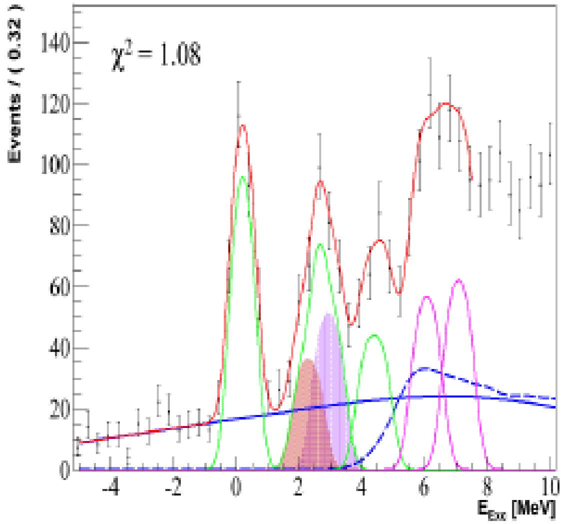
- **Weak dependence on the exit channel pot.**
- **Significant dependence on the entrance pot.**

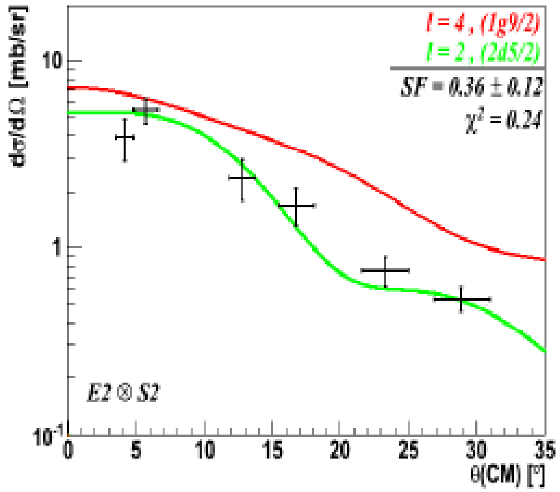
Adiabatic channel (ADWA) provides better agreement

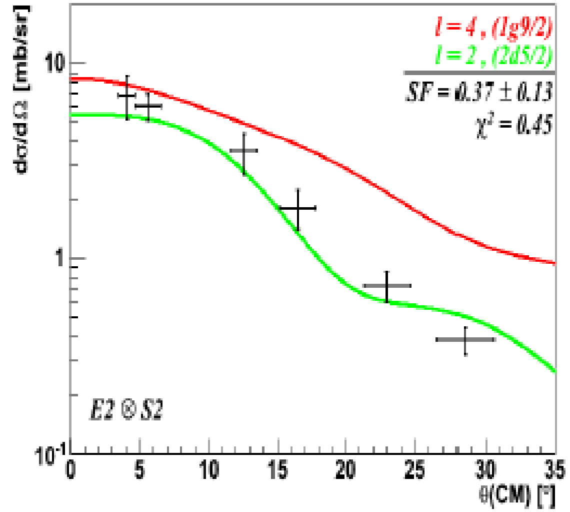
GS of ^{69}Ni : L=4 (1g9/2)
SF : C^2S = 0.52 ± 0.17

$^{68}Ni(d,p)^{69}Ni^*$ *first excited peak*







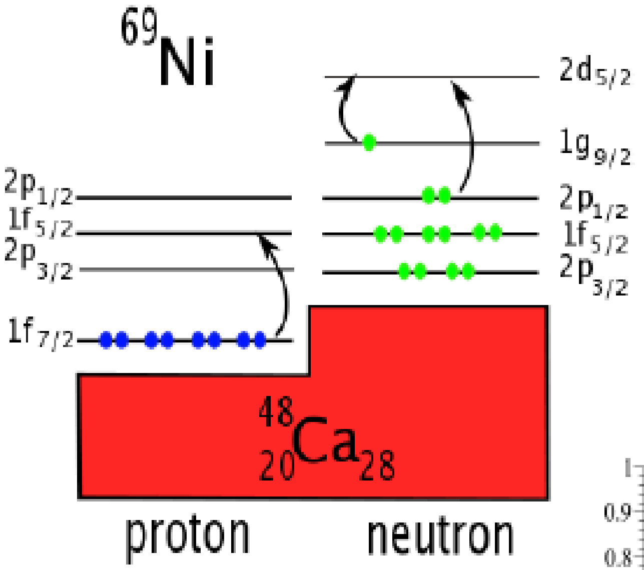


- L = 0, 2 and 4
- E_{exc} = 2.47 MeV
  - → **L = 2, SF = 0.76 ± 0.24**

- → E_{exc} = 2.11 MeV
  - → **L = 2, SF = 0.36 ± 0.12**
- → E_{exc} = 2.76 MeV
  - → **L = 2, SF = 0.37 ± 0.13**

From M.Moukaddam

Comparison with Shell model calculations

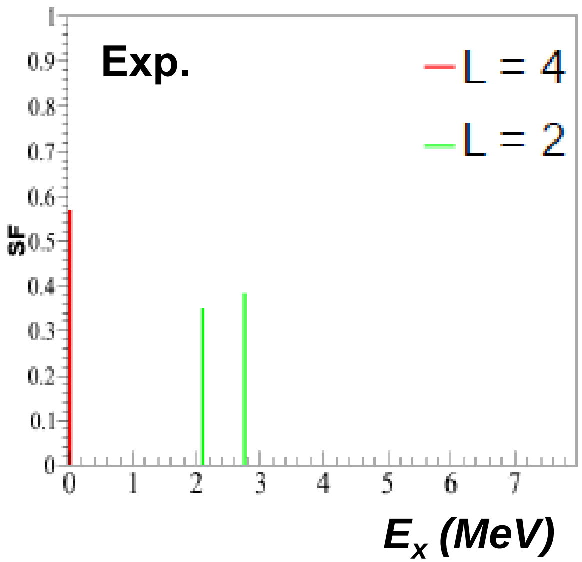


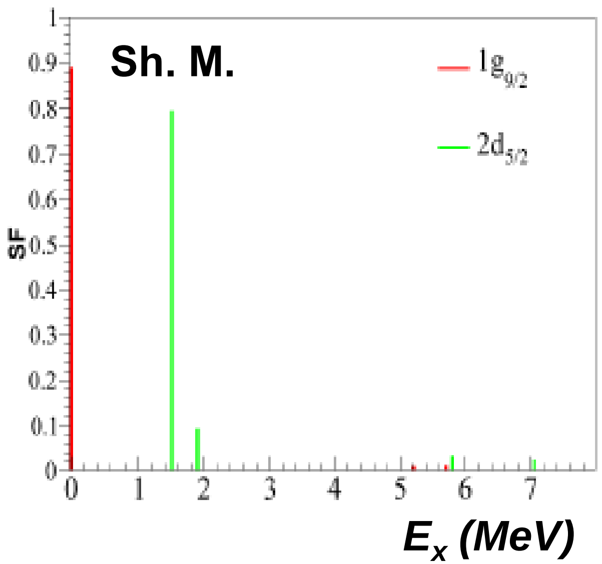
- **LPNS interaction**
- **fp shell + $1g_{9/2}$ and $2d_{5/2}$**

  S.Lenzi et al., PRC82 (2010)

  Sieja and Nowacki, submitted

Spectroscopic factors

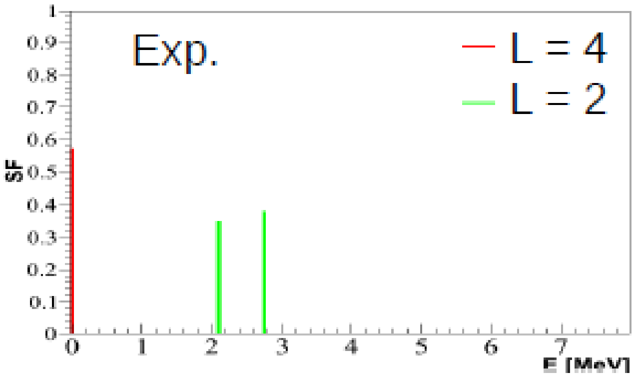


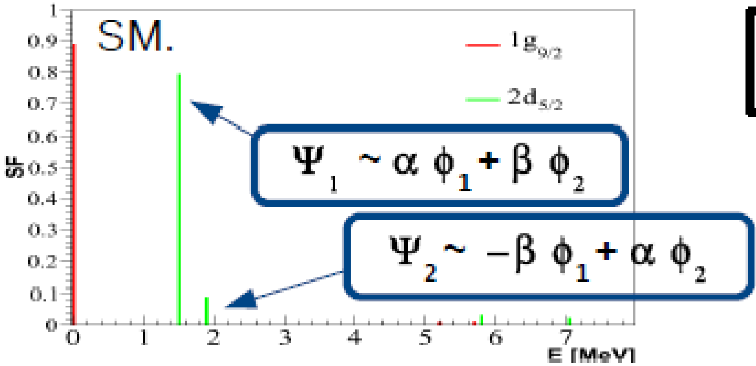


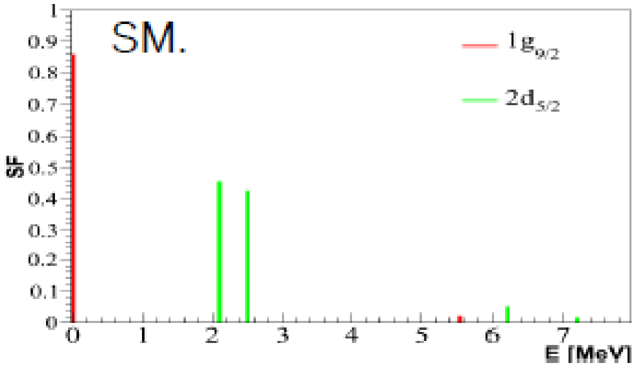
Good overall agreement

- **$1g_{9/2}$: large SF at 0 MeV**
- **$2d_{5/2}$: doublet of 5/2+ states**

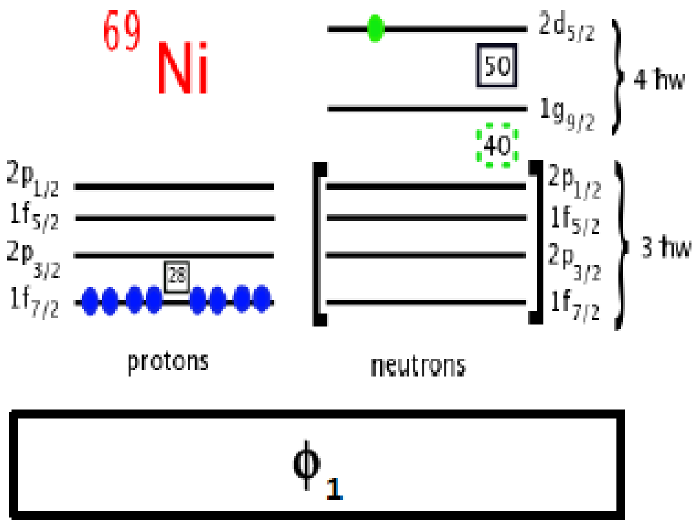
Comparison with Shell model calculations

