Reaction and structure studies with the MUGAST+AGATA setup @ VAMOS

- **Concept**
- **LOIs, Physics Cases**
- **Detectors, Design and test bench**
- **Electronics**
- **Targets**

Freddy Flavigny
(on behalf of the collaboration)

Motivations

Extend the range of direct reactions studies of exotic nuclei with Si arrays:

- Intermediate and heavier masses
- Higher excitation energies – Low sp strength
- Sometimes at mid-shell
- Detect/identify several channels altogether

Resolution, Efficiency, Sensitivity

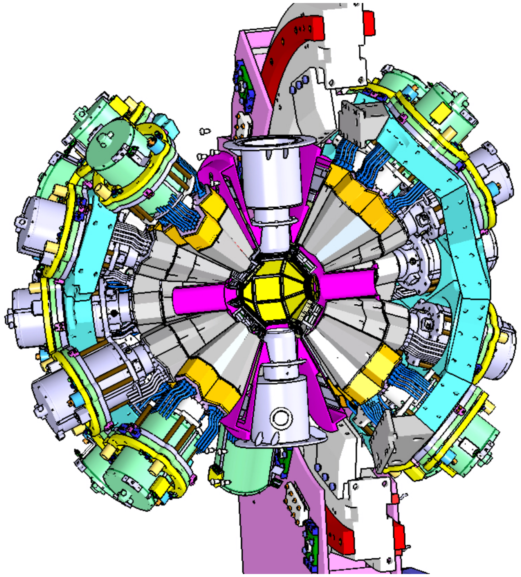
Ultimate setup : 4π-detection of particle and gammas with pulse-shape analysis

Projects ongoing :

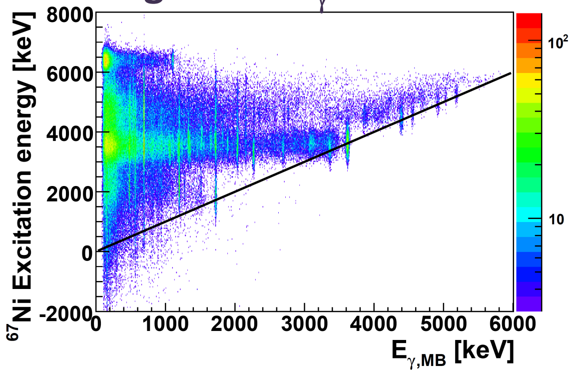
- TRACE
- GASPARD

(Many) Challenges

- Compactness
- Number of channels
- Digitization



goal: E*-E_γ matrix



Ex: J. Diriken et al. PRC 91 054321 (2015)
TREX+MINIBALL

MUGAST Motivations

Opportunities:

- AGATA at VAMOS-GANIL for some years
- SPIRAL1+ upgrade with new beams available
- Some Si detectors of future arrays progressively available

→ **Intermediate configuration: MUGAST (MUST2-GASPARD-TRACE)**

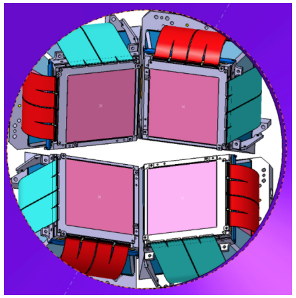
Particle detection:

- 4 GASPARD trapezoid DSSSD (backward/AGATA side)
- 1 Annular (S1-like) (backward close to 180°)
- 2 TRACE square detectors (@90°)
- 4 MUST2 Telescope (forward)

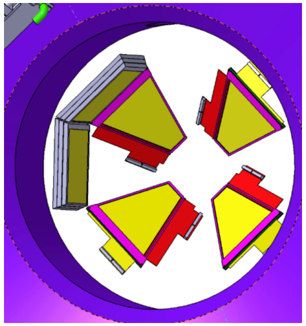
- Existing electronics (MUFEE+MUVI)

γ-detection (AGATA):

- Maximize eff: ≈ 8% @1 MeV @ 18cm *(for 11 triples)*
- Benefit from very good energy resolution (≈ 5 keV)

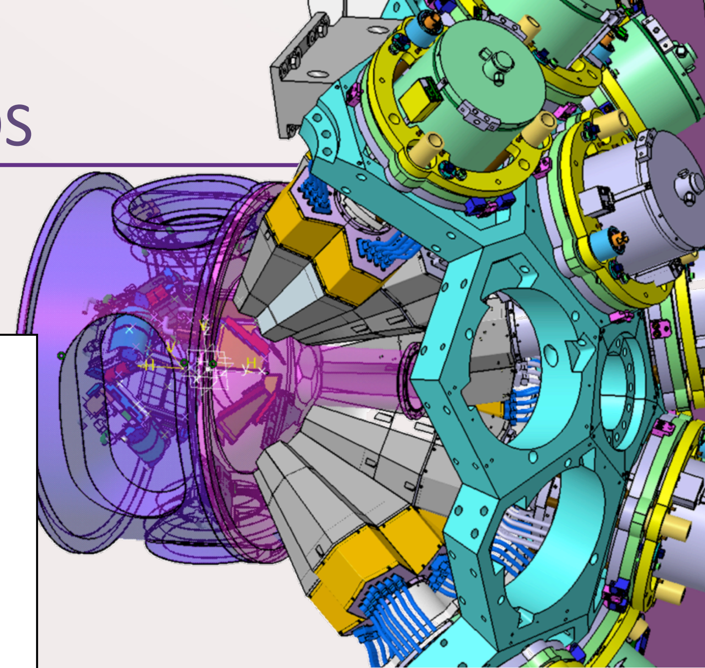


MUST2



TRAPEZ.
+SQUARE

MUGAST+AGATA @ VAMOS



→ **LoI for AGATA+MUGAST+VAMOS for the PAC @ GANIL**

Reaction studies using the MUGAST+AGATA setup at VAMOS

Letter of Intent to the AGATA collaboration

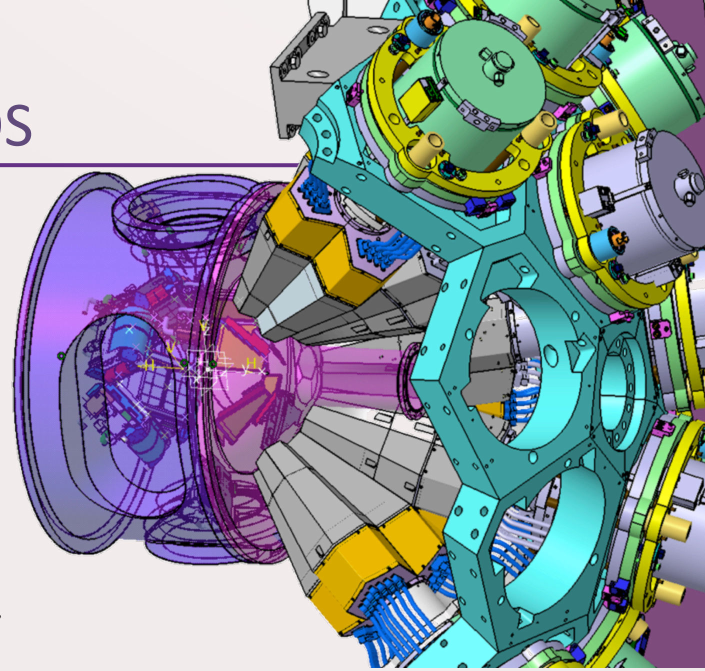
D.Beaumel, IPN Orsay
D.Mengoni, University and INFN Padova

1. Introduction

The GASPARD and TRACE high granularity Silicon arrays have been natively designed for optimal integration in new generation gamma detectors such as AGATA with the aim of performing high-resolution reaction studies. Indeed, the coupling to AGATA allows a very large gain in excitation energy resolution, in comparison with the case where the excitation energy is deduced from the recoil charged-particle measurement. The GASPARD and TRACE collaboration are now converging to build such new-generation Si ensemble in common, with a timeline of 2019-20 for completion of the final 4π array, ready for the emerging ISOL facilities, like SPES and SPIRAL1. A view of such ultimate GASPARD-TRACE setup sitting inside AGATA is shown in Fig.1.

The PAC found the proposition of combining MUGAST+AGATA with VAMOS compelling, and it was clear that much progress had already been made in realising this ambition, with significant development of the instrumentation. The aim to deliver a campaign around transfer reactions (including stripping) was well received as it was believed that this should be a core component of the future scientific programme of GANIL, building on the rich heritage of the programme that the present collaboration has led. The PAC is therefore supportive of this development and it would seem that the best course of action is to present this proposition to the GANIL Scientific Council as directed by the GANIL Director.

