Opportunities in Nuclear Structure and Dynamics with VAMOS

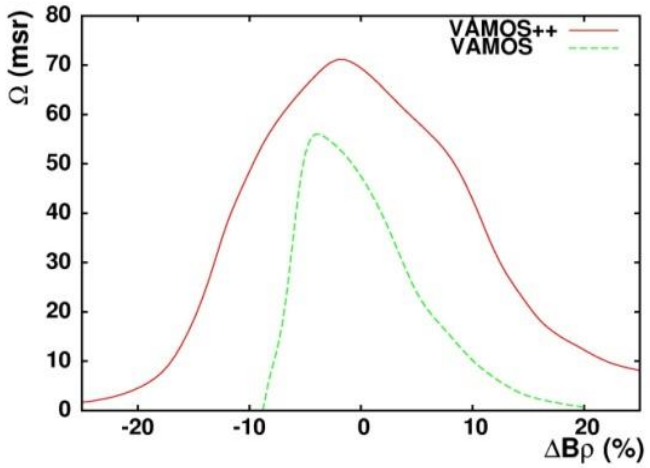
A. Lemasson

Colloque GANIL 2017

Short summary of VAMOS

VAriable **MO**de **S**pectrometer

In operation since 2001

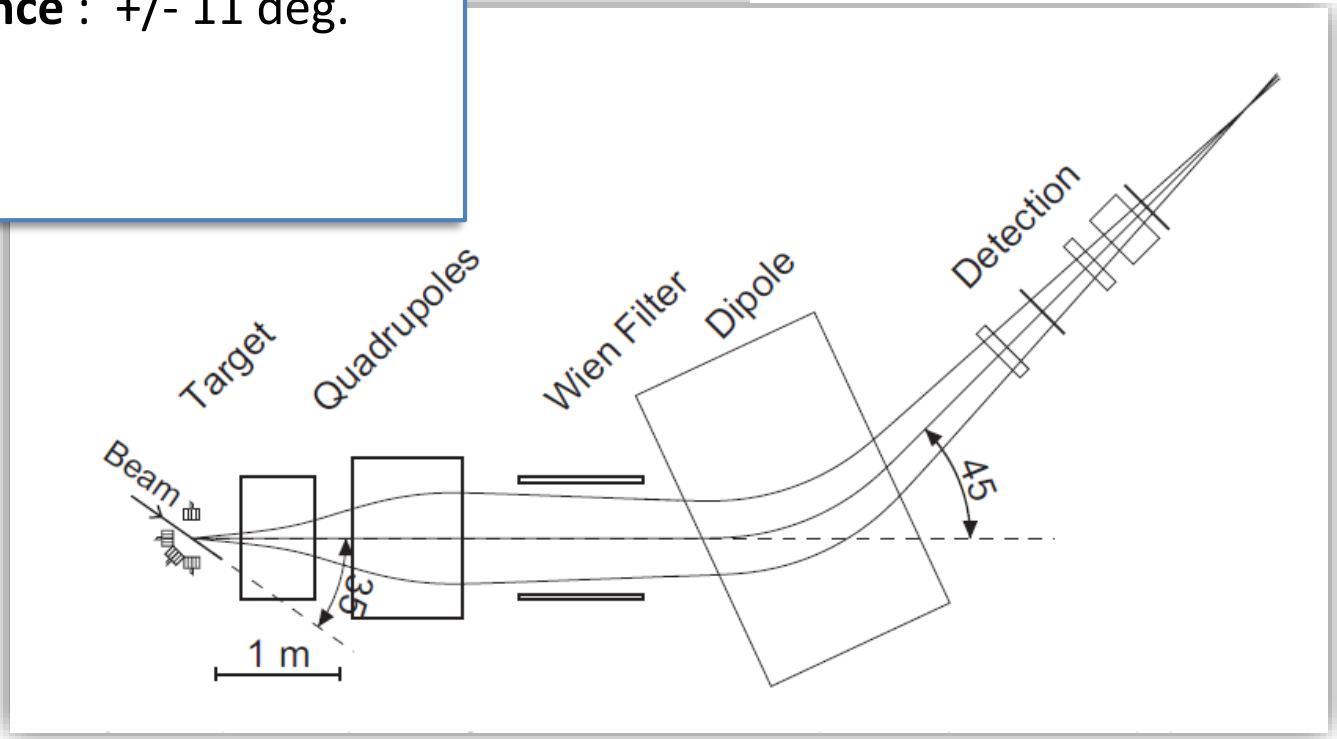


Horizontal acceptance : +/- 7 deg.

Vertical acceptance : +/- 11 deg.