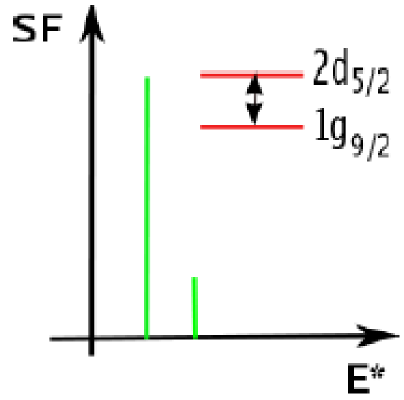


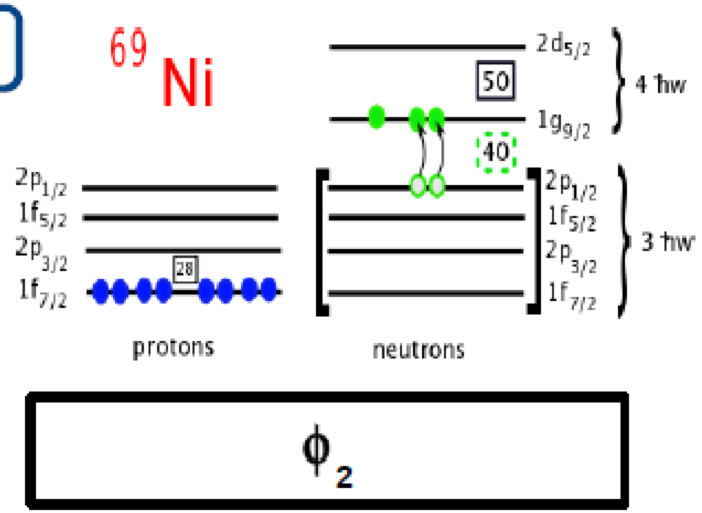


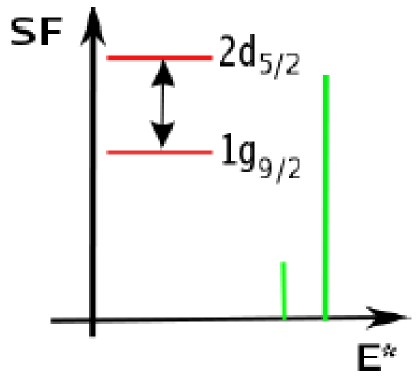


From M.Moukaddam









The s.p. energy of $2d_{5/2}$ has to be lowered to compensate absence of e.g. $3s_{1/2}$

Conclusions

- $^{68}Ni(d,p)$ @ 25 MeV suitable for study of (L ≥ 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 (E2⊗S1)	χ2	SF (E2⊗S2)	χ2	SF average
0.00	4	9/2+	0.62±0.20	0,10	0.52±0.17	0,28	0.57±0.19
2.11	2	5/2+	0.37±0.13	0,41	0.36±0.12	0,24	0.36±0.13
2.76	2	5/2+	0.39±0.14	0,58	0.37±0.13	0,45	0.38±0.14

- 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

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

Limitations of the present setup:
Particle coverage (in view of lower E experiments)
γ – ray efficiency (~8%)

New generation detectors for transfer studies

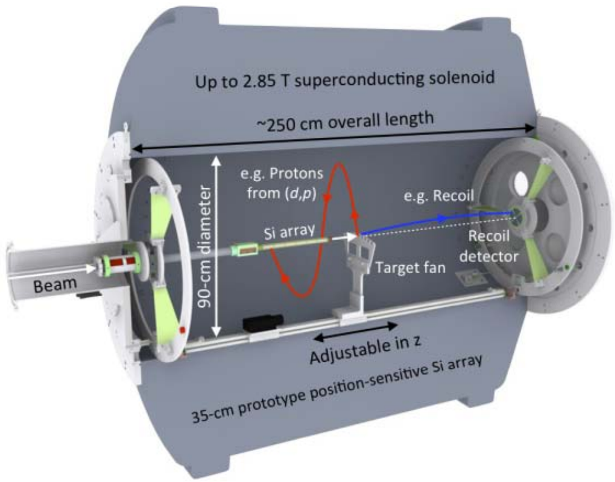
TRACE

GASPARD

HYDE

Silicon based

Solenoid spectrometer



Active Target

actar TPC

Trends for new Si-based arrays

From present facilities to :

Light ions (A≤40) beams ➔ Heavier ions (Fission fragments)

New Si-arrays are optimized for particle–gamma coincidences
i.e. integration capabilities in new generation gamma arrays

Other features:

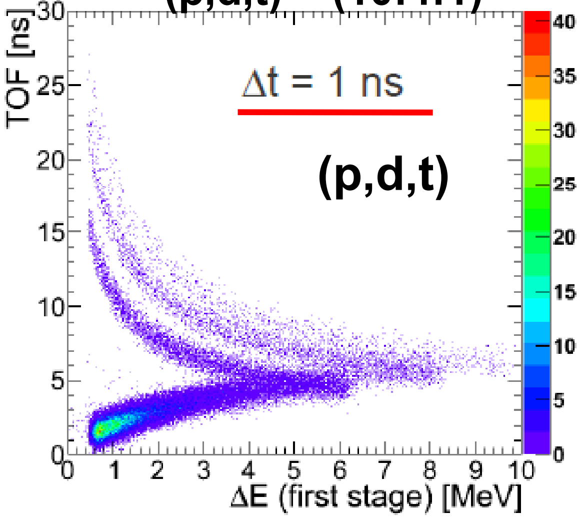
- ***State of the art techniques for PID***
  PSA with digital electronics
- ***Special targets***

PID of low-E light particles (simulations)

TIME OF FLIGHT

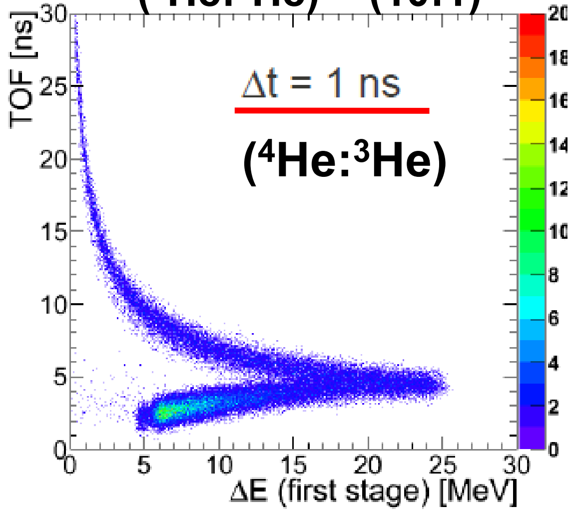
Z = 1

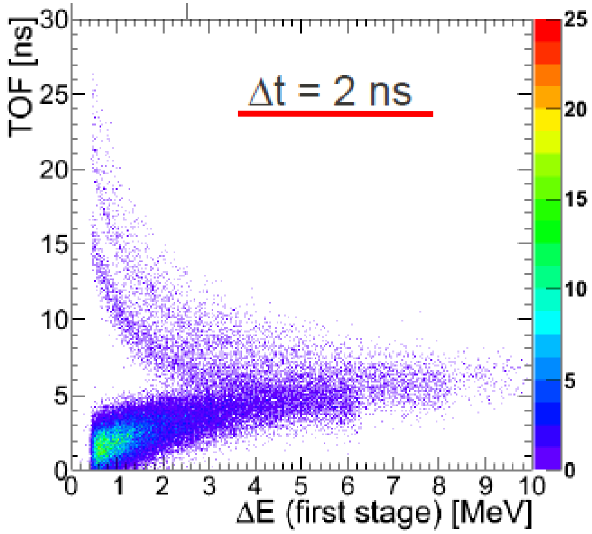
(p,d,t) = (10:4:1)



Z = 2

(^{4}He:^{3}He) = (10:1)



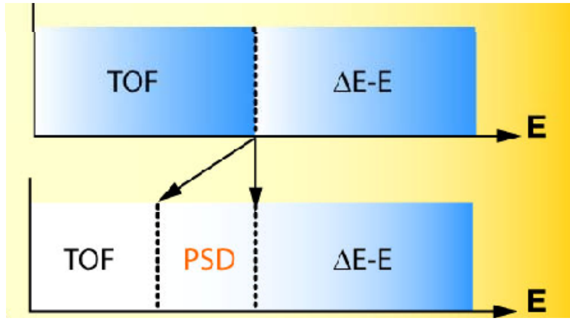


No separation for t/^{3}He, ^{6}He/^{6}Li

NEED FOR THIN LAYERS OF Si

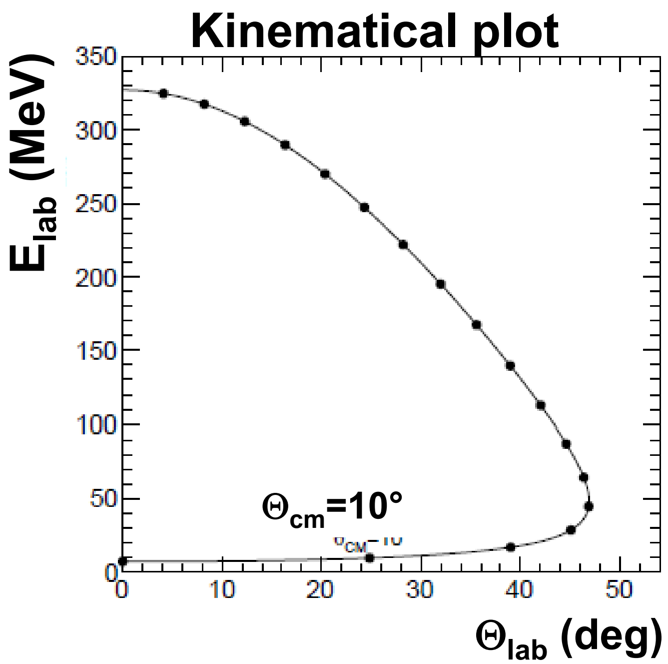
- ***handling problems***
- ***strong inhomogeneities***
- ***dead layers, thresholds***