MUGAST+AGATA @ VAMOS



→ LoI for AGATA+MUGAST+VAMOS for the PAC @ GANIL

Nuclear astrophysics:

- **^{15}O(^{6}Li,d)^{19}Ne** *(C.Diget, Univ. of York, N. de Séréville, IPNO)*
- **^{25}Al(^{3}He,d)** *(N.de Séréville, F. Hammache, IPNO)*
- **^{30}P(^{3}He,d) or (d,p)** *(N.de Séréville, F.Hammache, IPNO)*
- **^{60}Fe(d,p)** *(A.Matta, W.Catford, University of Surrey)*
- **^{79}Se(d,p)^{80}Se** *(G. de Angelis, INFN-LNL, D.Mengoni, University of Padova, C.Domingo Pardo, CSIC Valencia)*

Shell evolution

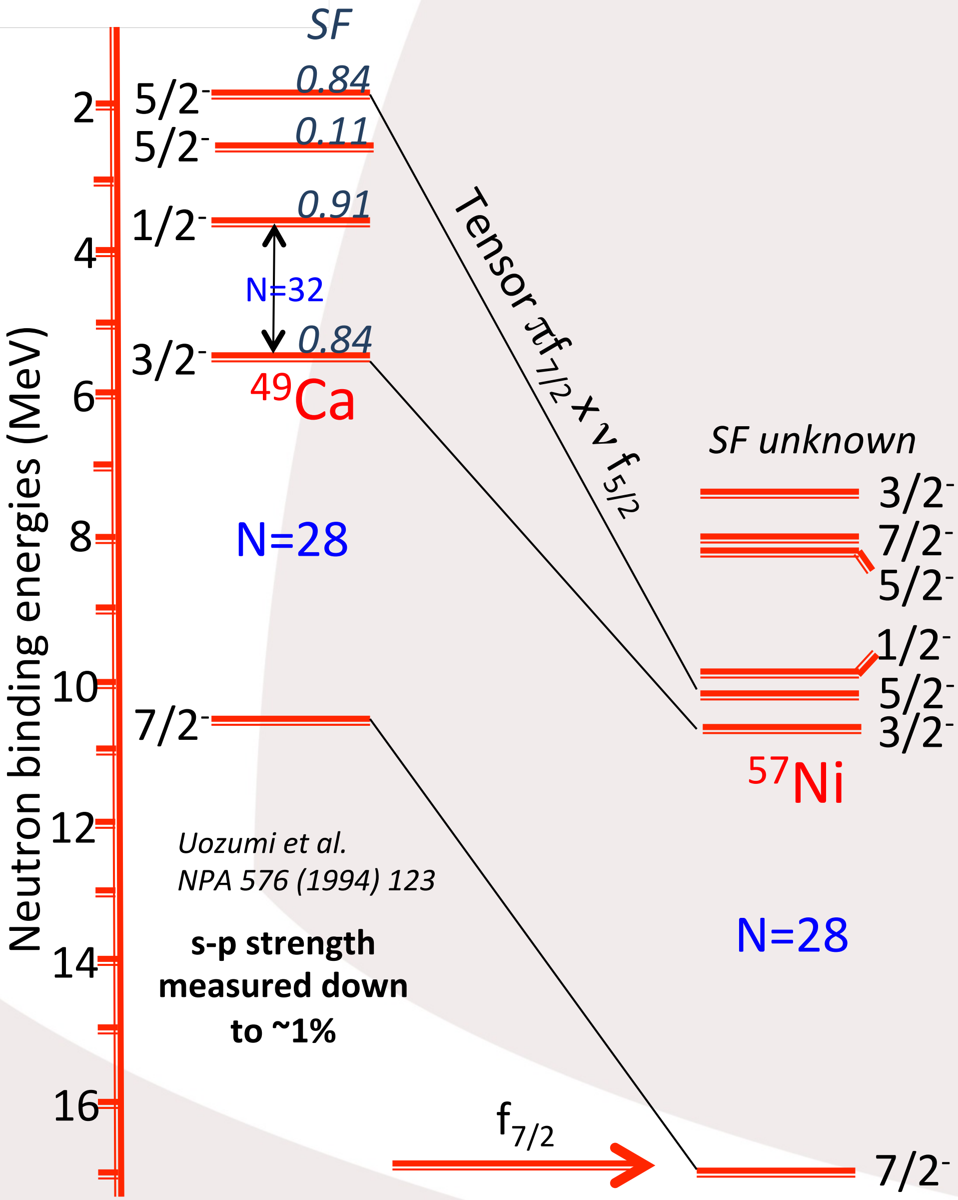
- **^{56}Ni(d,p)**(d,t) *(F.Flavigny, IPNO, O.Sorlin, GANIL)*
- **^{28}Mg(d,p)** *(A.Matta, W.Carford, University of Surrey)*
- **^{74}Kr(d,p)** *(A.Matta, W.Carford, University of Surrey)*
- **^{48}Cr(d,p)^{49}Cr** *(A.Gadea, CSIC Valencia)*
- ^{30}Mg(d,d)**(d,p)** *(B.Fernandez-Dominguez, University of Santiago, W.Catford, University of Surrey)*
- **^{67}As,^{63}Ga(^{3}He,d)** *(D.Mengoni, University of Padova)*
- **^{44,46}Ar(t,p)** *(D.Mengoni, University of Padova)*
- **^{66}Ni(t,p),^{44}Ar(t,p) (^{14}C,^{12}C)(^{18}O,^{16}O)** *(L.Fortunato, J.A.Lay, University of Padova)*

Clusters, pairing, correlations & others

- **^{56}Ni(^{3}He,p)(^{6}Li,α)** *(M.Assie, IPNO)*
- ^{45}K + ^{7}Li -> ^{46}Ca+α *(S.Leoni, University of Milano, B.Fornal, Krakow)*
- ^{16}O + ^{A}Z *(G.Verde, INFN Catania and IPNO)*
- ^{14}O(p,p) *(I.Stefan, IPNO)*

- **8 independent LoI + Umbrella LoI**
- **Mostly stripping reactions** (backward)

Shell evolution in the N=29 nuclei

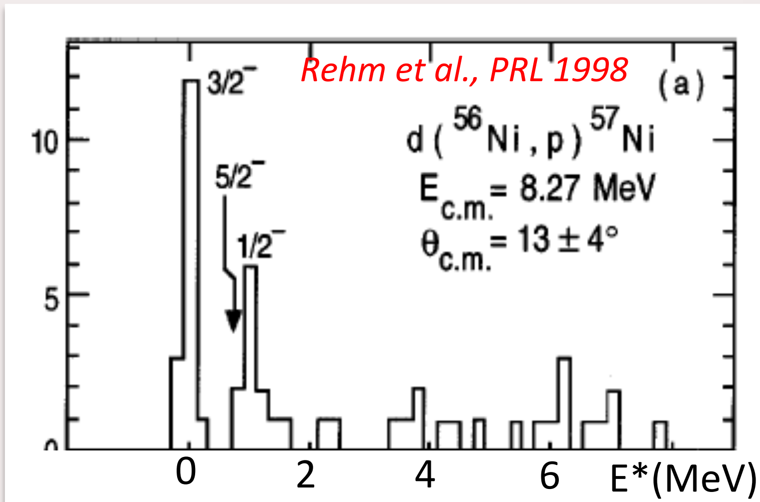


Effect of filling $\pi f7/2$ on $\nu(f5/2,p3/2,p1/2)$ and $\nu(g9/2)$

- Disappearence of N=32 gap
- Reduction of SO splittings
- Shell re-ordering

→ **Tensor component of NN force ?**

☹ No Spec. Factors measured



Trapezoid detectors and test bench

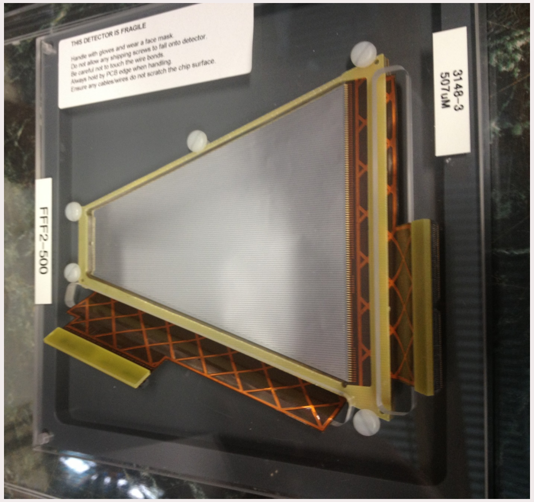
Ordered to Micron semiconductors :