Max Bρ : 1.6 Tm

ΔM/M : 2 10^{-3}



S. Pullanhiotan et al. , NIM A 593 (2008) 343

M. Rejmund *et al.*, NIM A 646 (2011) 184

VAMOS++ today

EXOGAM at Focal Plane

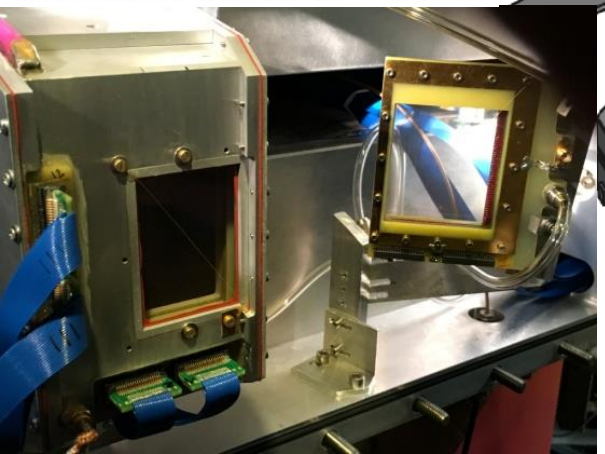
Focal Plane Detection

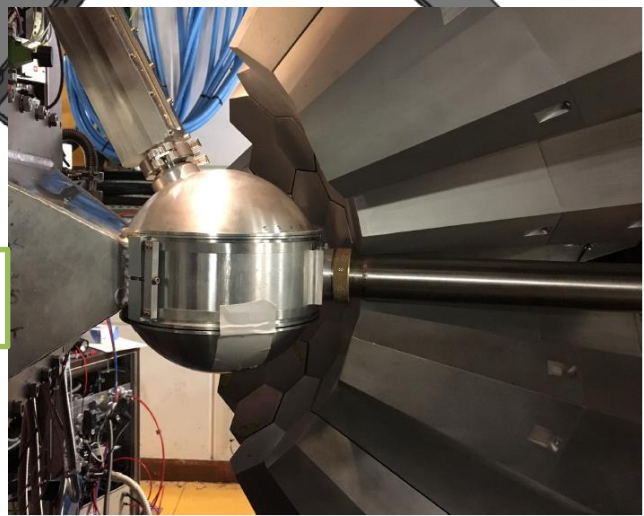
Ionization Chambers MWPC

DPS-MWPC

Second Arm

AGATA





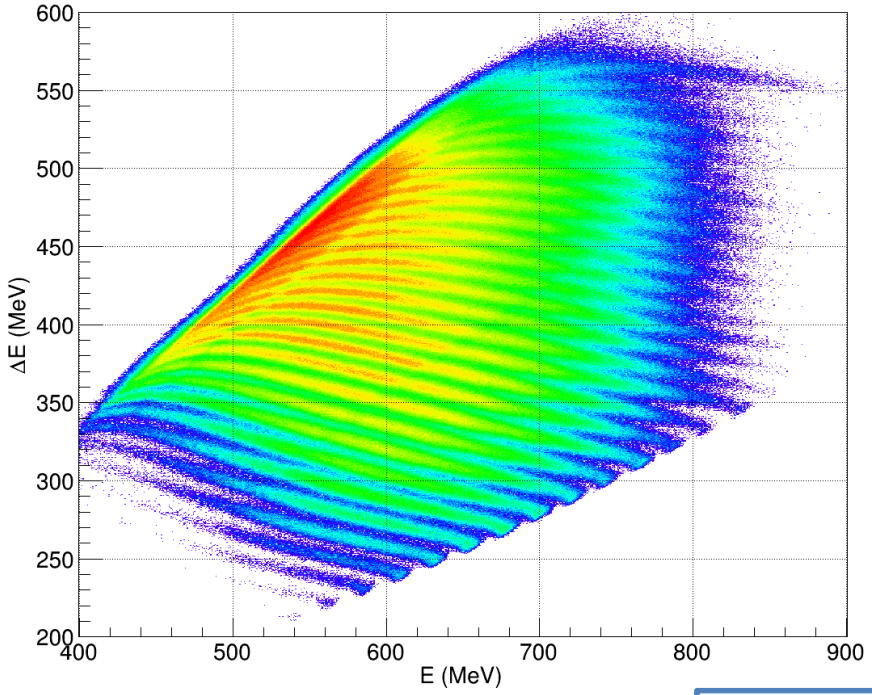
Versatility arises from variety of detectors

(Ionization Chambers, Drift Chambers, MWPC, Plastic, Silicon Wall…)

Continuous devellopement of detectors
starting from VAMOS++
(driven by the goal to improve performances)

- 2010 : Upgrade of the Focal Plane detection (x2 size)
- 2012 : New MWPC at the entrance
- 2014 : Upgrade to Ionization Chambers (Phase 1)
  Upgrade of electronics readout
- 2015 : Upgrade to Ionization Chambers (Phase 2)
- 2016 : EXOGAM at the Focal Plane
- 2017 : Large Size MWPC at the Focal Plane
  Upgrade to NUMEXO 2

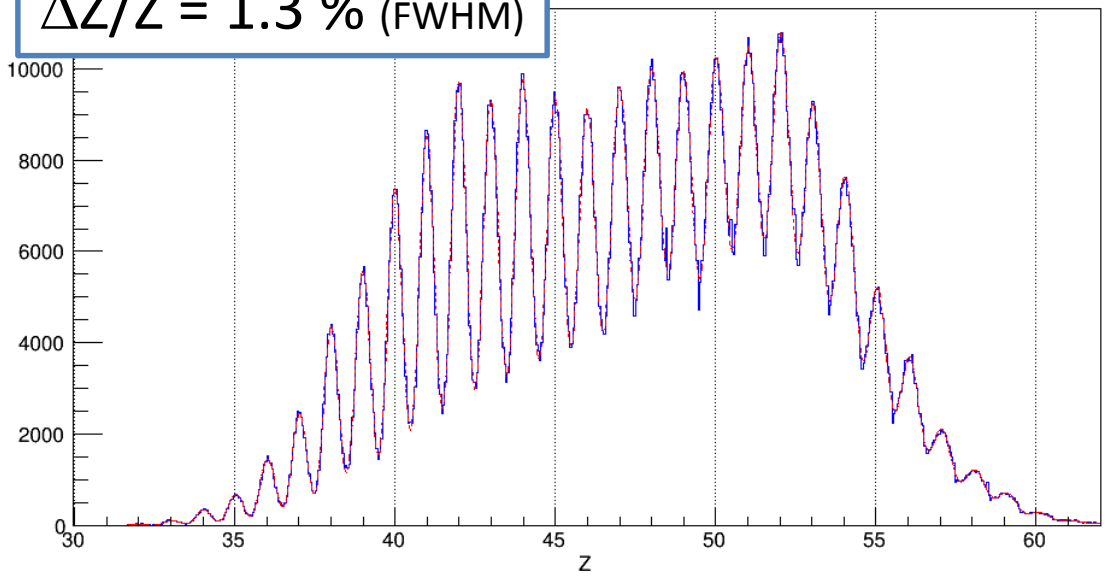
What is next ? What are your needs ?