PSA



- **More compact device (crucial !)**
- **Less Si layers**
- **Need nTD**
- **Digital electronics**

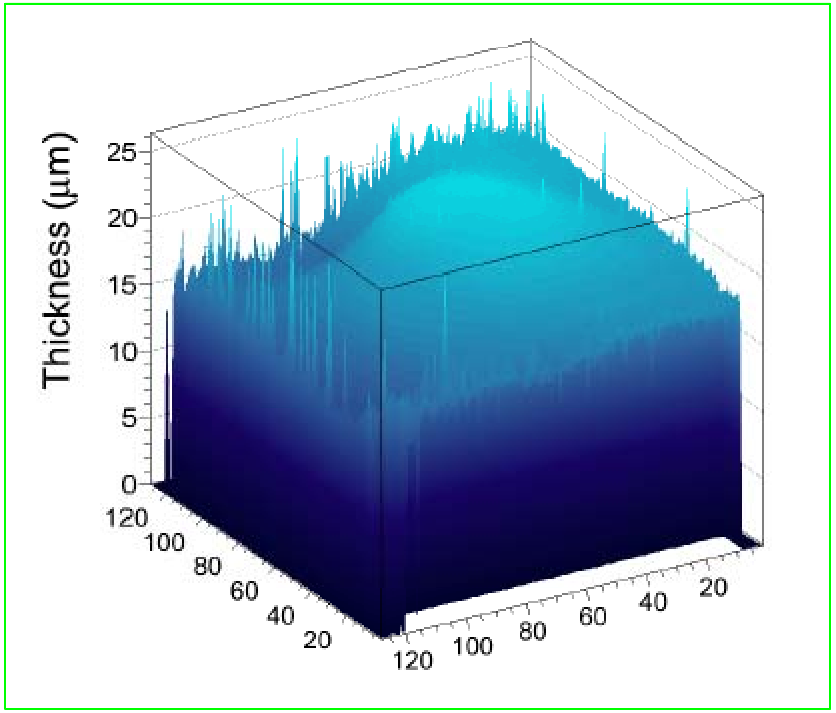
Study of $^{9,11}Li(d,^{3}He)$ @ 50 MeV/u at RIKEN



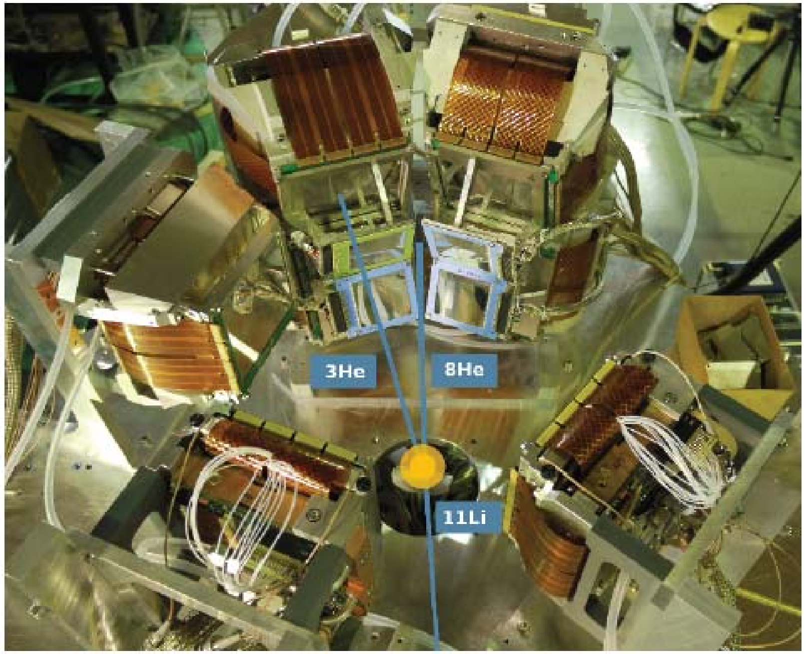
- Detection of low-E (8-12 MeV) ^{3}He required
- Large ^{4}He background

Thickness mapping using MUST2 and α-source

Detector#2 Thickness map



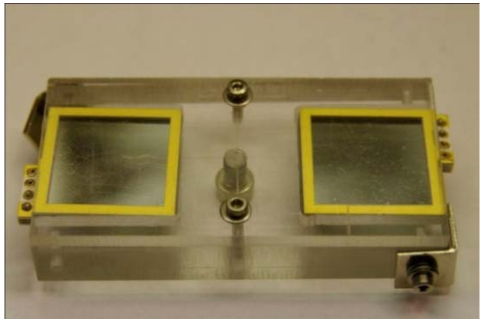
STRONG THICKNESS INHOMOGENEITIES



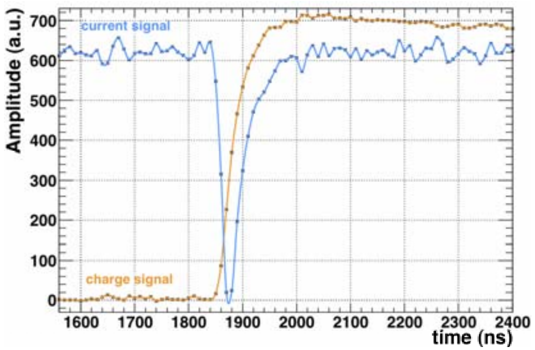
PSA with monopad detectors

Study at the Orsay tandem : monoenergetic beams and $^{7}Li+^{12}C$ reaction

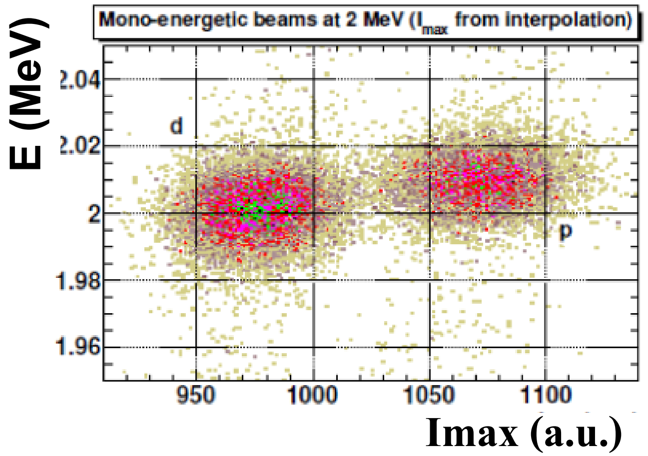
IPNO –Huelva-Padova-collaboration

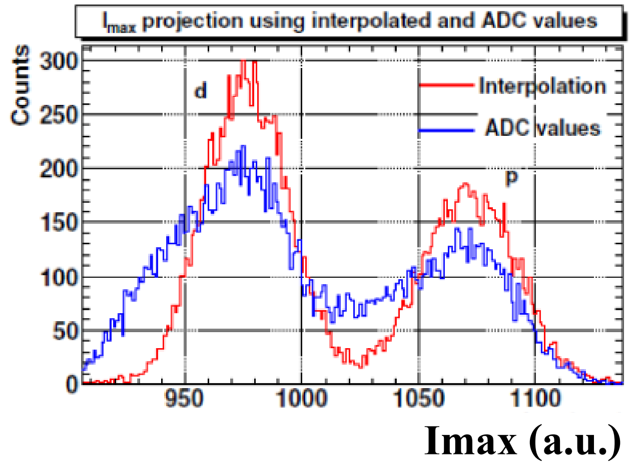


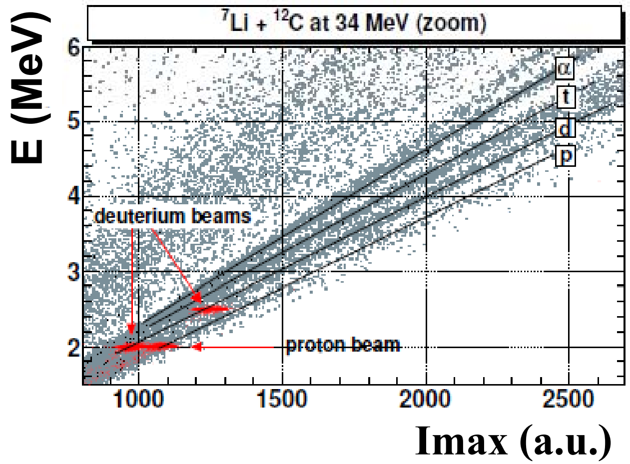
- **nTD monocell detectors from CANBERRA (FAZIA)**
- **2x2 cm^2, thickness: 500 μm**
- **PACI preamps, 100 MHz TNT-2 Digitizers**

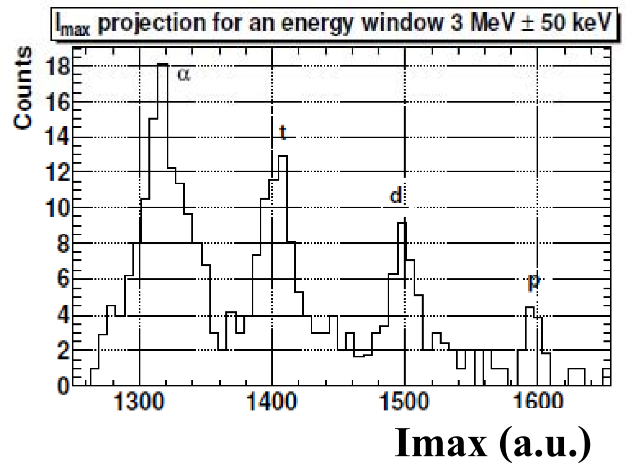


Imax : Maximum of the current signal









J.Duenas et al, NIM A (2012)