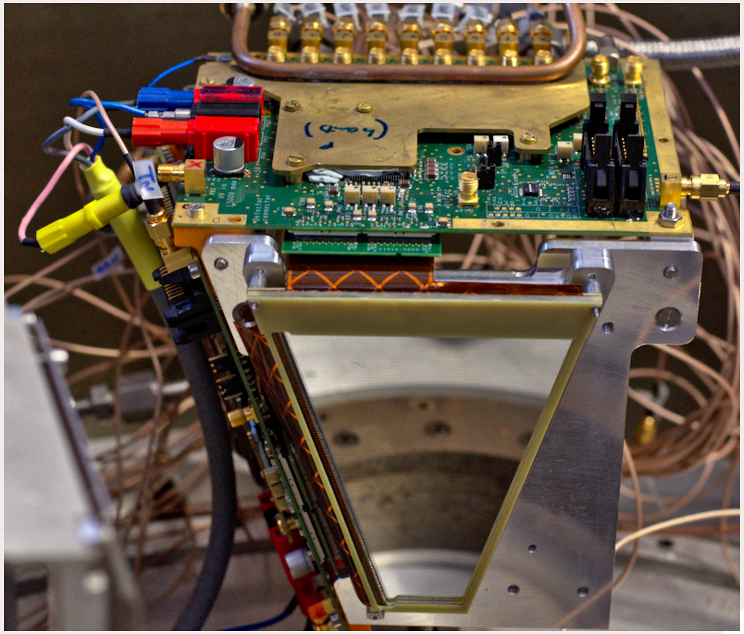
- **2 trapez**. prototypes nTD DSSSD ordered by IPN
  (delivered end of june 2015)
- **3 more trapezoid « series » ordered**
  (1 Surrey, 1 Santiago University, 1 IPN)
- **2 square** proto. nTD DSSSD **+ 1 thick sq. DSSSD**
  (ordered by INFN end of 2014, under fabrication)

Test bench mounted @ Orsay :

- Digital test bench (GASPARD purposes)
- **Analog test bench** (256 channels) :
  Trapezoid + MUFEE + MUVI + GANIL acq.

Aim → End of 2016 validation of prototypes





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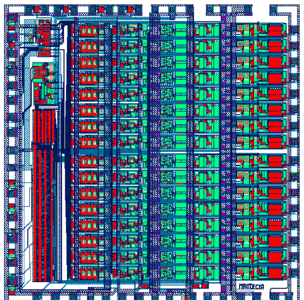
ORSAY

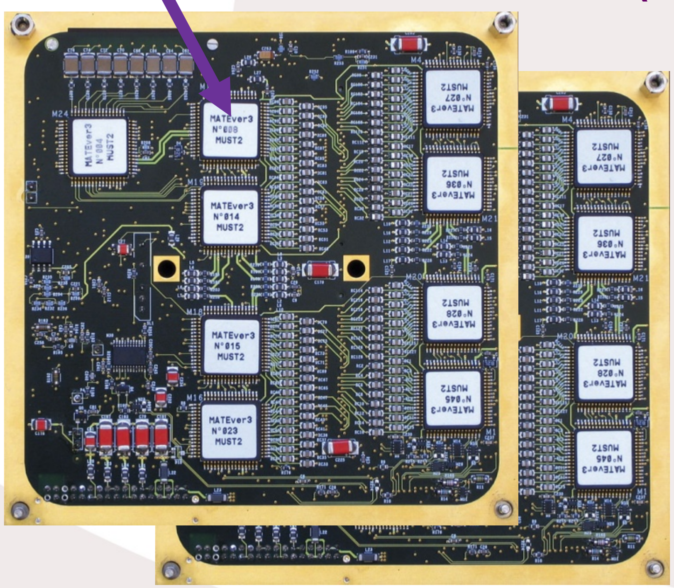
MUGAST Electronics : MUFFEE + MUVI



- 16 channels 28 mW/ch
- Energy & Time
- Si, Si(Li) and CsI
- Multiplexer
- I2C interface

- High linear. pulser
- T sensor

MOTHER BOARDS (IPNO)



1 telescope

VACUUM

AIR

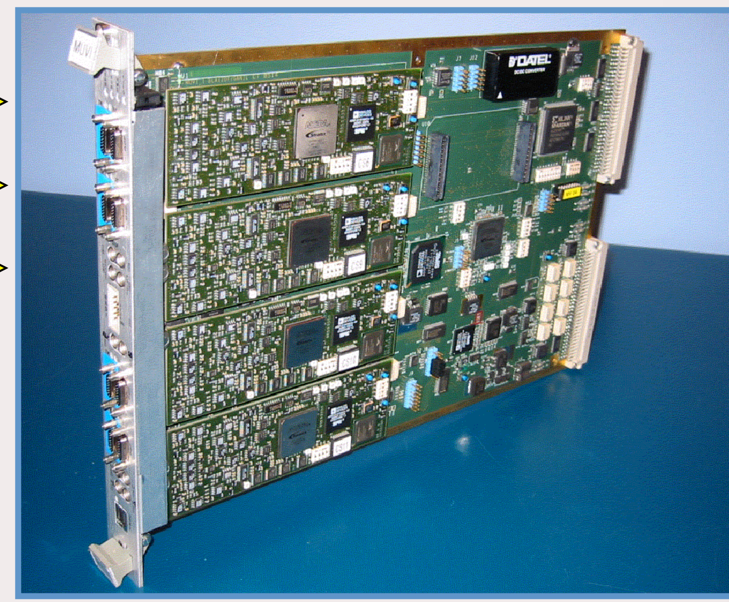
4 analog bus

Control signals

I2C bus

VXI board (GANIL)

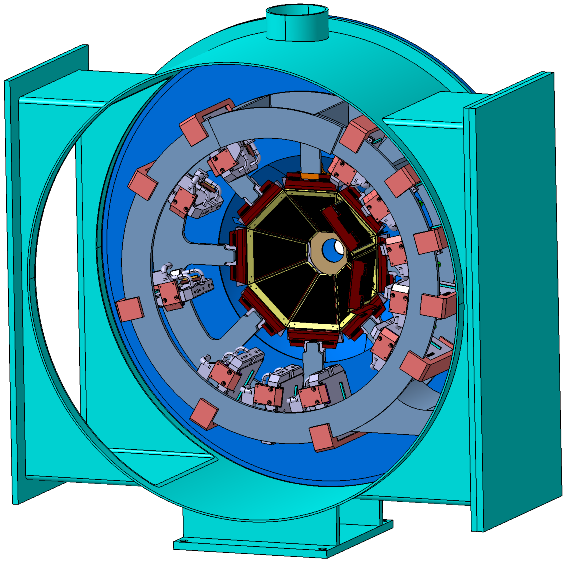
16 ADC14 bits
2.3K parameters
2MHz
Slow Control I2C
Pedestal substraction
DNL correction

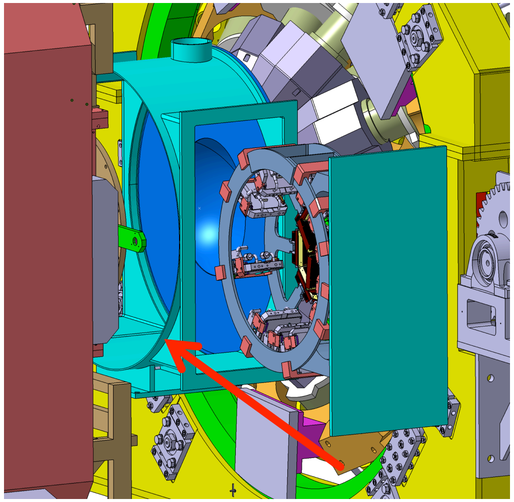


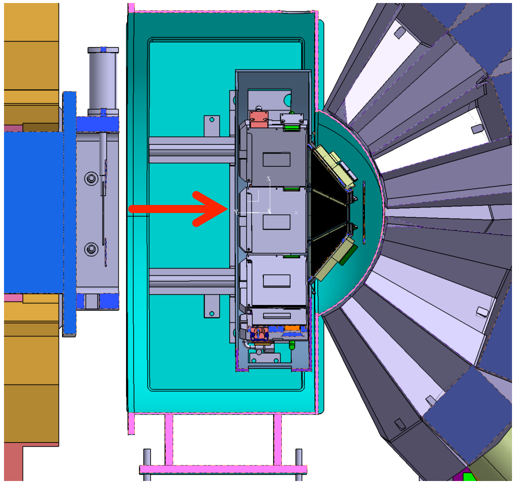
4 telescopes

Design of the reaction chamber @IPN (E. Rindel)

- Distance AGATA-target = 18 cm
- No electronics behind trapezoid detector
- Capability of handling more trapezoids
- Possibility of second layer.
- Fully removable backward array
- Option for cryogenic target