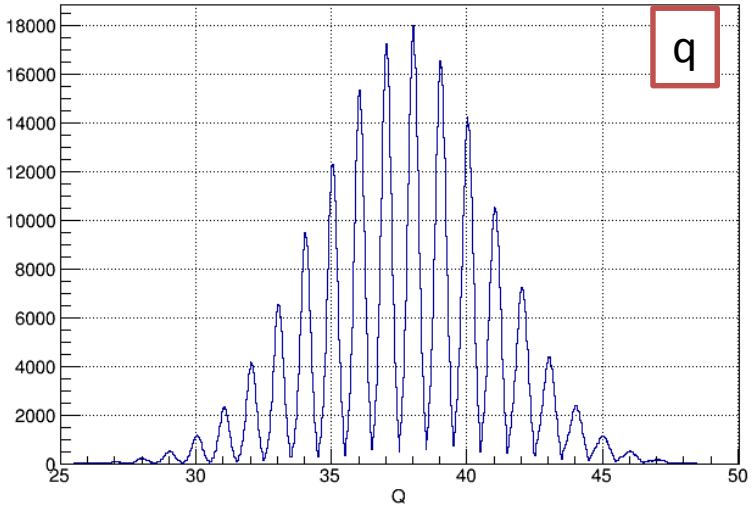
Isotopic identification (Z,A,q)

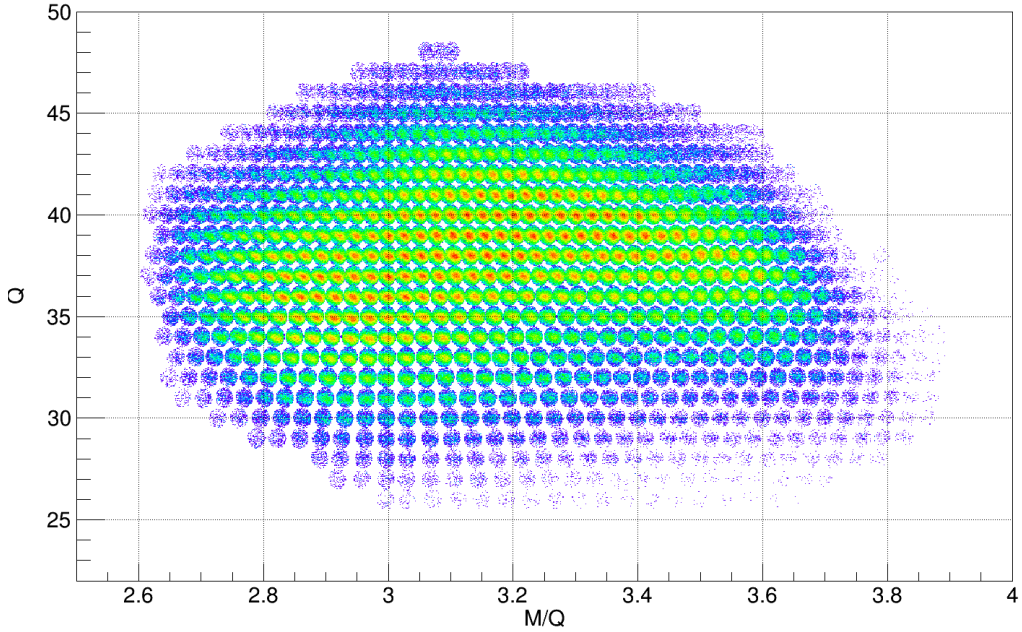
Energy range :
4 to 8 MeV/A !

ΔZ/Z = 1.3 % (FWHM)

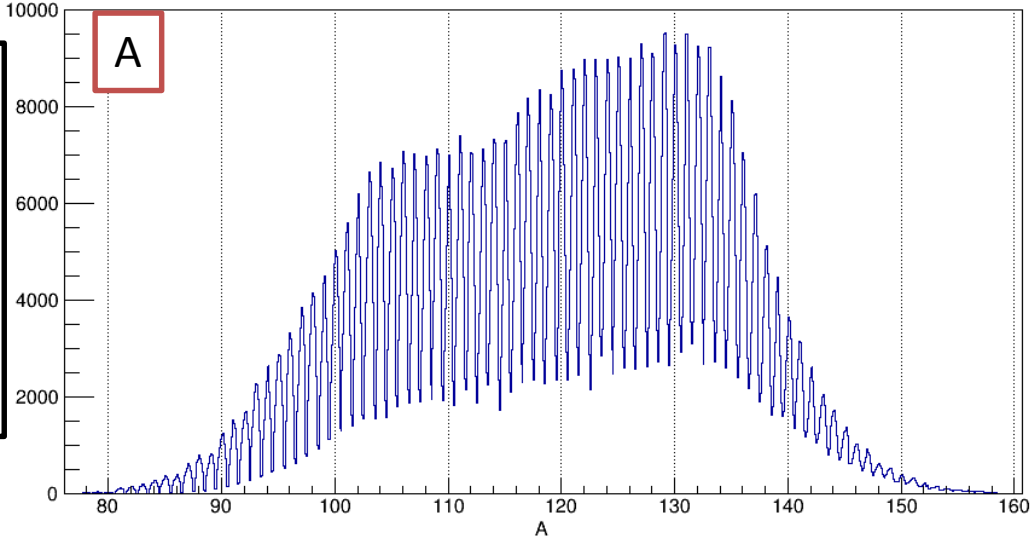


Isotopic identification(Z,**A**,**q**)