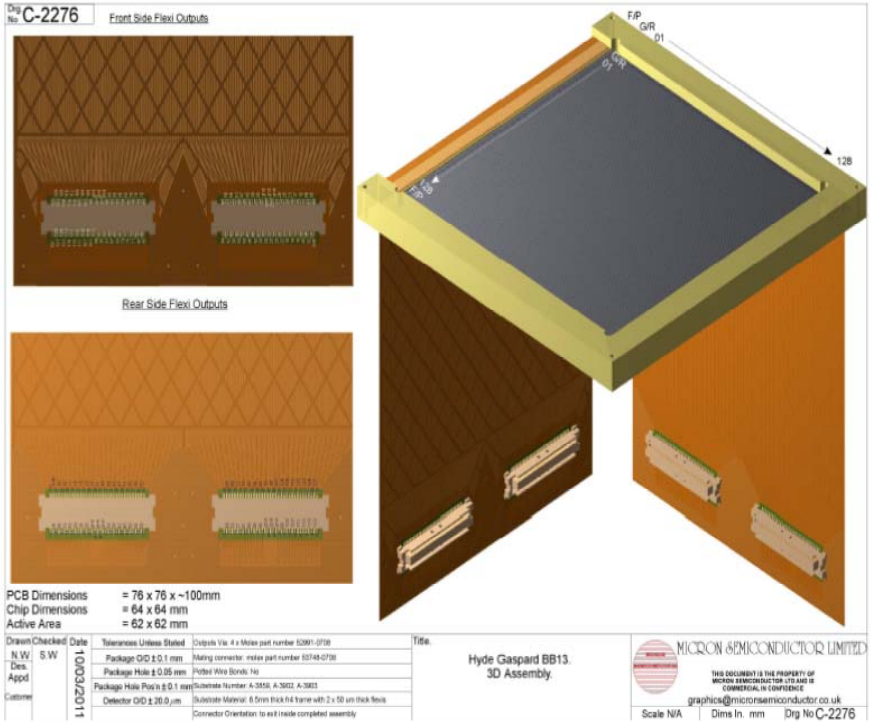
PSA with high granularity nTD DSSDs

Study at the Orsay tandem : monoenergetic beams and $^{7}Li+^{12}C$ reaction

IPNO –Huelva-Padova-BARC(Mumbai) collaboration

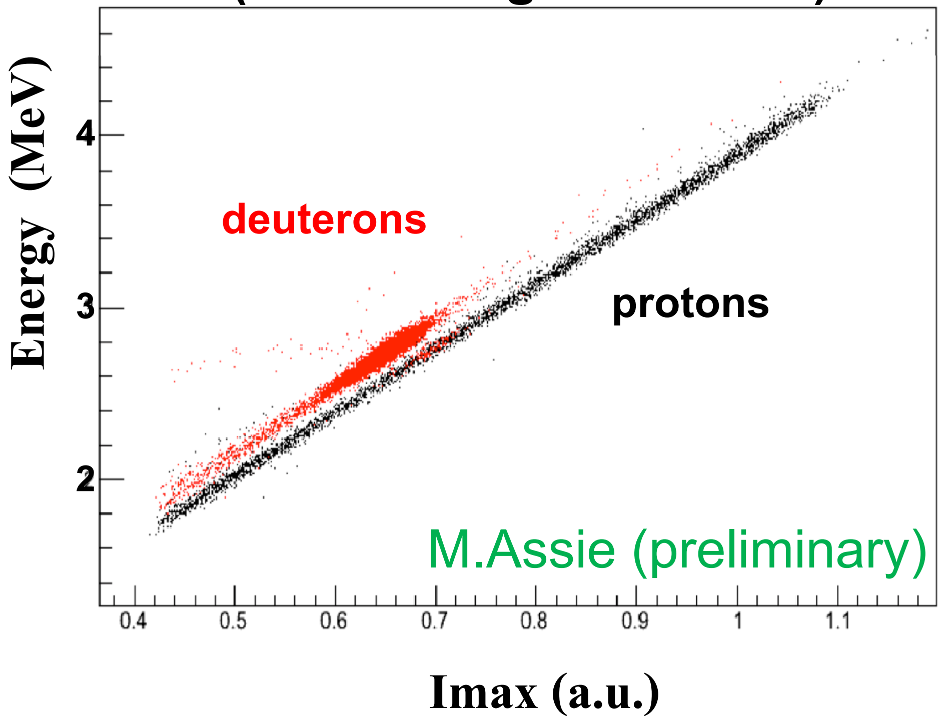
GASPARD-HYDE prototypes

- nTD Silicon 128,128 strips
  Pitch: 485 µm
- Thin FR4 frame with 90° kaptons



Particle ID

(monoenergetic beams)

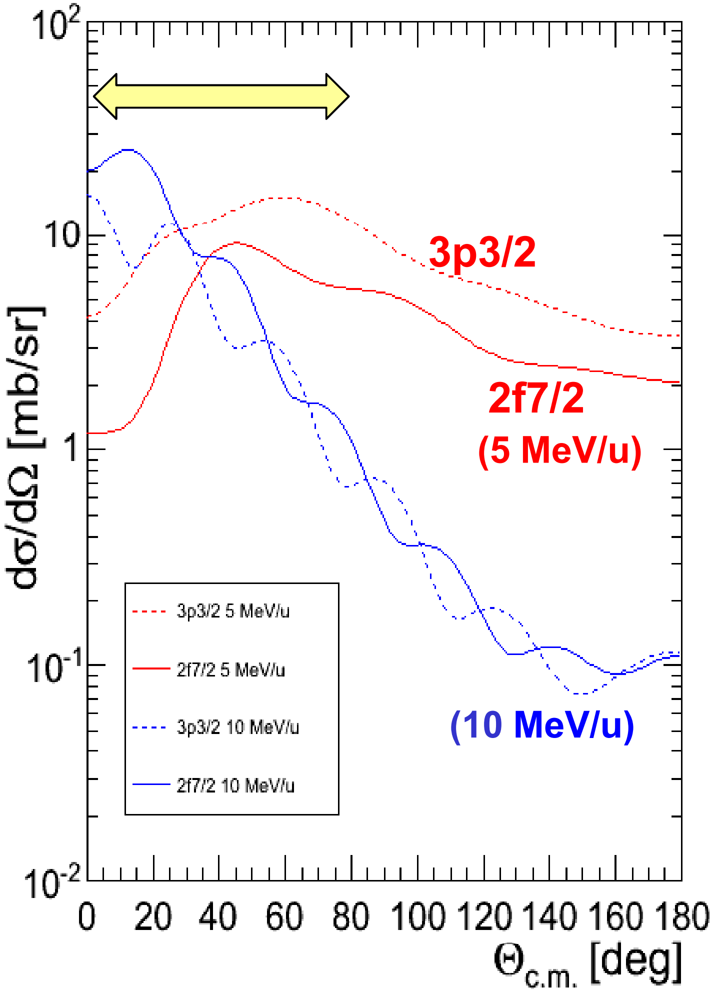


Data under analysis

Importance of angular coverage

Simulations for $^{132}Sn(d,p)^{133}Sn$

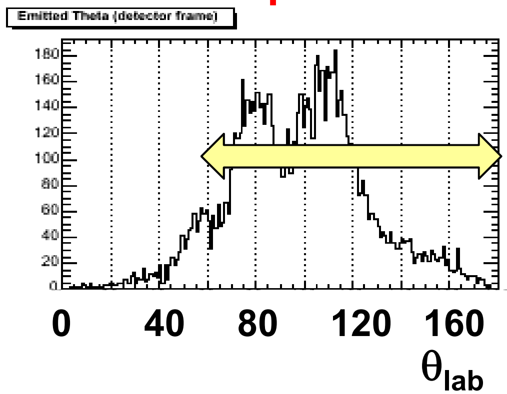
CROSS-SECTIONS
FRESCO (ZR-FRC)