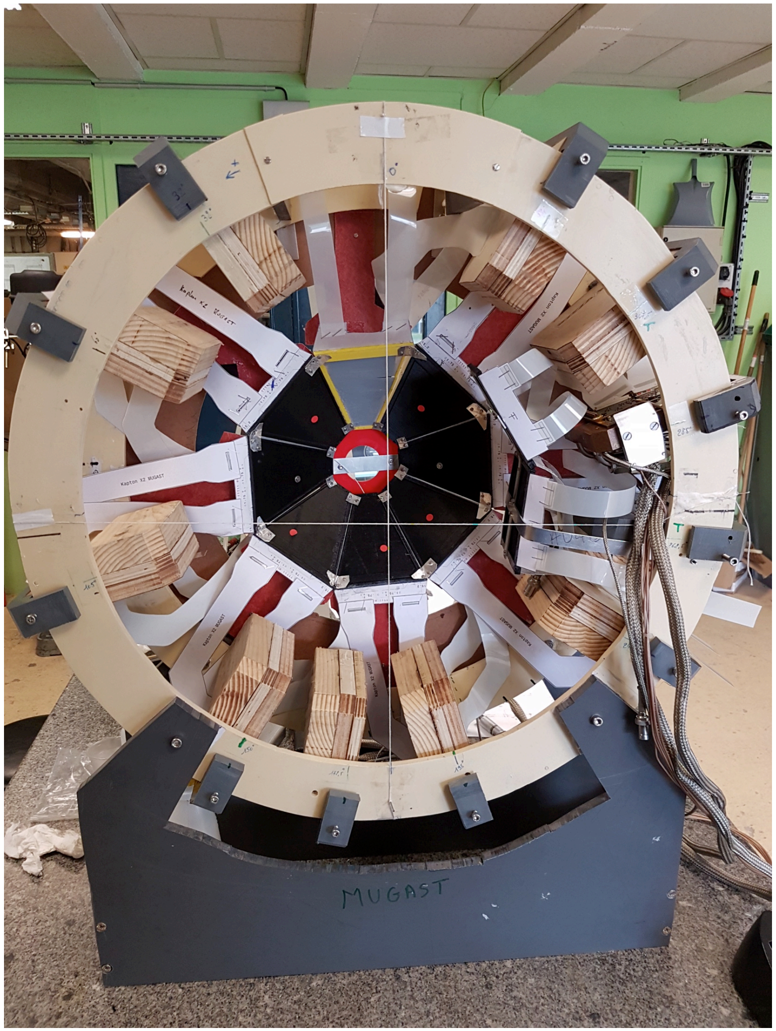






→ Financed: 42kE
Univ. of Surrey (W. Catford)

Design + cabling → 3D-printed model



Model used for:

- Definition of kaptons from boards to detectors:
  - Shape
  - Length
  - Rigidity
- Best positionning of cooling blocks
- Realize space/rigidity constraints

Cryogenic target

Important physics interest for :

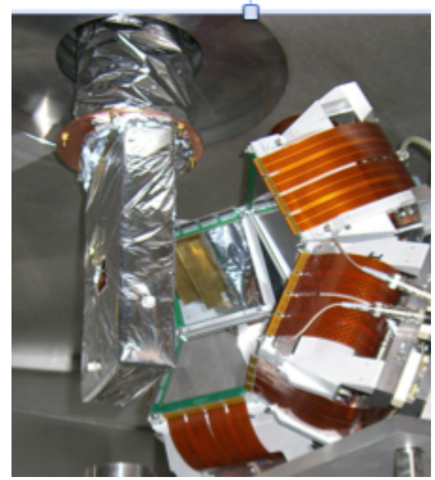
- p addition : (3He,d)
- np transfer: (3He,p) (4He,d)

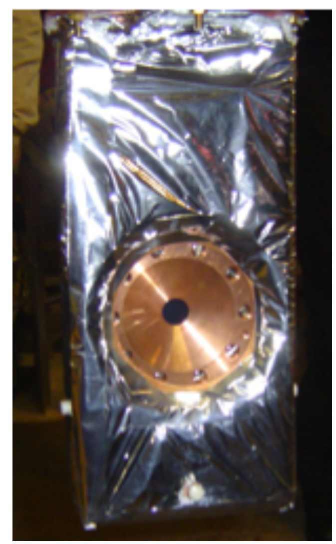
^{4}He,^{3}He target of IPNO-DA:

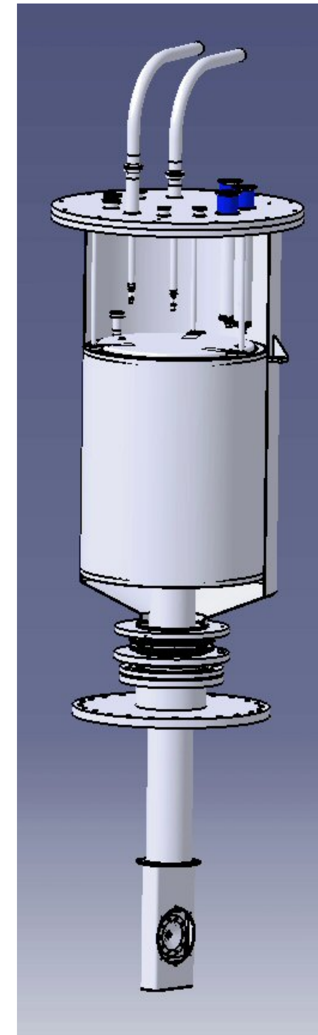
- Specifications:
  - diameter = 16 mm
  - thickness = 3 mm
  - T ≈ 8 K
  - P = 1 bar
  - Window: Havar (3.8 μm)

- Used in 2007:
  - ^{22}Ne(α,^{6}He)^{20}Ne
  - ^{22}Ne(α,^{6}Be)^{20}O

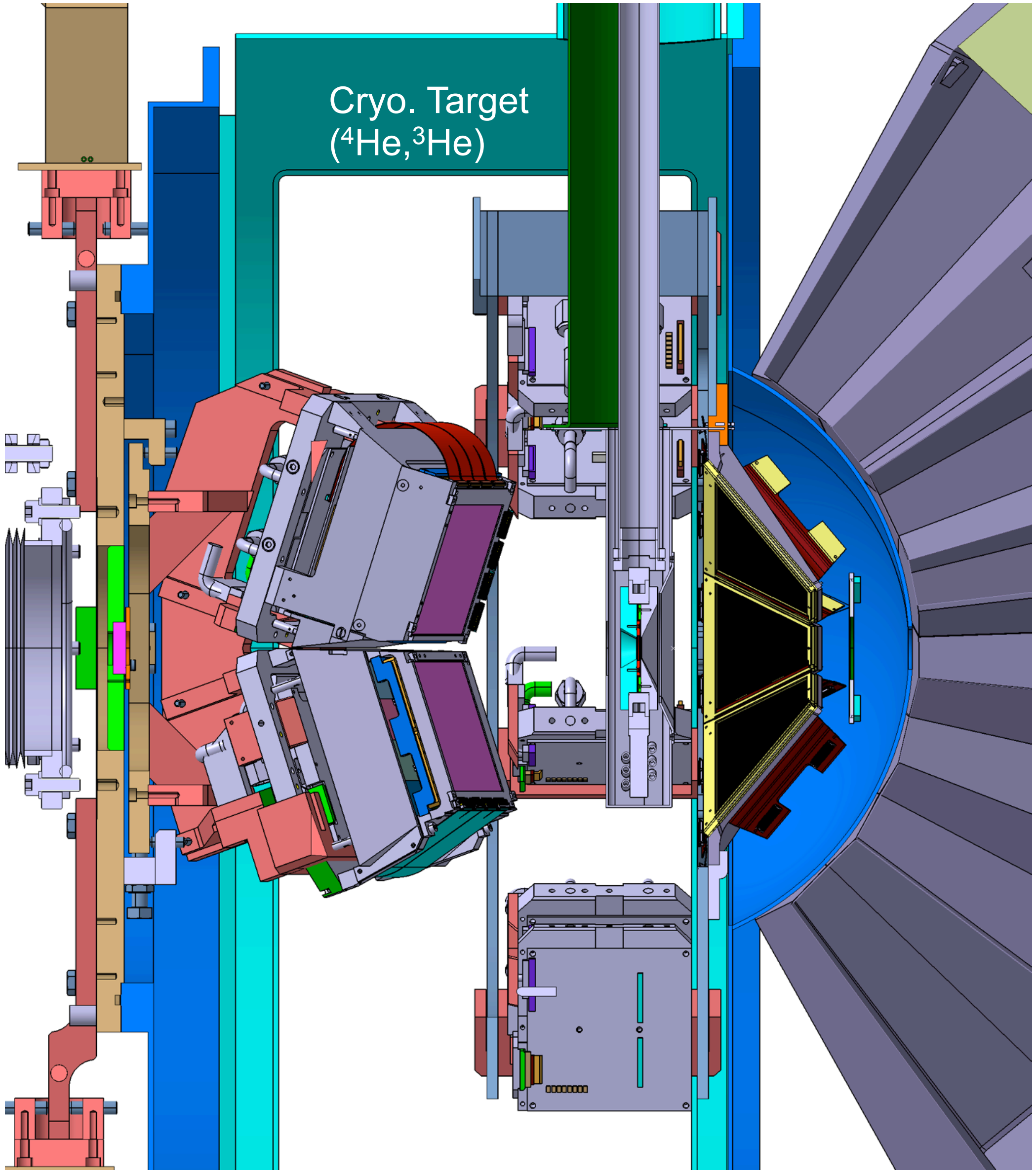
- Exists and ^{3}He possible
- Reparation, redesign, testing: not yet funded