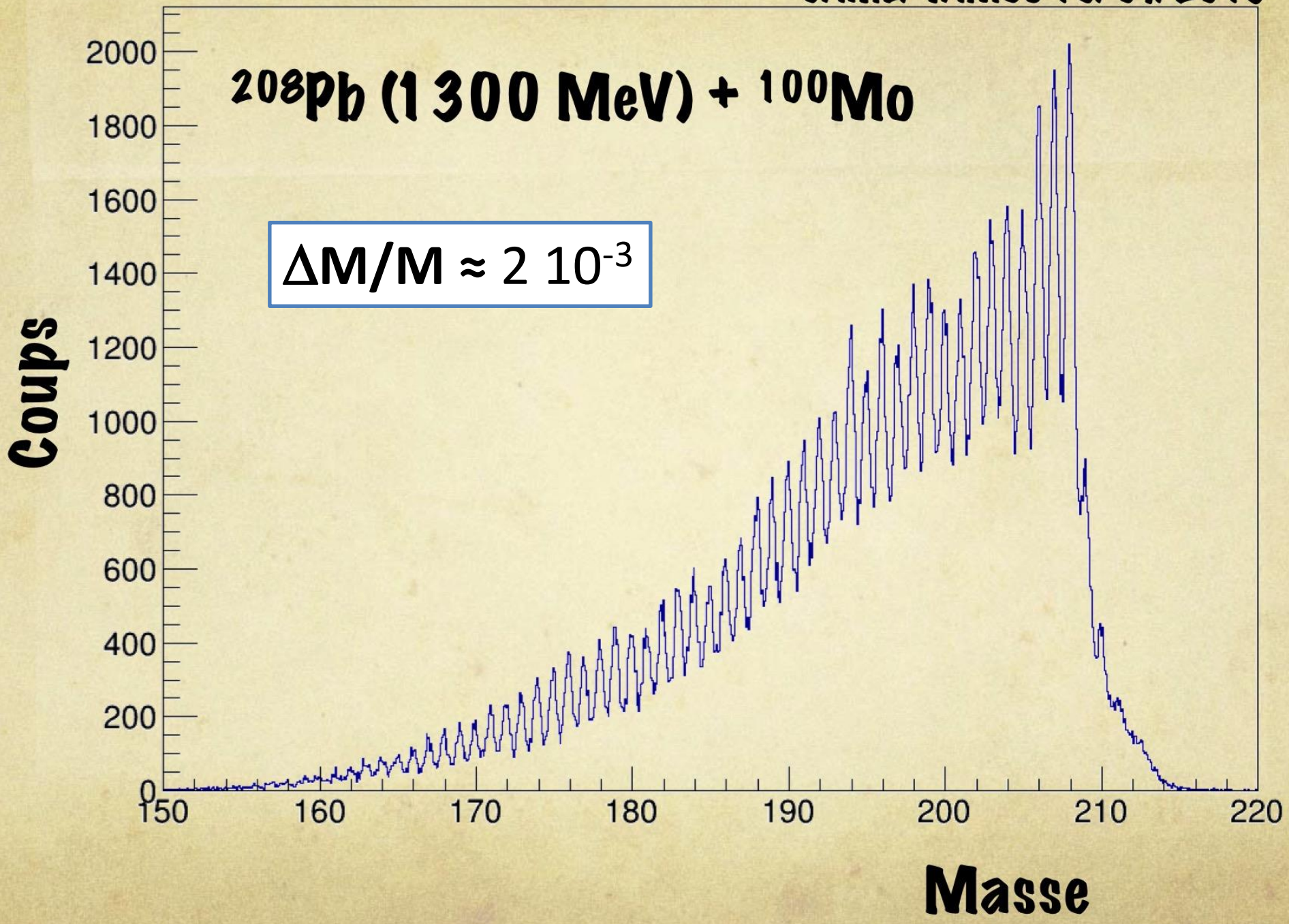




- $\sigma_{\Delta E}/\Delta E \approx 2.2\ \%$ (FWHM)
- $\sigma_q/q \approx 1.3\ \%$ (FWHM)
- $\sigma_A/A \approx 3\text{x}10^{-3}$ (FWHM)