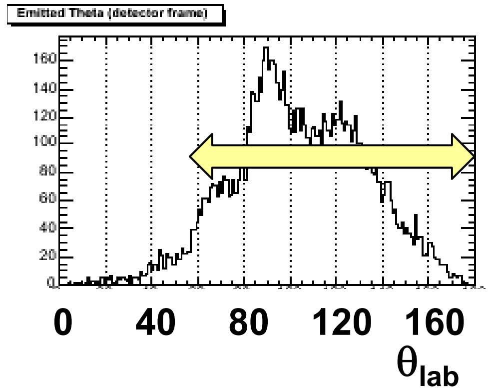
YIELDS

10 MeV/u

3p3/2

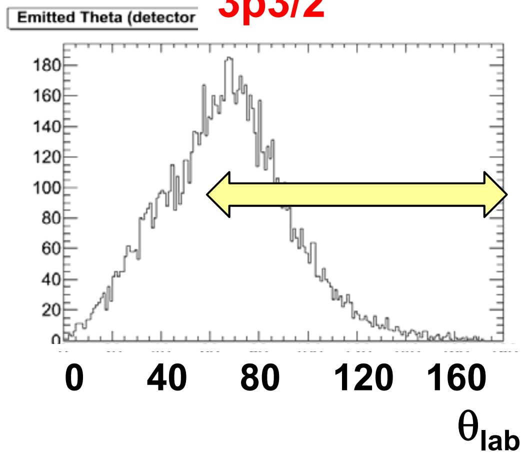


2 f7/2

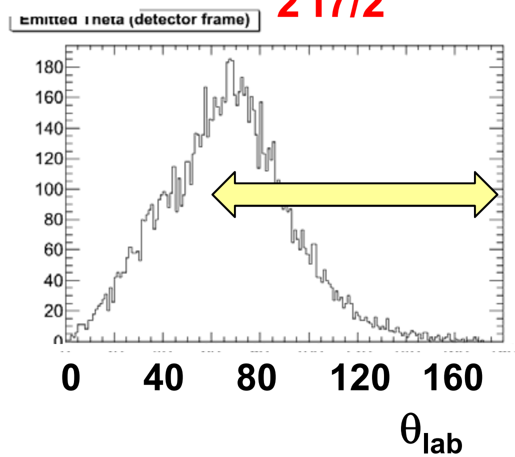


5 MeV/u

3p3/2



2 f7/2



N. de Séréville, IPNO

The GASPARD array

GAmma SPectroscopy and PArticle Detection

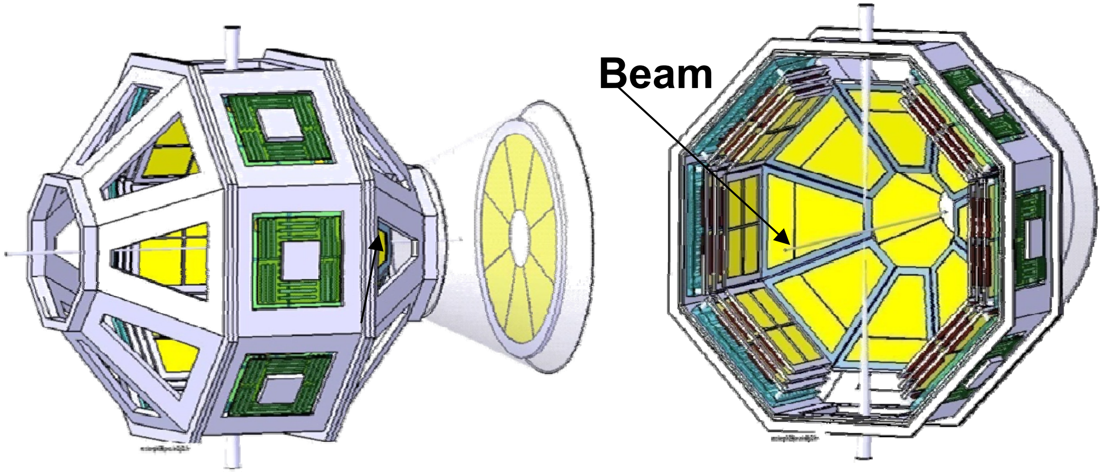
4π silicon array fully integrable in PARIS, AGATA

Layers of Silicon :

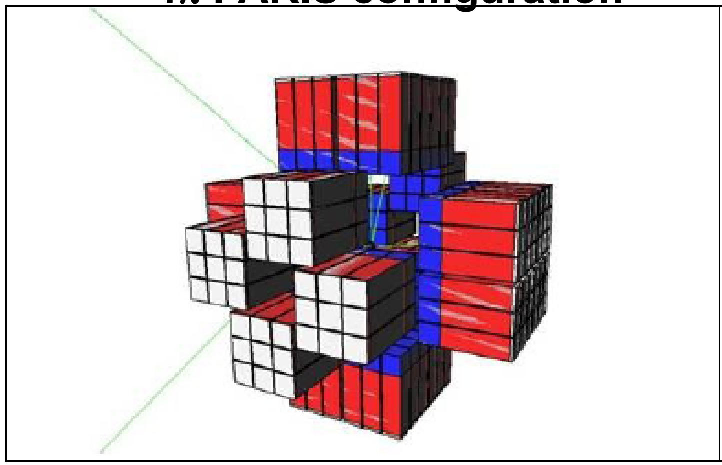
- 300 μm DSSD (p < 1mm)
- (2x) 1.5 mm DSSD (FWD)
- (1x) 1.5 mm DSSD (BWD)

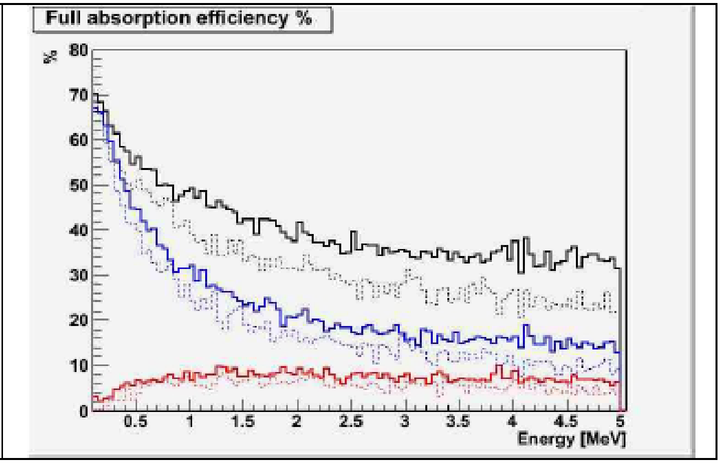
15000 electronic channels

Integration of pure H target



4π PARIS configuration



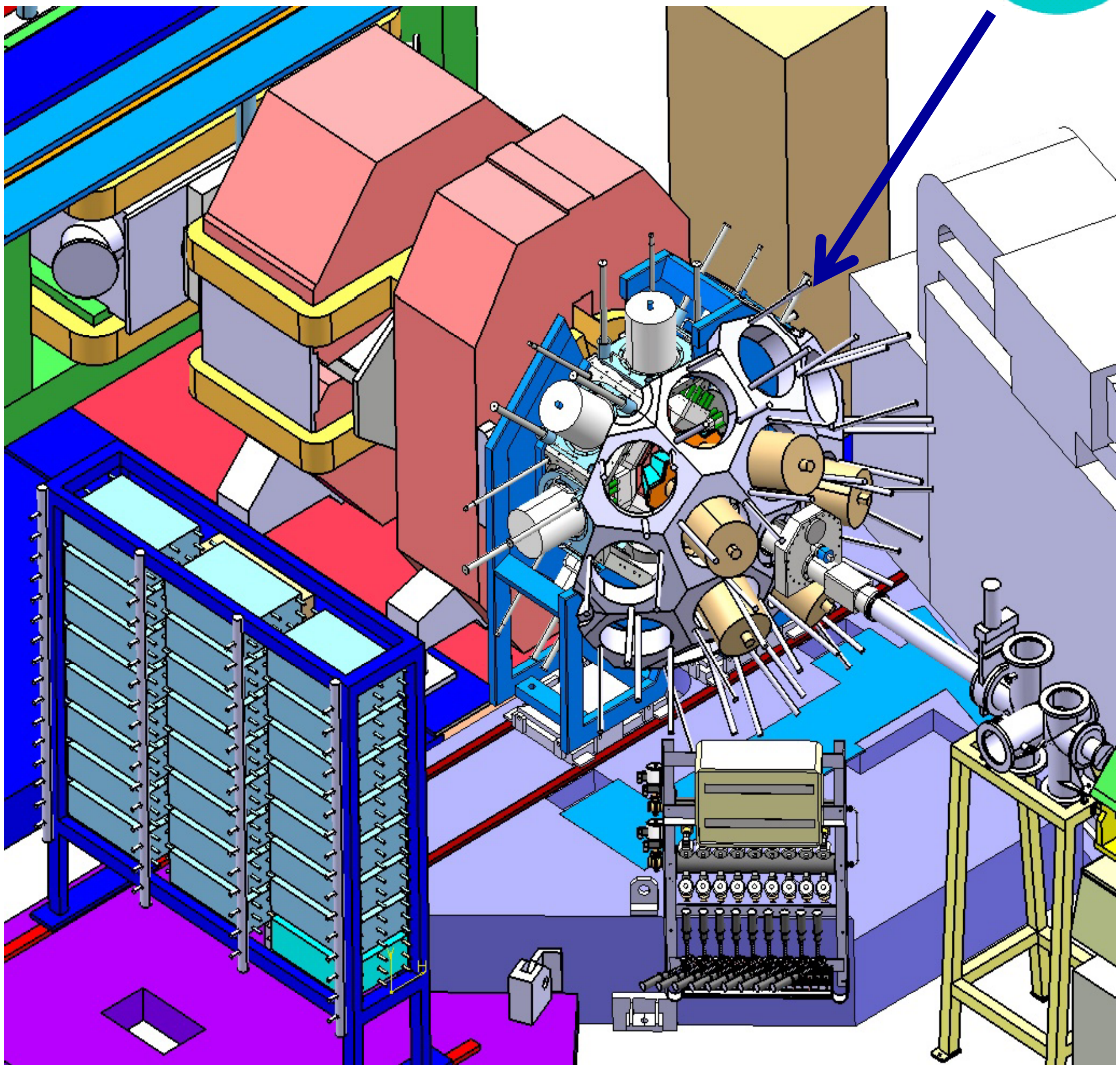


Efficiency gain of a factor ~20 for p-γ coincidences for $^{132}Sn(d,p)$ @ 10 MeV/u w/r to previous MUST2 + EXOGAM setup

Resolution: ~40 keV at 10 MeV/u with 2mg/cm^2 CD2 target

AGATA at GANIL

GASPARD
INSIDE !



Courtesy A.Gadea

The CHyMENE H/D windowless target

Cible d'HYdrogène Mince pour l'Etude des Noyaux Exotiques

System providing continuous extrusion of ^1H or ^2H through a rectangular extruder nozzle defining the target-film thickness

CHyMENE collaboration :