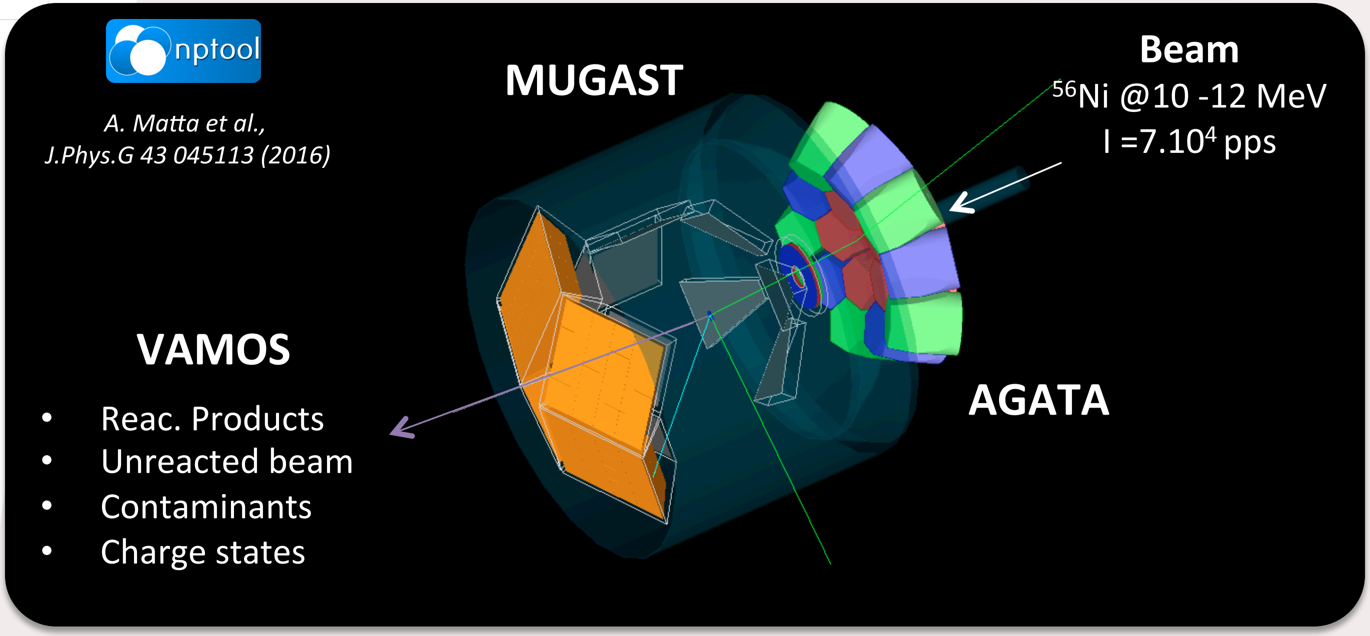


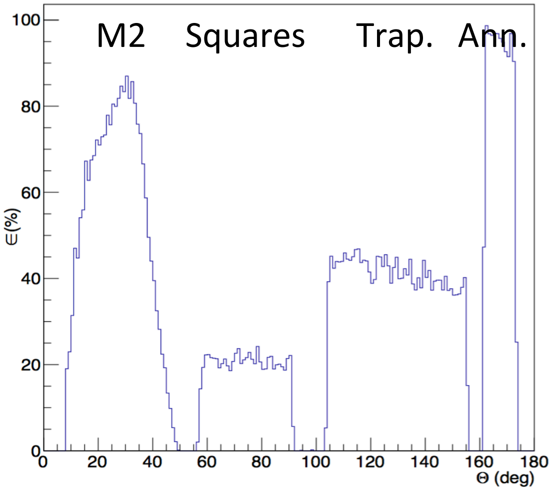


Full coupling (preliminary)



Simulations



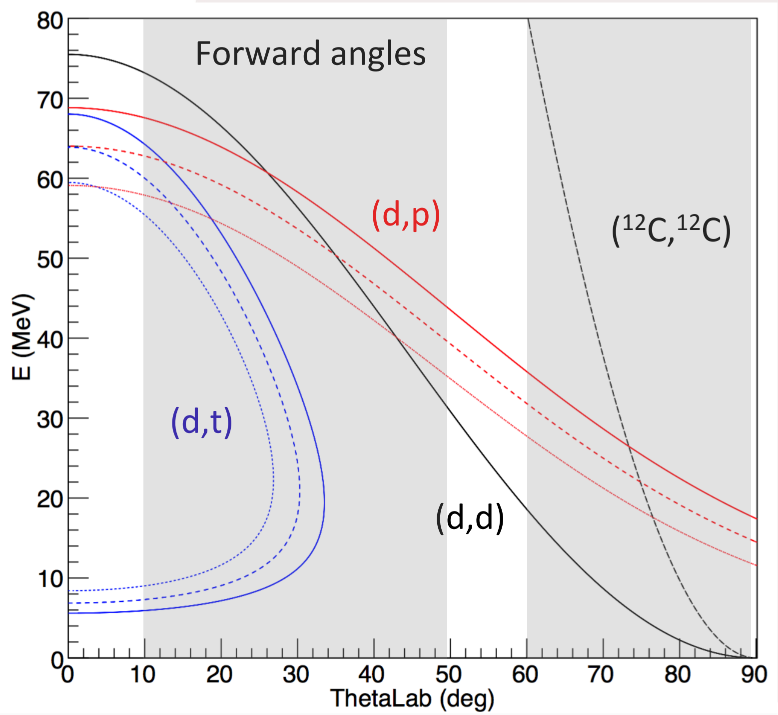


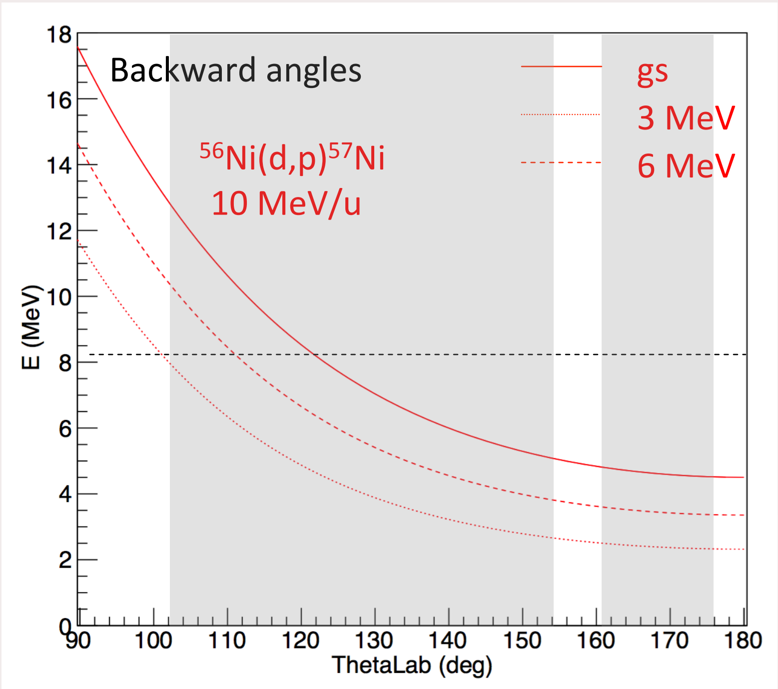
Particle detection

- **4 MUST2 Telescopes at forward angles**
  - Distance : 18 cm [10-50]°
- **2TRACE squares around 90°:**
  - Distance : 13.5 cm [60,90]°
- **4 Trapezoids and one Annular:**
  - Distance : 10.5 cm – Ann: 13.4cm
  - Angles: [105-155]° + [161-174]°

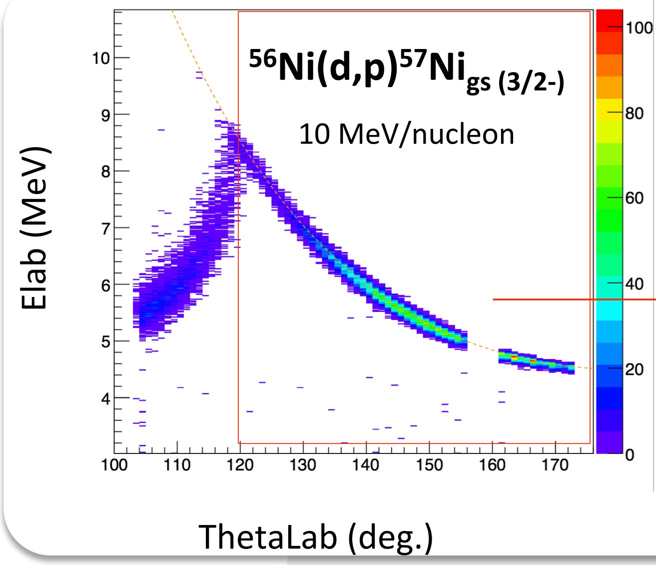
Beam / Kinematics : $^{56}Ni(d,p)^{57}Ni$