GANIL/VAMOS 19/07/2015

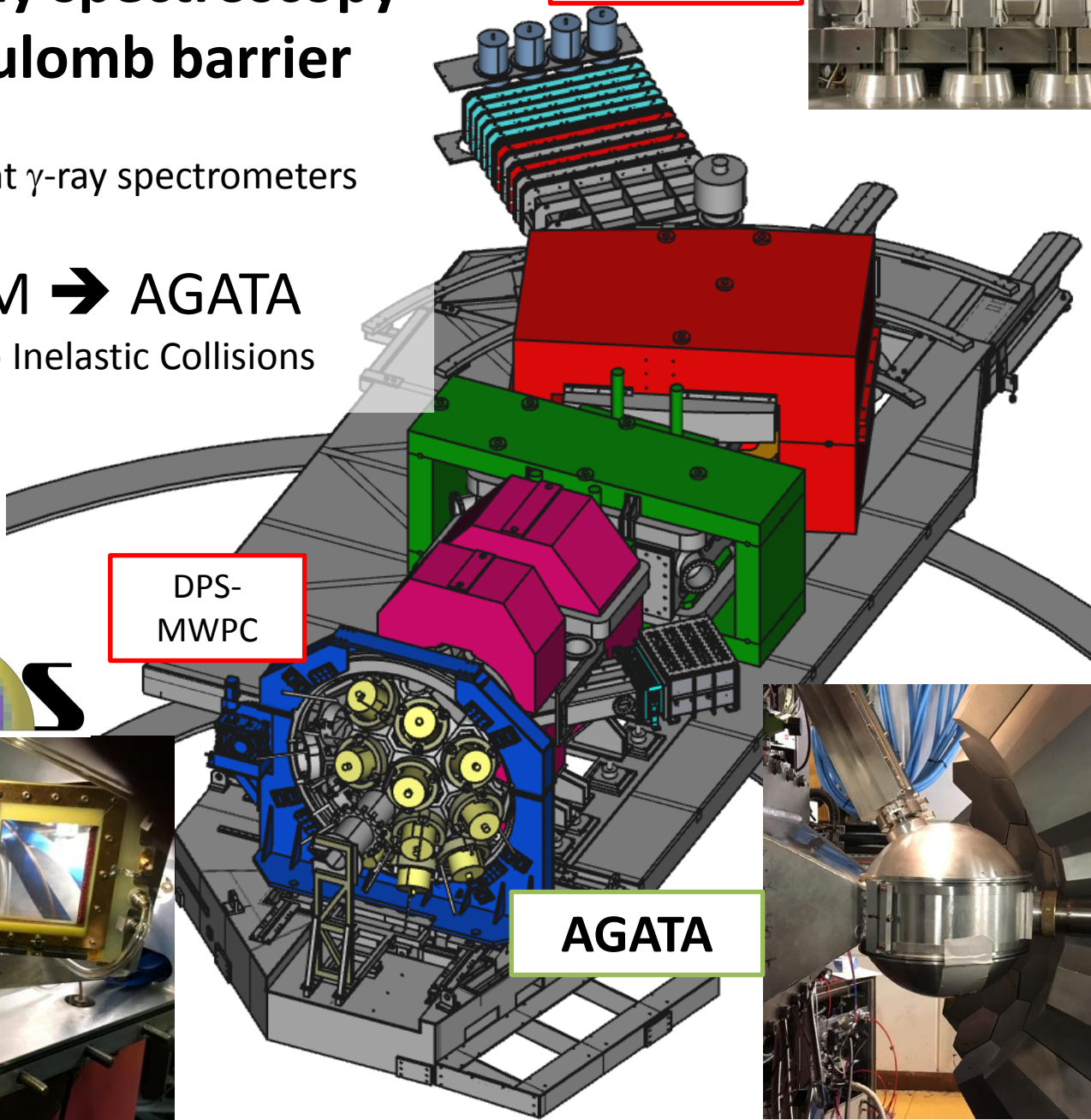


Prompt γ-ray spectroscopy at the Coulomb barrier

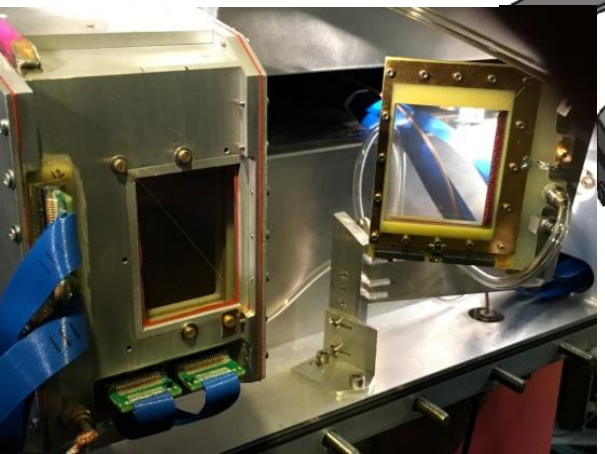
Coupling to efficient γ-ray spectrometers

EXOGAM ➔ AGATA

Fission, Deep Inelastic Collisions



VARIABLE MODE SPECTROMETER



Prompt γ-ray spectroscopy at Coulomb barrier energies at GANIL

- ✓ **Heavy ions stable beams (^{238}U)**
  High intensity around the Coulomb barrier
- ✓ **Inverse kinematics :**
  High kinematical focusing
- ✓ Coulomb barrier (v/c~0.1), Angular momentum
- ✓ **VAMOS++:** Large(st) Acceptance, high resolution (mass) spectrometer
- ✓ **Great γ-ray spectrometers** : EXOGAM -> AGATA
- ○ Challenges
  - – Low energy / Counting rate on γ-ray detectors

Prompt γ-ray spectroscopy of **isotopically identified fission fragments**

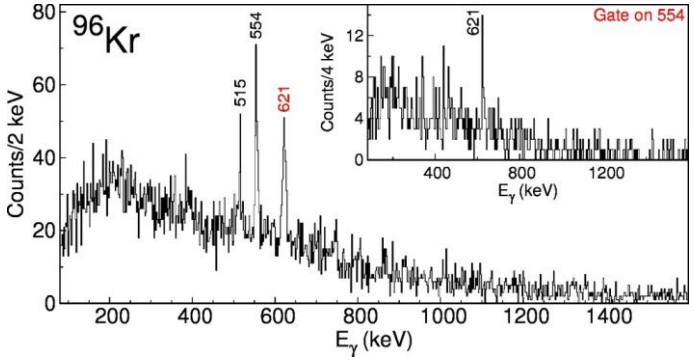
VAMOS+AGATA

Spectroscopy, γ–γ

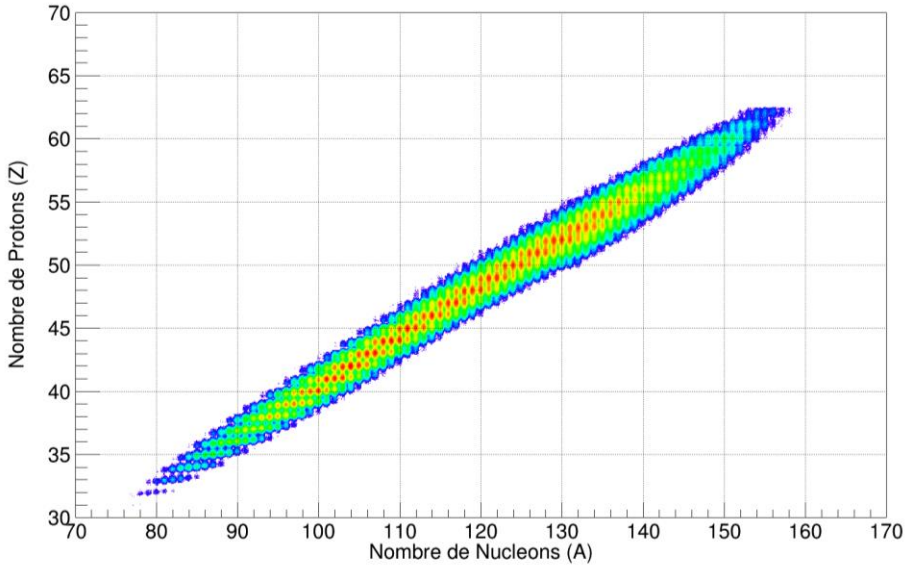
M. Rejmund later today

J. Dudouet tomorrow

E. Clément tomorrow



Phys. Rev. Lett. **118** 162501 (2017)