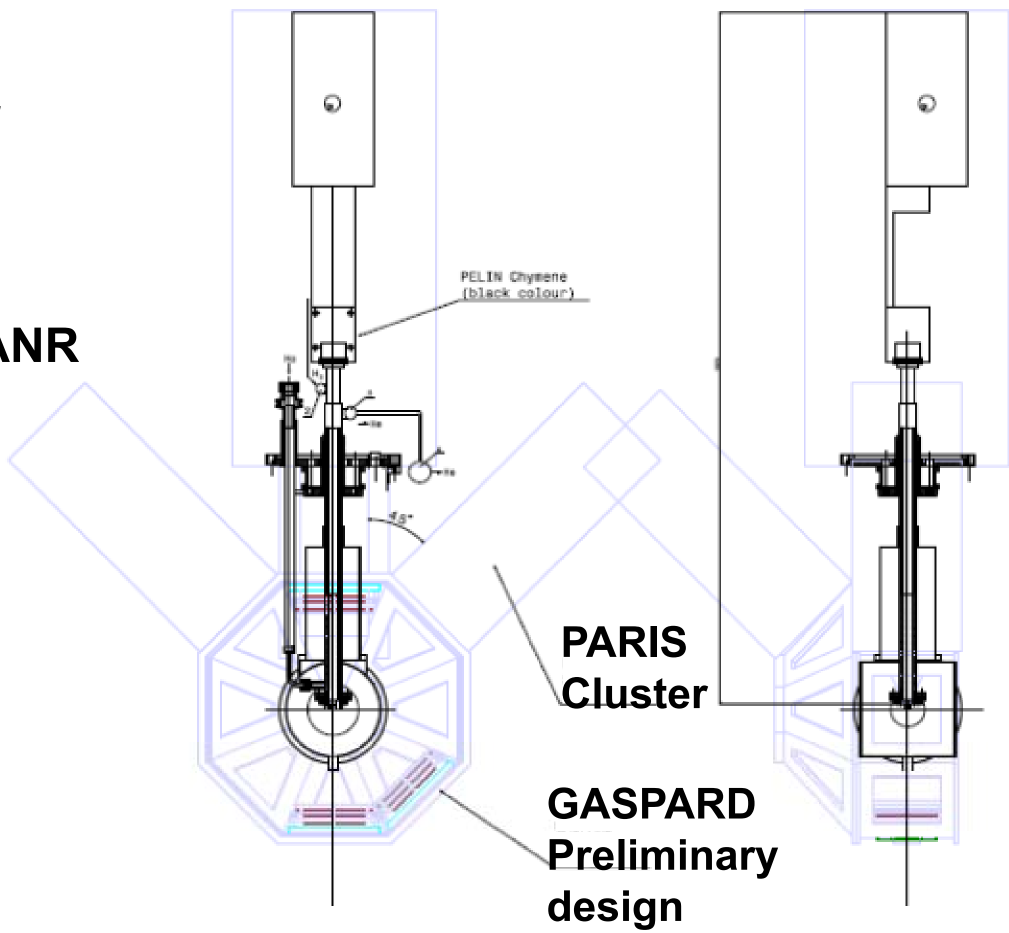
- **CEA/IRFU Saclay**
  project coordinator: A. Gillibert
- **CEA/DAM Bruyères**
- **IPN Orsay**

Now funded by the French agency ANR
~ 550 k€ over 4 years

100 μm thick target of pure H "routinely" produced with the old PELIN prototype

CHyMENE now being designed for integration in GASPARD

PELIN prototype with GASPARD/PARIS :



13 LoI's related to GASPARD

SHELL EVOLUTION

- How Magic is ^{78}Ni ?
  W.Catford, O.Sorlin
- Spectroscopic studies around ^{78}Ni and beyond N=50 via transfer and coulex
  G.De France, A.Gadea, X.Valiente, R.Orlandi
- Neutron shell evolution in weakly bound ^{134,135}Sn via (d,p) reactions
  V.Lapoux, O.Sorlin

PAIRING

- Probing the pairing interaction through two-neutron transfer reactions
  D.Beaumel
- Study of pair transfer in ^{134}Sn via ^{132}Sn(t,p)
  O.Sorlin, K.Wimmer
- 2p capture on ^{15}O and proton correlation in 2p emission from excited states of ^{17}Ne
  M.Assié, F. De Oliveira

CLUSTERS

- Exploration of cluster breakup in light nuclei
  J.A.Scarpaci, M.Assié

+ NEAR BARRIER REACTIONS, PDR, ASTROPHYSICS,…

Study of pairing far from stability

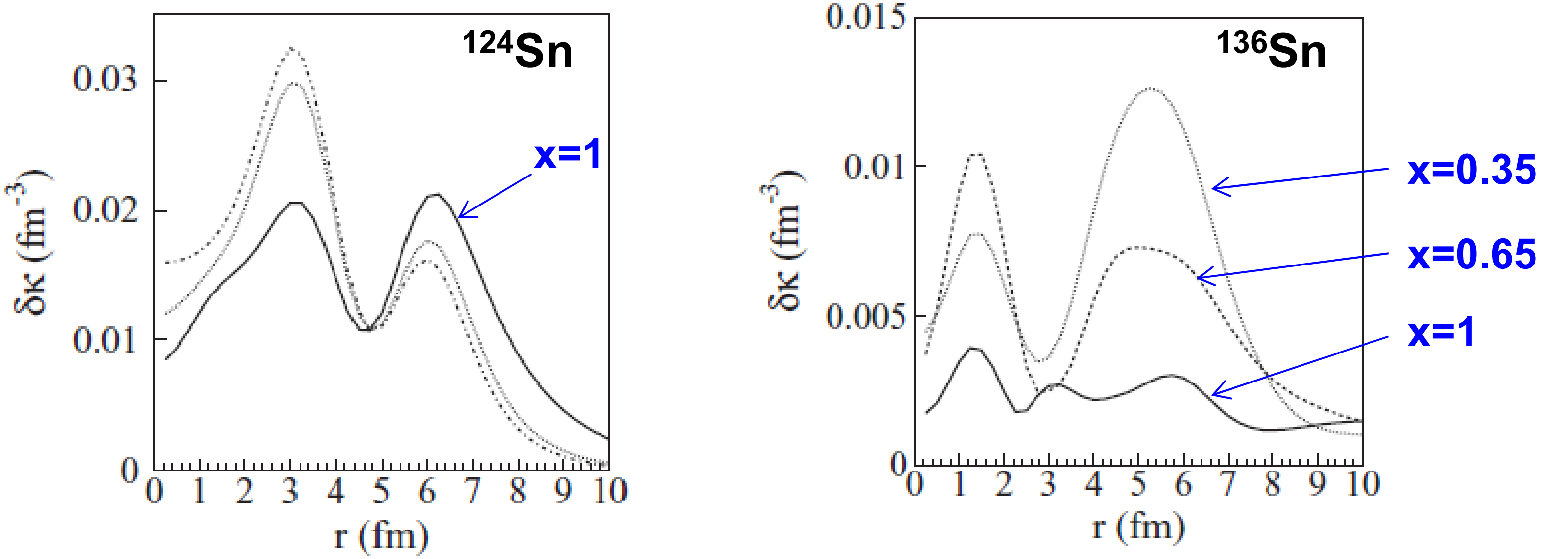
- *Pairing properties of dilute neutron matter (neutron-rich) ?*
- *Deep nature of the pairing interaction. Volume/surface character ?*

Well-known similarity between paring field ⬄ 2-body transfer operator
Study of pairing vibrations in Skyrme-HFB-QRPA (E.Khan et al, PRC 2009)
Surface/volume mixing of the DD pairing int. can be tuned :

$$V(\vec{r}_1 - \vec{r}_2) = V_0\left[1 - x\left(\frac{\rho(r)}{\rho_0}\right)^{\gamma}\right]\delta(\vec{r}_1 - \vec{r}_2)$$

x = 0.35, 0.5, 0.65 → mixed interactions
1.0 → surface interaction

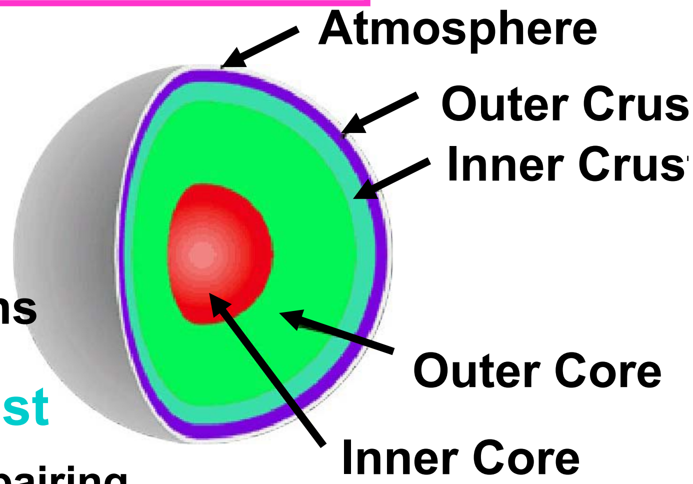
Transition densities for pair addition mode



Good sensitivity of pairing vibrations to the surface/volume nature of the pairing interaction for neutron-rich isotopes

Study of pairing far from stability

Pairing and neutron stars

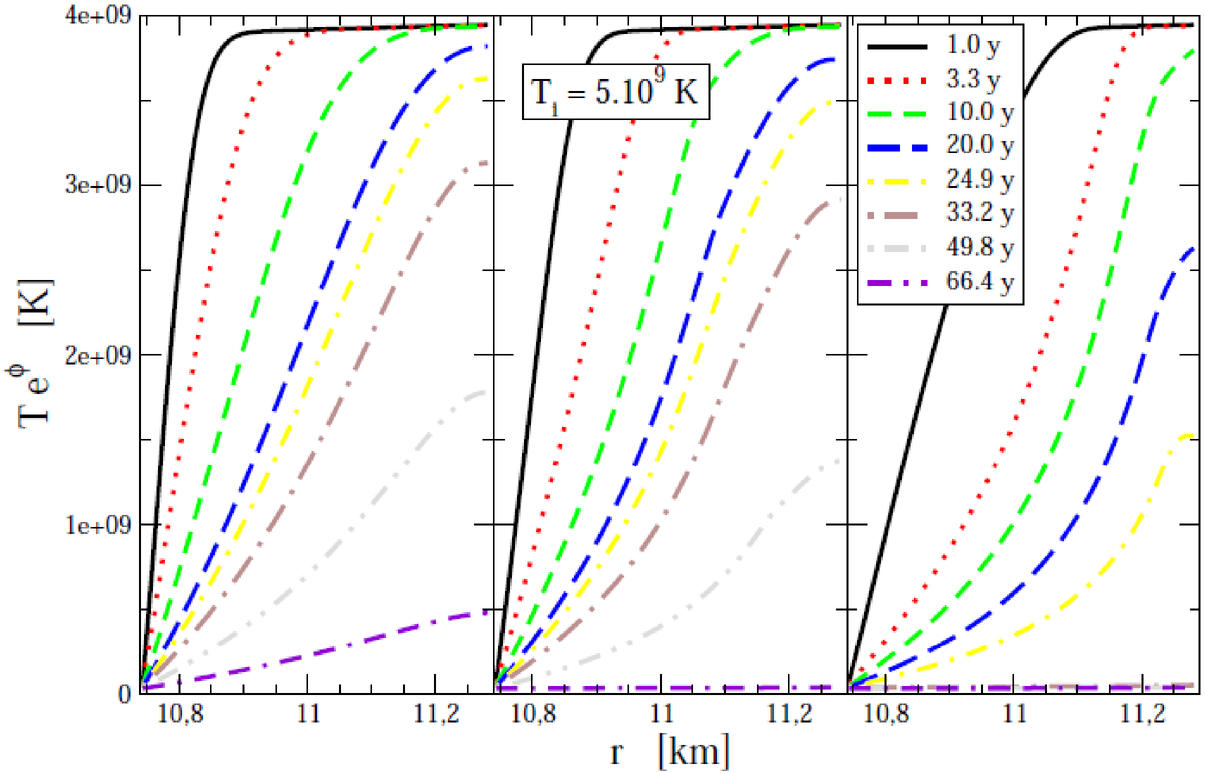


Composition of the crust:

- **Lattice of nuclear clusters**
- **unbound superfluid neutrons**

Time evolution of the temperature inside the crust

No pairing **Weak pairing** **Strong pairing**



M. Fortin, F. Grill, J.Margueron, N. Sandulescu, PRC(2010)

Study of pairing in neutron-rich nuclei

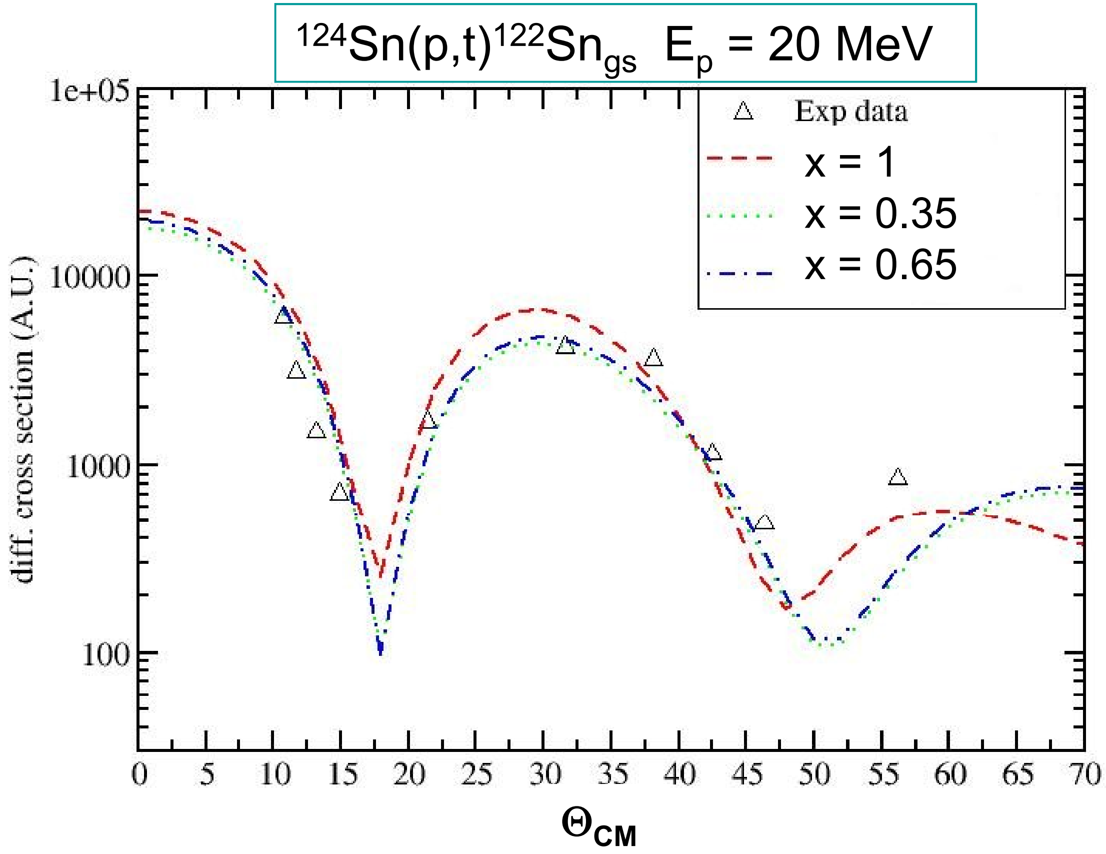
For zero-range DWBA, the pairing transition density directly provides the form-factor to calculate pair-transfer cross-section

Application to $^{124}Sn(p,t)^{122}Sn_{gs}$ E_p = 20 MeV

- **1-step ZR DWBA code DWUCK4**
- **Optical potentials from Global formulae**
- **Form-factor calculated in HFB+QRPA using density-dependent ZR pairing interaction**

$$V_{pair}(r,r') = f_{pair}(r)\,\delta(r-r')$$

$$f_{pair} = V_0[1 - x.(\rho(r)/\rho_0)^{\alpha}]$$



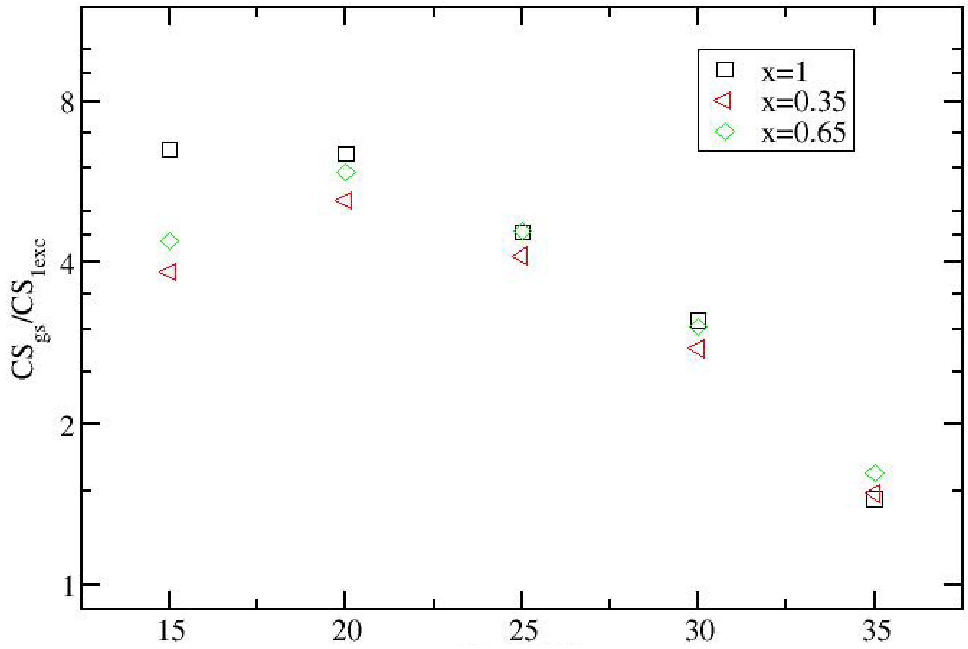
✓ ***Good agreement with the data***

✓ ***Almost no dependence on pairing interaction***

Study of pairing in neutron-rich nuclei

$^{136}Sn(p,t)^{134}Sn$

Ratio of gs→gs and gs→0^+_2 cross-sections



Proton incident energy (MeV)

A first evidence of a measurable effect related to the nature of the pairing interaction

E.Pllumbi, M.Grasso, D.Beaumel, E.Khan, J.Margueron, J. Van de Wiele
Phys. Rev. C 83 (2011)

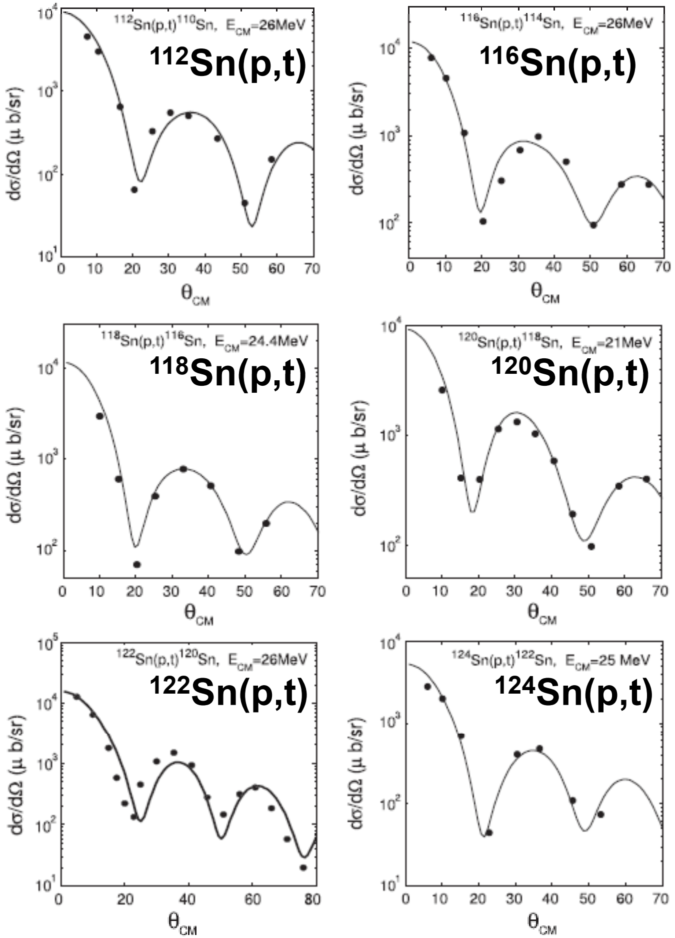
Measure (p,t) and (t,p) reactions with e.g. GASPARD & CHyMENE