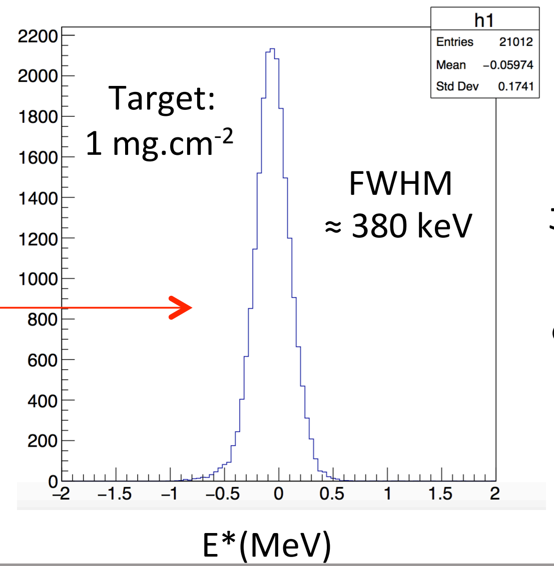
Beam:	$^{56}Ni(12+)$
Intensity:	$7*10^4$ pps
Energy:	10 MeV/nucleon
A/Q:	4.667
Q(d,p):	+8 MeV

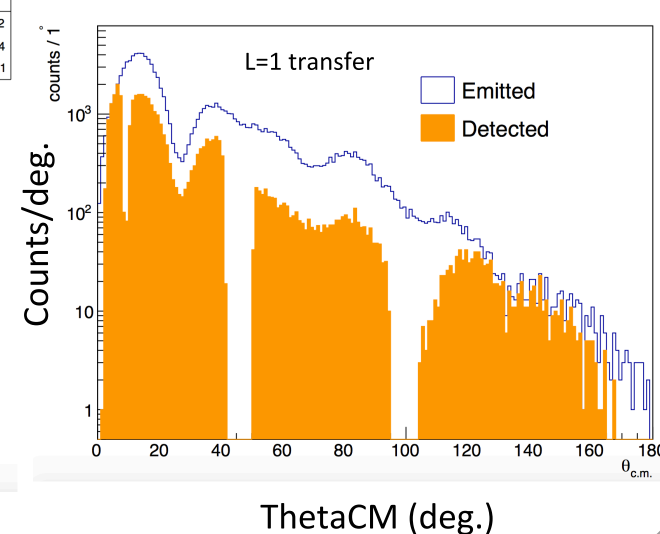




Simulations: ^{56}Ni(d,p) and ^{28}Mg(d,p)





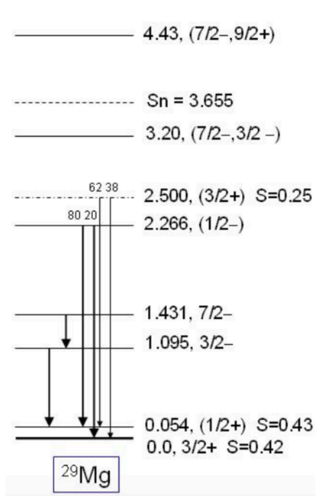


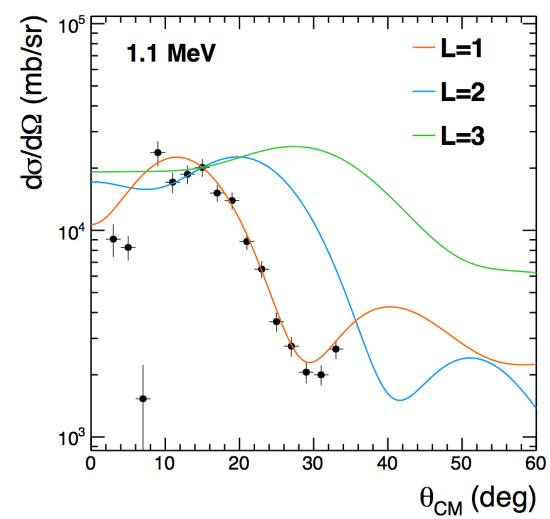
^{28}Mg(d,p)^{29}Mg

10 MeV/nucleon – 1mg.cm^{-2}

10^5 pps. – 1 week exp

shell	J^π	E (MeV)	ℓ	σ (mb)	N_R	N_D	N_C
1d3/2	$3/2^+$	0	2	7	35k	5k	350
2s1/2	$1/2^+$	0.054	2	5	24k	5k	350
2p3/2	$3/2^-$	1.1	1	17	80k	25k	1750
1f7/2	$7/2^-$	1.4	3	18	83k	25k	1750
2p1/2	$1/2^-$	2.3	3	8	39k	12k	840
1d3/2	$3/2^+$	2.5	3	10	44k	14k	980
1f7/2	$7/2^-$	4.4	4	19	87k	25k	1750





Conclusion, Status and Timeline

ITEM	STATUS	who
>> DETECTORS		
Trapezoids proto (x2)	Commissionning	IPNO, P2IO
Trapezoids pre-serie (x3)	Ordered	Surrey/IPNO +Santiago
Squared proto (x2) + Thick proto	Ordered	INFN-Padova
Annular (x1) th = 500um	Available	IPNO, Surrey
>> ELECTRONICS		
MUST2 FEE boards x10 +1?	Available	
(MUST2 FEE new boards x5 boards+components+ASIC	Order 2016	IPNO, Saclay, LPC
MUST2 Digital boards (x4)	Available	
Kaptons prototypes	Ordered: test 09/16	IPNO
Final Kaptons (x48)	Designed	IPNO
Cables & feedthroughs	2016-2017	IPNO
>> MECHANICS		
Chamber VAMOS and supports	Final for end 2016	Surrey

- **Reaction chamber** design ongoing **(fully funded)**
- Test bench mounted @ IPN and operational
- Kaptons:
  - design close to final:
  - Prototypes ordered for test
- ASIC for MUST2: OK
  - Encapsulation needed
- new MUFEE cards study: → OK
- Cryogenic target possibility (not yet funded)

Backup

Difficulties to be aware of

1) Beam Contamination

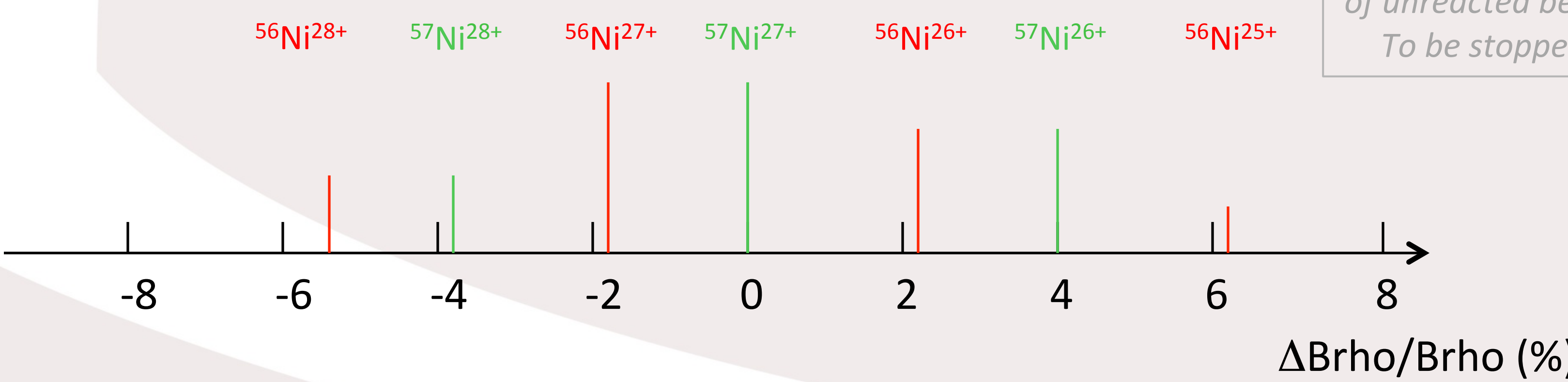
Primary beam	Target	^{56}Ni (12+) pps	^{56}Co(11+) pps
58Ni	12C	7.3E+04	1.6E+06
58Ni	Nb	4.0E+04	1.7E+06

Charge state	% 0.5 mg/cm^2	% 1 mg/cm^2	% 2 mg/cm^2
28+	17	16	15
27+	42	41	39
26+	31	32	34
25+	8	9	11

2) Charges states in VAMOS after secondary target (preliminary)

Even if fully stripped $^{56}Ni^{28+}$ onto a CD_2 target at 12 MeV/nucleon:

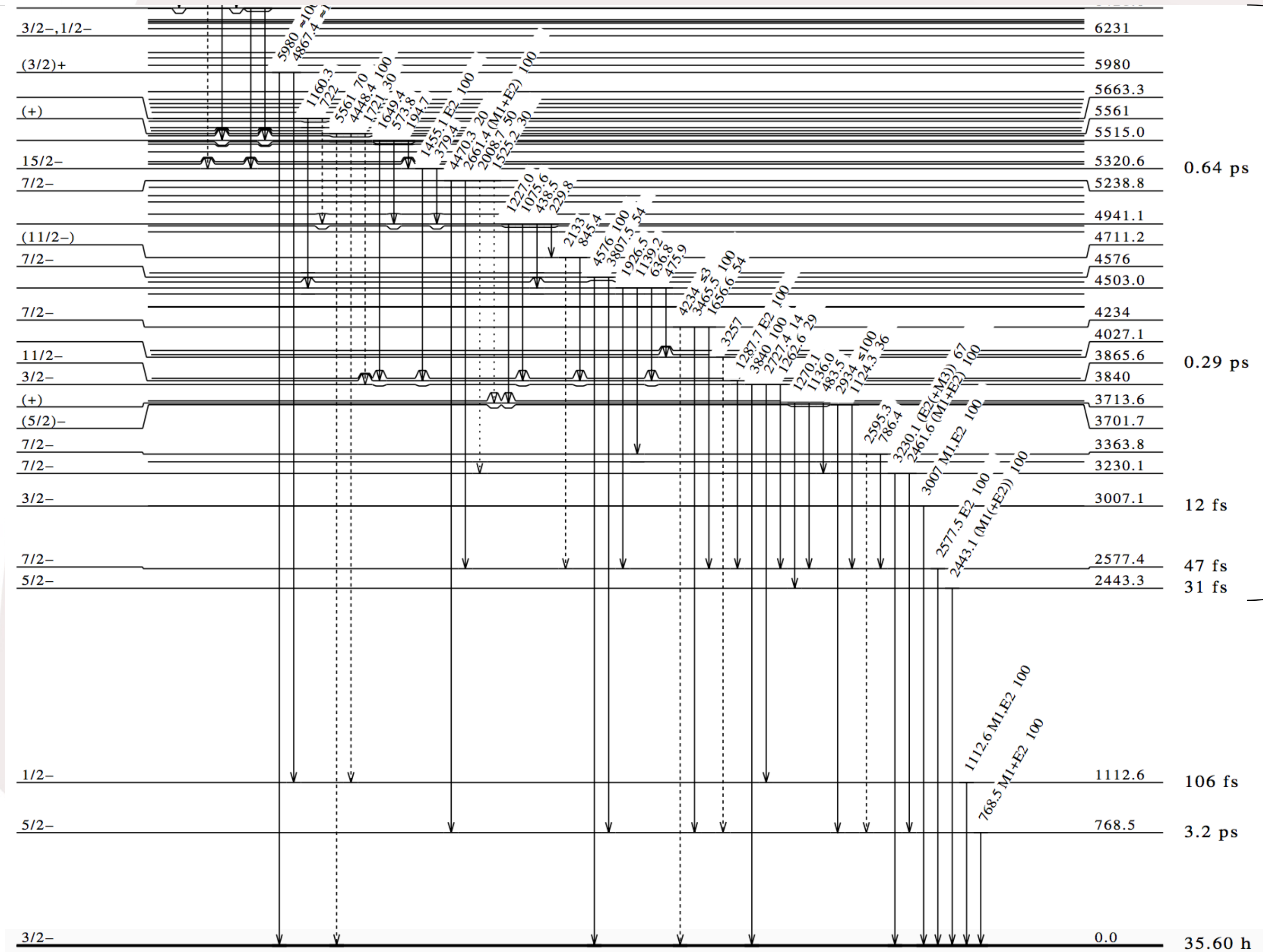
7.10^4 pps of unreacted beam To be stopped



^{57}Ni level scheme

Populated in ^{58}Ni(p,d)

^{58}Ni(0+) $(p3/2)^2 \times \nu^{-1}$



Single-p. strength ??

^{56}Ni

^{57}Ni

Interprated as ^{56}Ni(2+,4+,6+) $\times (p3/2)^1$

Populated in (d,p)

Simulations

nptool

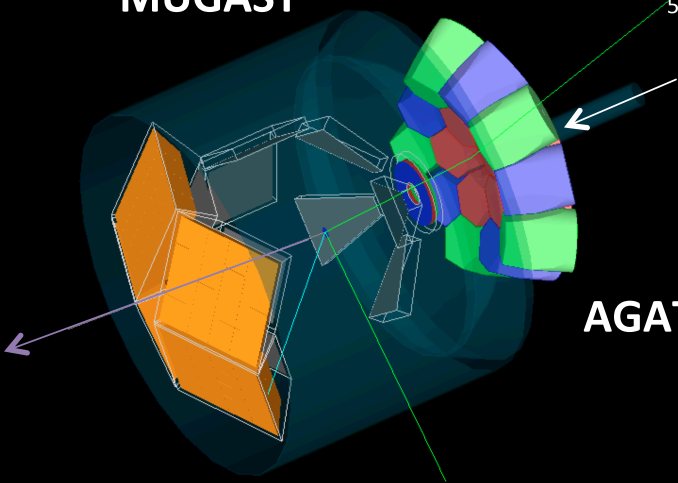
A. Matta et al., J.Phys.G 43 045113 (2016)

MUGAST

Beam

^{56}Ni @10 -12 MeV

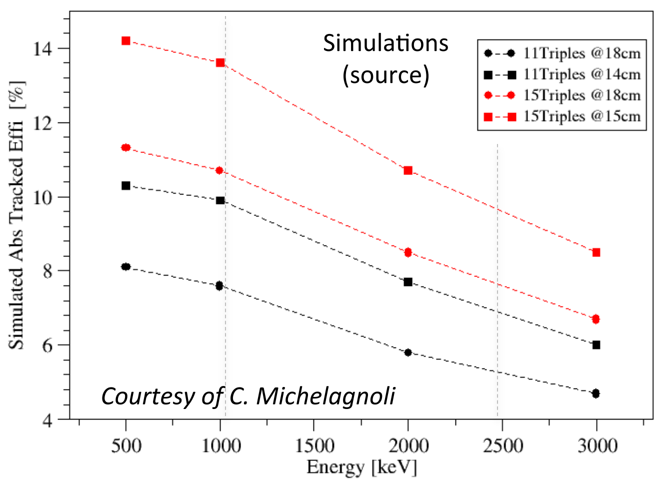
I =7.10^4 pps



AGATA

VAMOS

- Reac. Products
- Unreacted beam
- Contaminants
- Charge states



γ detection

At 18 cm (current goal)

- ε(1.0 MeV) ~ 8%
- ε(2.5 MeV) ~ 5 %

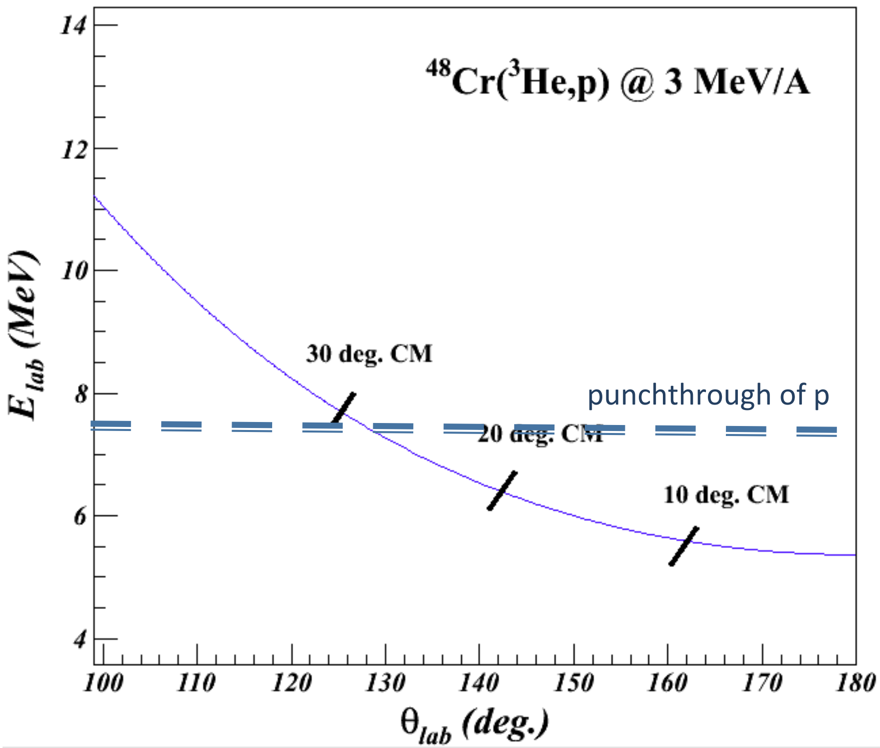
33 det.