+ Plunger, LaBr3
Fatima / PARIS

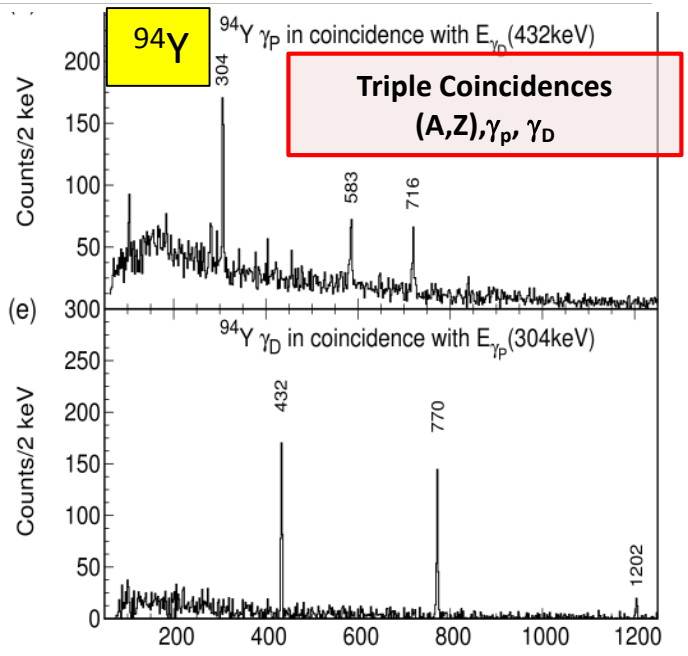
+ EXOGAM at Focal Plane

Prompt-delayed correlations

Lifetime Measurements

C. Delafosse tomorrow

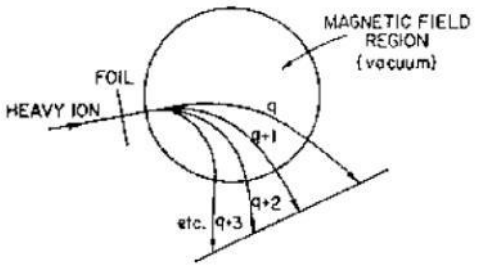
E. Clément tomorrow

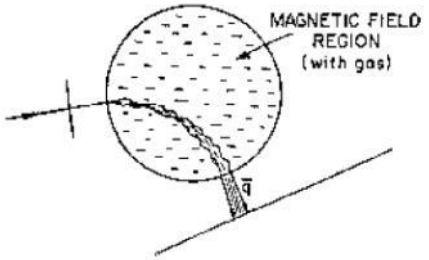


Eur. Phys. J A **53** 162 (2017)