For day1 LoI, ^{132}Sn beam too low in energy for (p,t) reactions

Recent calculations for $^{A}Sn(p,t)^{A-2}Sn$

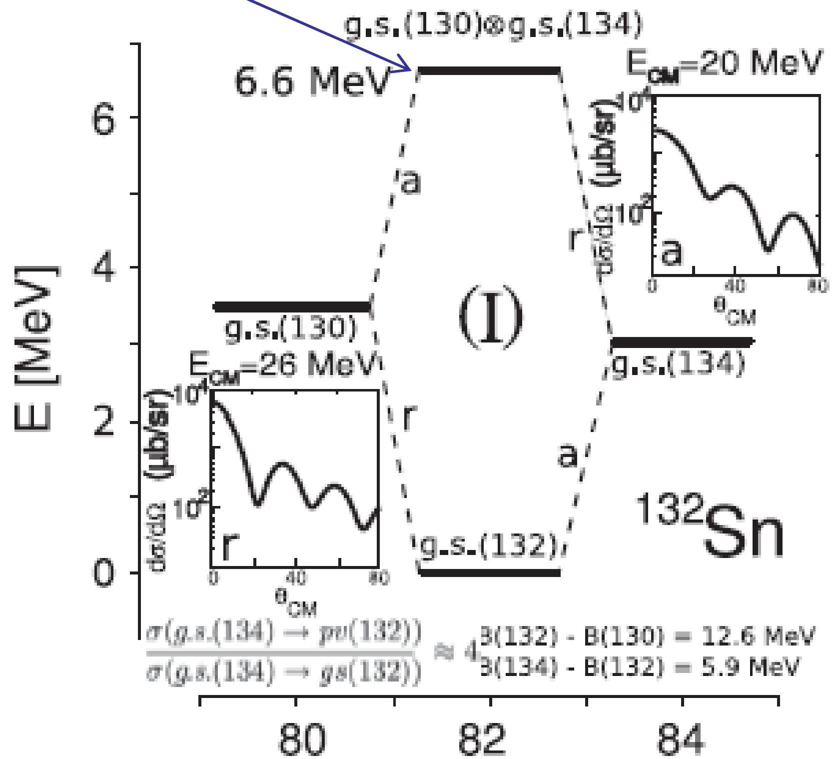
2nd order DWBA
(Simultaneous+sequential+non orthogonality)
Spectroscopic amplitudes from BCS

G. Potel et al, PRL 107 (2011)



Reproduce very well absolute cross-sections for stable Sn

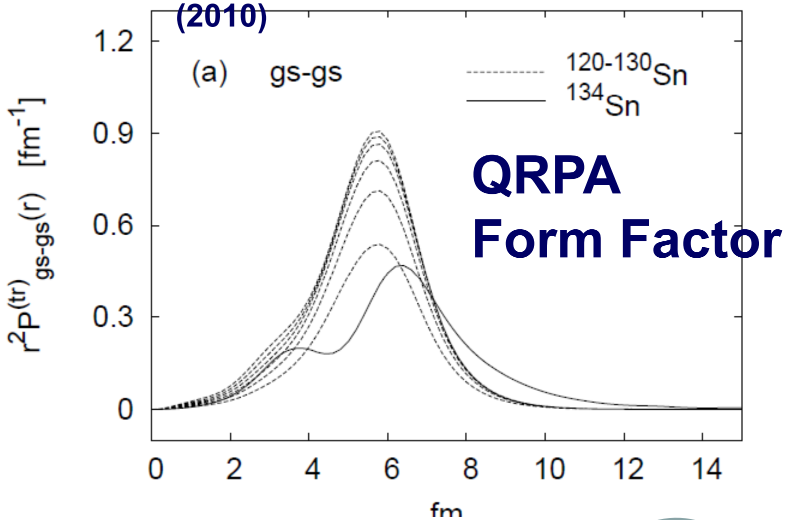
Predicted pairing vibration

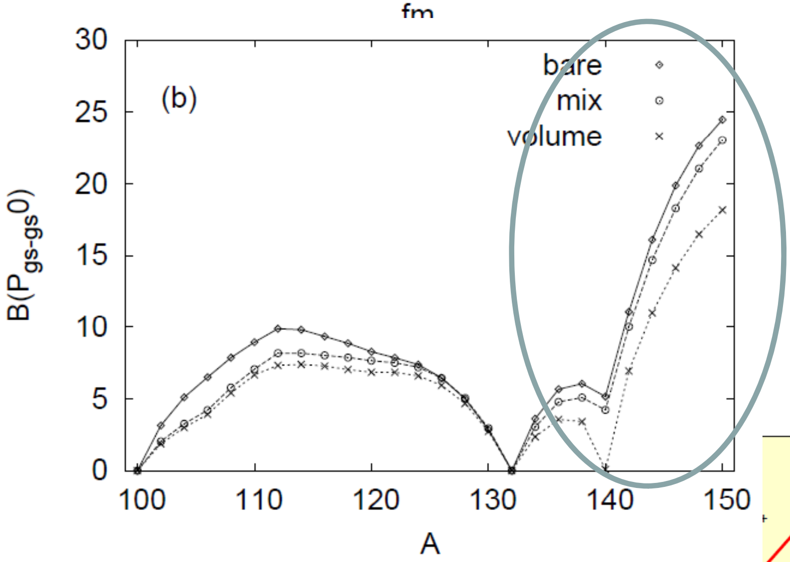


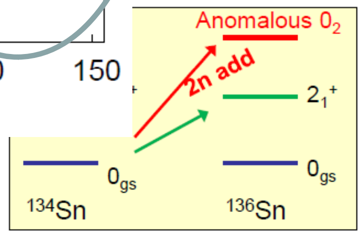
Transfer Reactions → *nn*-pairing in *Sn* Isotopes

Pair Transition density – Skyrme HFB + QRPA approach

M. Matsuo et al., PRC 82, 024318 (2010)







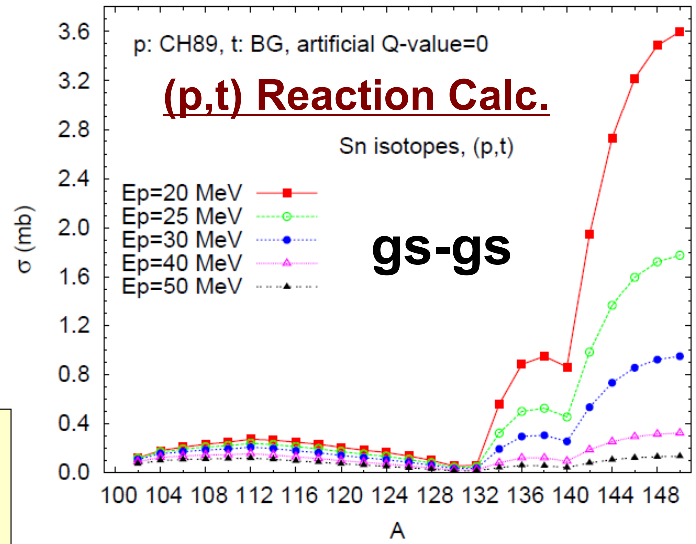
Courtesy J.Lee, RNC

How to see & interpret these *nn*-pairing structure in Transfer Reaction ?

Establish Reliable Framework by Systematic Reaction Calc.

One-step transfer (TWOFNR) + QRPA Form Factor

Reaction Calc: D.Y. Pang (BAUU)



Reaction Calc: 0_2^+ & 2_1^+ (in progress)

Possible study: $^{132}Sn(p,t)^{130}Sn$

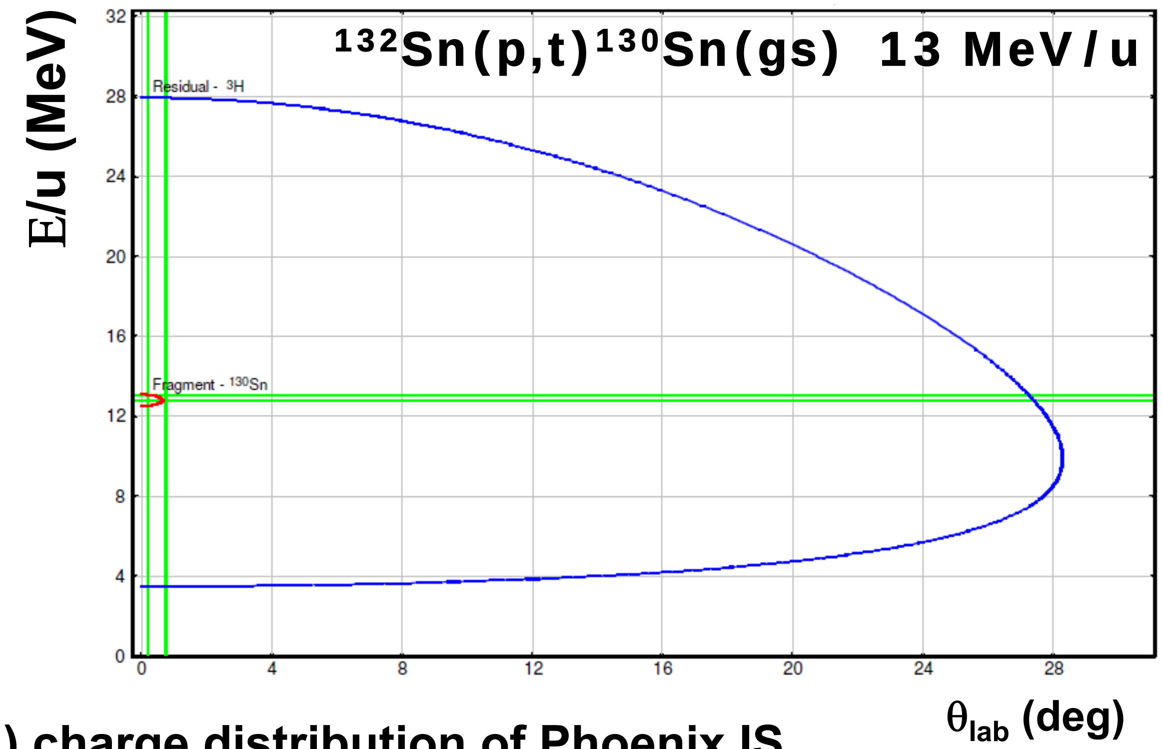
(p,t) reaction requires several tenths of MeV/u for stable or proton-rich nuclei *but :*

- ***Q-value more favourable for neutron-rich nuclei***

- ***1-step DWBA often used***
  e.g. $^{120}Sn(p,t)$ at 26 MeV
  (Guazzoni et al., PRC1999)

- ***Favourable kinematics allows "thick" target***

CHyMENE very well-suited
GASPARD
γ-detection (PARIS)



BEAM:
Extrapolation of the (measured) charge distribution of Phoenix IS
Rate = 5.10^4 pps of ^{132}Sn at 12.9 MeV/u

Development of an alternative EBIS could allow more than 10^7 pps of ^{132}Sn at 15-20 MeV/u

Collaboration: IPN Orsay/Saclay/GANIL

MUST2

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