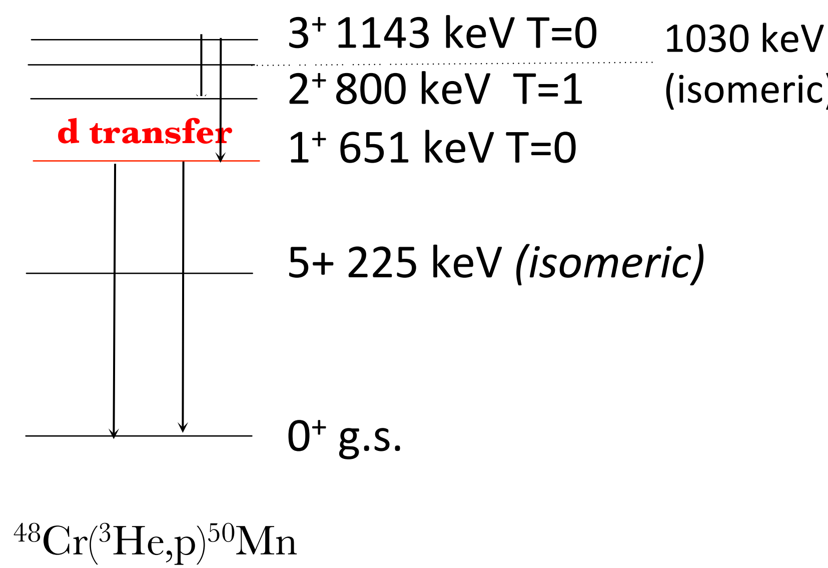
- ε(1.0 MeV) ~ 11 %
- ε(2.5 MeV) ~ 8 %

45 det.

CASE OF ^{48}CR WITH SPIRAL1

- (p,^{3}He) reaction not possible with 11MeV/A at maximum (Q=-13,4 MeV)
- **(^{3}He,p) reactions favoured at low energy**





γenergy :T=0 651 keV, 343 & 492 keV

Backward detection of protons with GASPARD

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

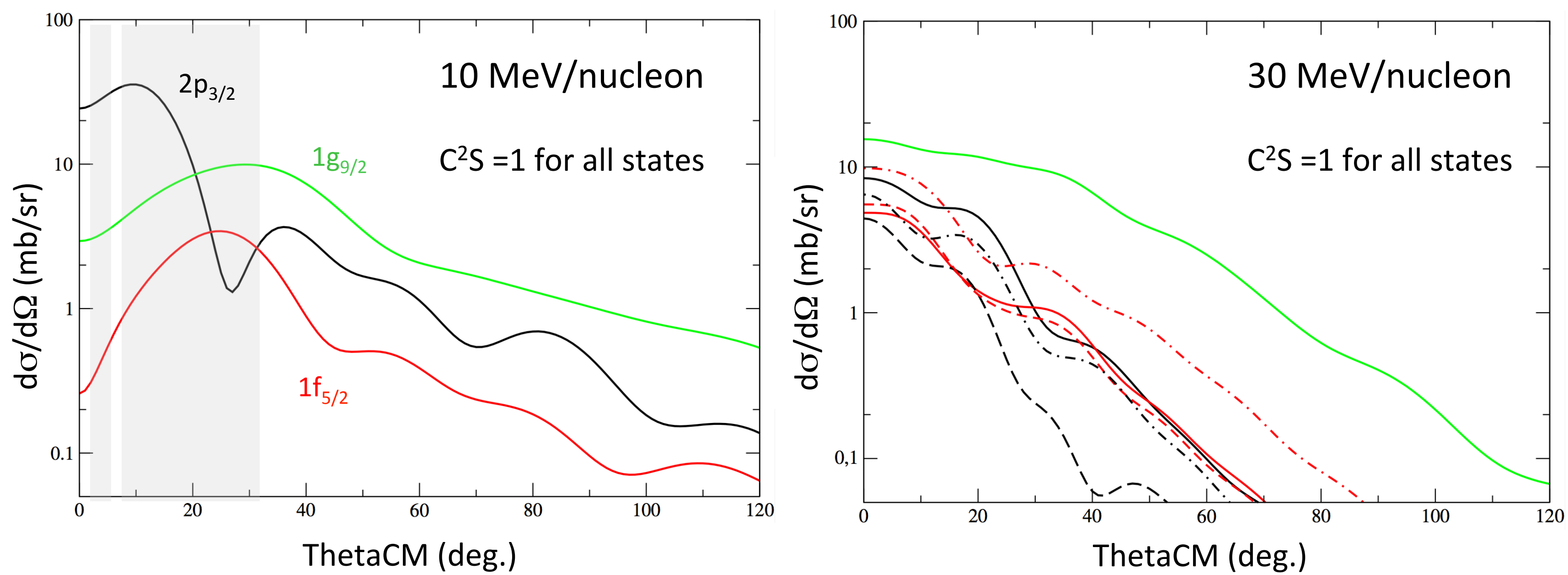
Statistics : $^{56}Ni(d,p)^{57}Ni$

- **Statistics :**
  - Beam: 7.3*10^4
  - Target: **2 mg.cm^{-2}**
  - Effic. (p) rec.: 85%
  - Effic. (p) geo: 40 % * 70%
  - Effic. (γ): 8 % at 1 MeV
    4% at 2-3 MeV

In 9 days (27 UTs)

	E (MeV)	C²S	Xsec (mb)	Cnts(p)	Cnts(p+γ)
Main sp-states	0	0.9	19	**35000**	**--**
	0.769	0.9	5	**9700**	**800**
	1.113	0.9	8	**14000**	**1100**
	3.701	0.6	27	**19000**	**1500**
Low sp-strength If γ (2.5 MeV)	3 - 6	0.1	20	**2000**	**80**
If γ (1.0 MeV)		0.1	20	**2000**	**160**

Cross section estimates – DWBA: $^{56}Ni(d,p)^{57}Ni$



E (MeV)	nlj	Xsec @10 A.MeV (mb)	Xsec @30 A.MeV (mb)
0	2p3/2	19	4.3
0.769	1f5/2	5.3	2.7
1.113	2p1/2	7.8	1.3
2.443	1f5/2	5.9	2.5
2.577	1f7/2	12	6.0
3.007	2p3/2	20	2.8
3.009	1g9/2	27	26

At 10 MeV/nucleon:

- Higher cross sections than 30 MeV/nucleon
- Better matching for L=1 orbitals but L=3,4 ok

- Well-defined shape for angular distributions
- L=1 and 3 shape very different (1st max)

- Higher E* states favored due to high Qvalue (+8 MeV)

Theory: ESPE, SF, etc

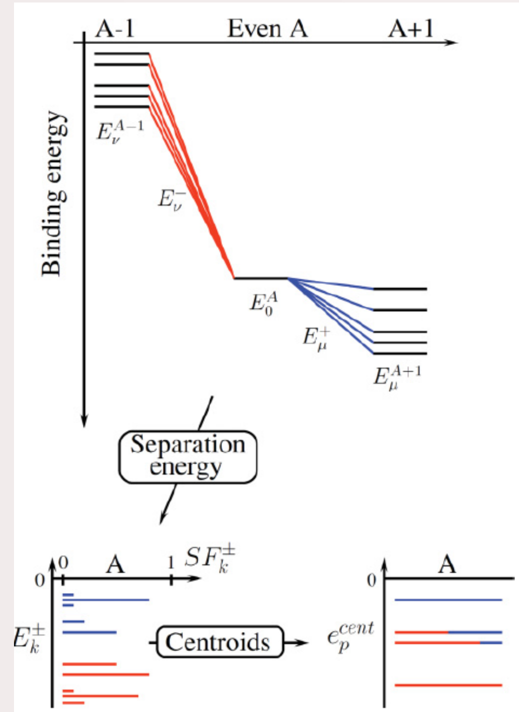
Baranger sum rule:

$$e_p^{\text{cent}} \equiv \sum_{\mu \in \mathcal{H}_{A+1}} S_\mu^{+pp} E_\mu^{+} + \sum_{\nu \in \mathcal{H}_{A-1}} S_\nu^{-pp} E_\nu^{-}$$

Full expansion:

$$\underbrace{\overset{\text{many-body observable}}{E_\mu^{+}}}_{\text{invariant under } U(\lambda)} \equiv \underbrace{\overset{\text{single-particle components}}{\sum_p s_\mu^{+pp}(\lambda)\, e_p^{\text{cent}}(\lambda)}}_{\text{varies under } U(\lambda)} + \underbrace{\overset{\text{correlations}}{\sum_{pq} s_\mu^{+pq}(\lambda)\, \Sigma_{qp}^{\text{dyn}}(E_\mu^{+};\lambda)}}_{\text{varies under } U(\lambda)} \,,$$

T. Duguet, V. Soma et al , arxiV 1411.1237 (2014)
T. Duguet, V. Soma et al , PRC87 011303(R)
T.Duguet. G.Hagen, PRC85 034330



Experimentally:

Major assumption in treatment : separation of reaction mechanism and structure inputs

Cross section
to populate a final state μ

$$\sigma_\mu = \sum_{p \in H < H_1} \left| \left\langle \varphi_\mu{}^{A-1} \middle| a_p{}^{-} \middle| \varphi_0{}^{A} \right\rangle \right|^2 \times \sigma_p$$

reaction

Structure