VAMOS Gas Filled

large acceptance separator



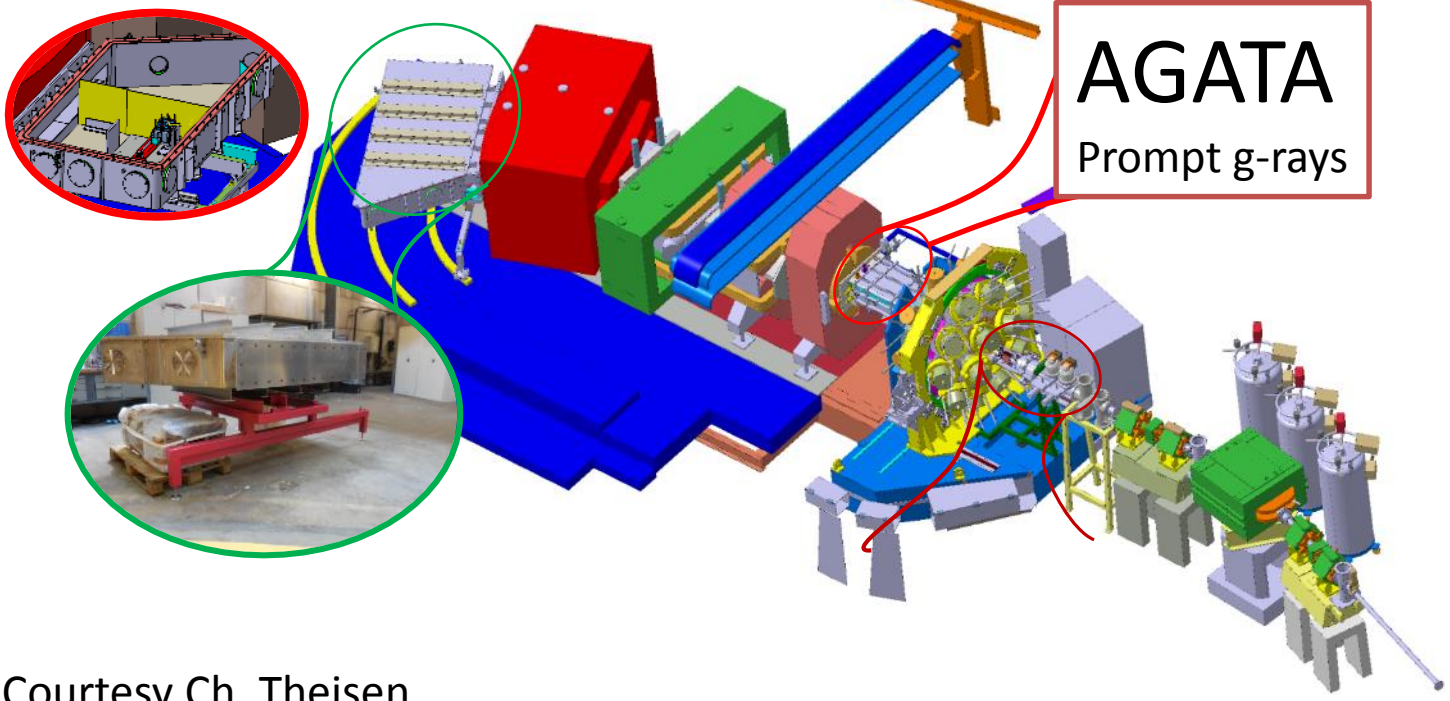


MUSETT

Recoil Decay tagging

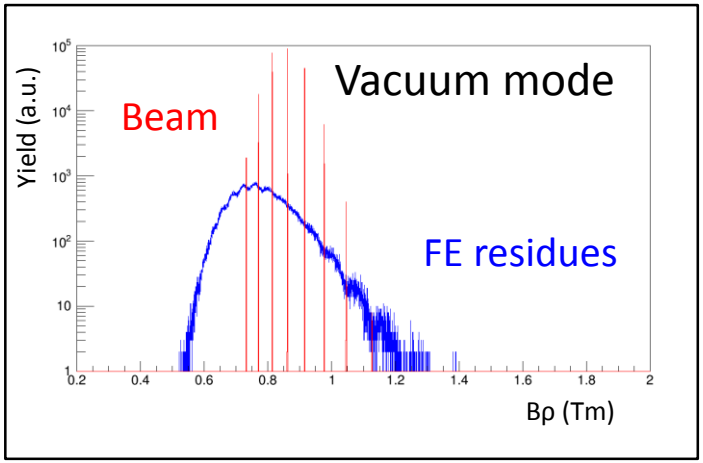
AGATA

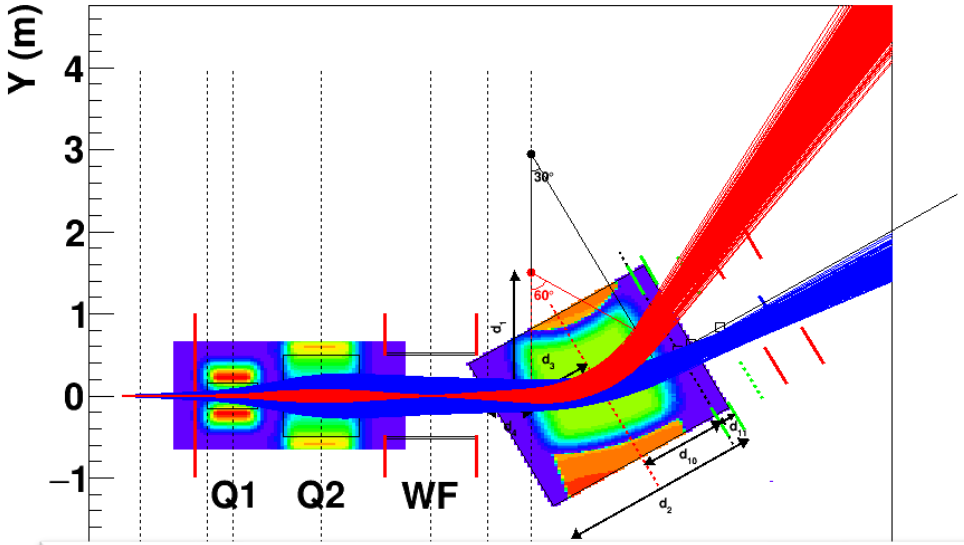
Prompt g-rays



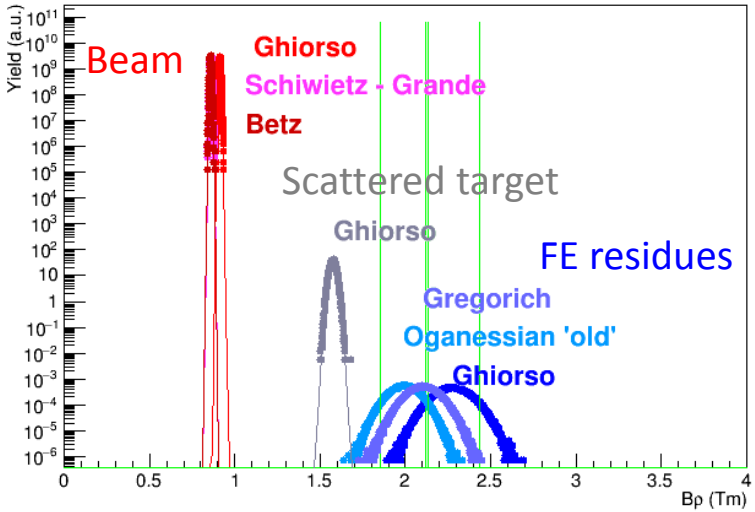
Courtesy Ch. Theisen

$^{48}Ca + {}^{208}Pb \rightarrow {}^{254}No + 2n$

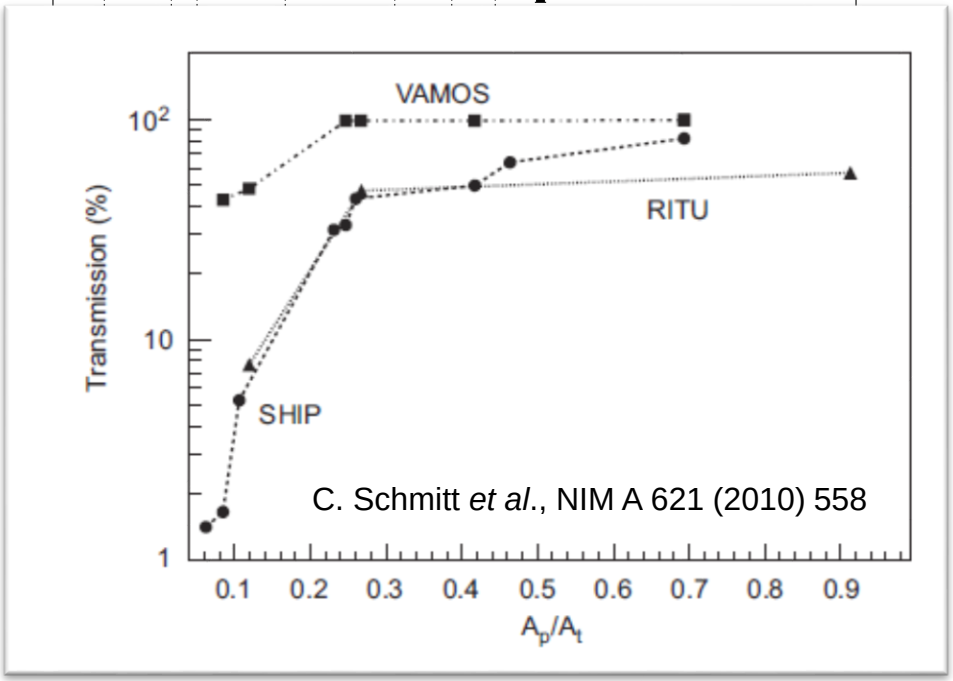




Magnetic rigidity Bρ



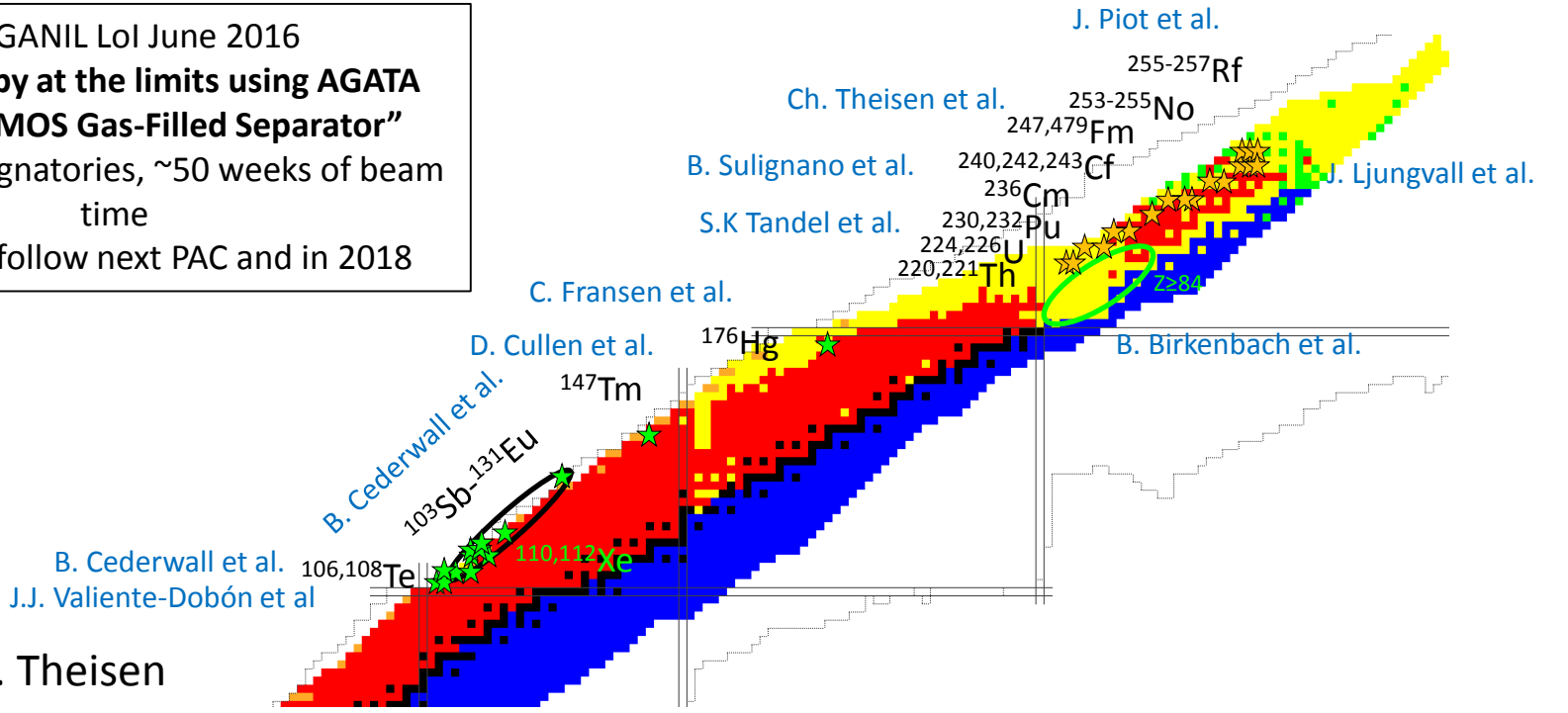
Courtesy Ch. Theisen



1. Focal plane
   - Beam dump -> Ongoing
   - MUSETT & ToF detection -> Ongoing
   - Detection shielding -> Ongoing
   - New focal plane chamber -> OK
2. Low pressure regulation -> OK
3. Transition He - vacuum
   - C Window -> OK
4. Adaptation of AGATA target chamber -> OK

=> Ready for second half of 2018 ?

PAC GANIL LoI June 2016
"Spectroscopy at the limits using AGATA and the VAMOS Gas-Filled Separator"
31 labs, 180 signatories, ~50 weeks of beam time
Proposal to follow next PAC and in 2018

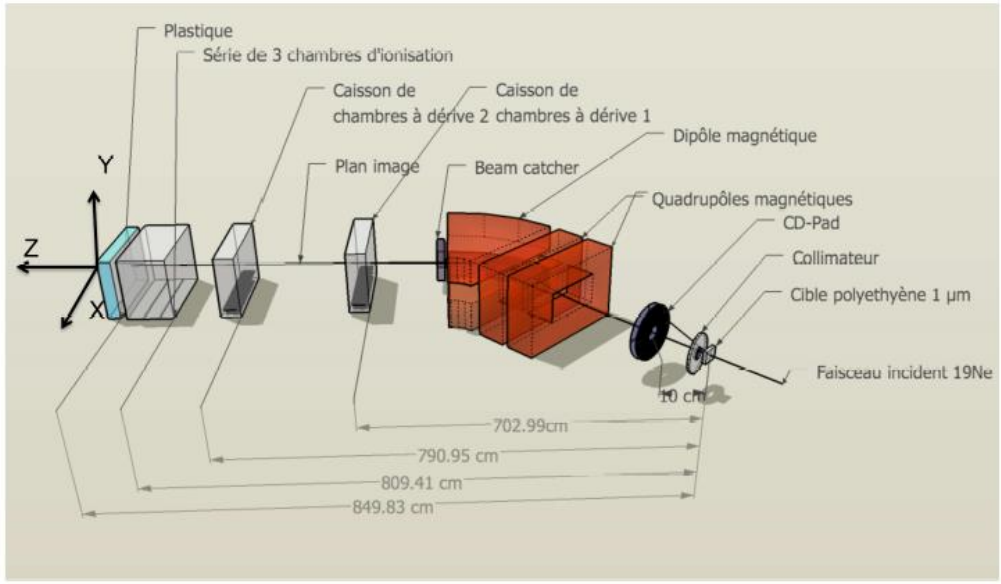


Courtesy Ch. Theisen

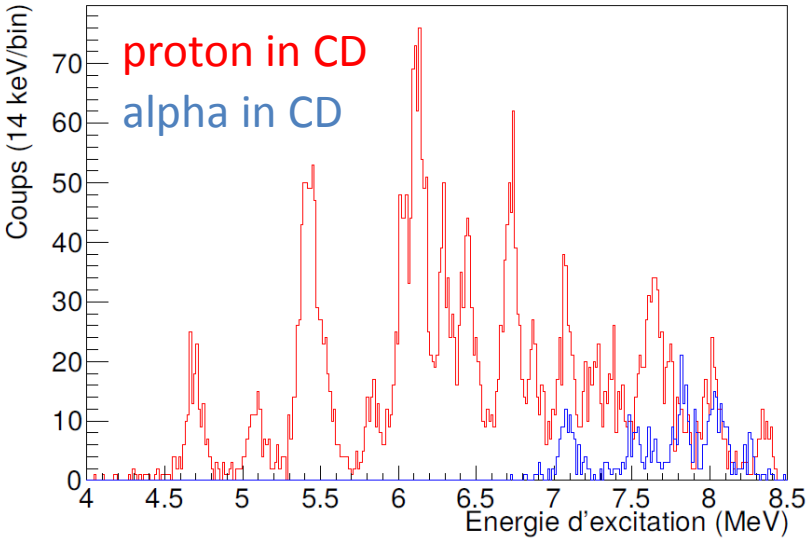
VAMOS competing with Q3D

$^{19}Ne(p,p')^{19}Ne^*$, I ~ 10^7pps

- inverse kinematics with RIB
- inelastic protons in VAMOS
- α, p in CD PAD
  (annular silicon detector)



F. Boulay PhD GANIL 2015



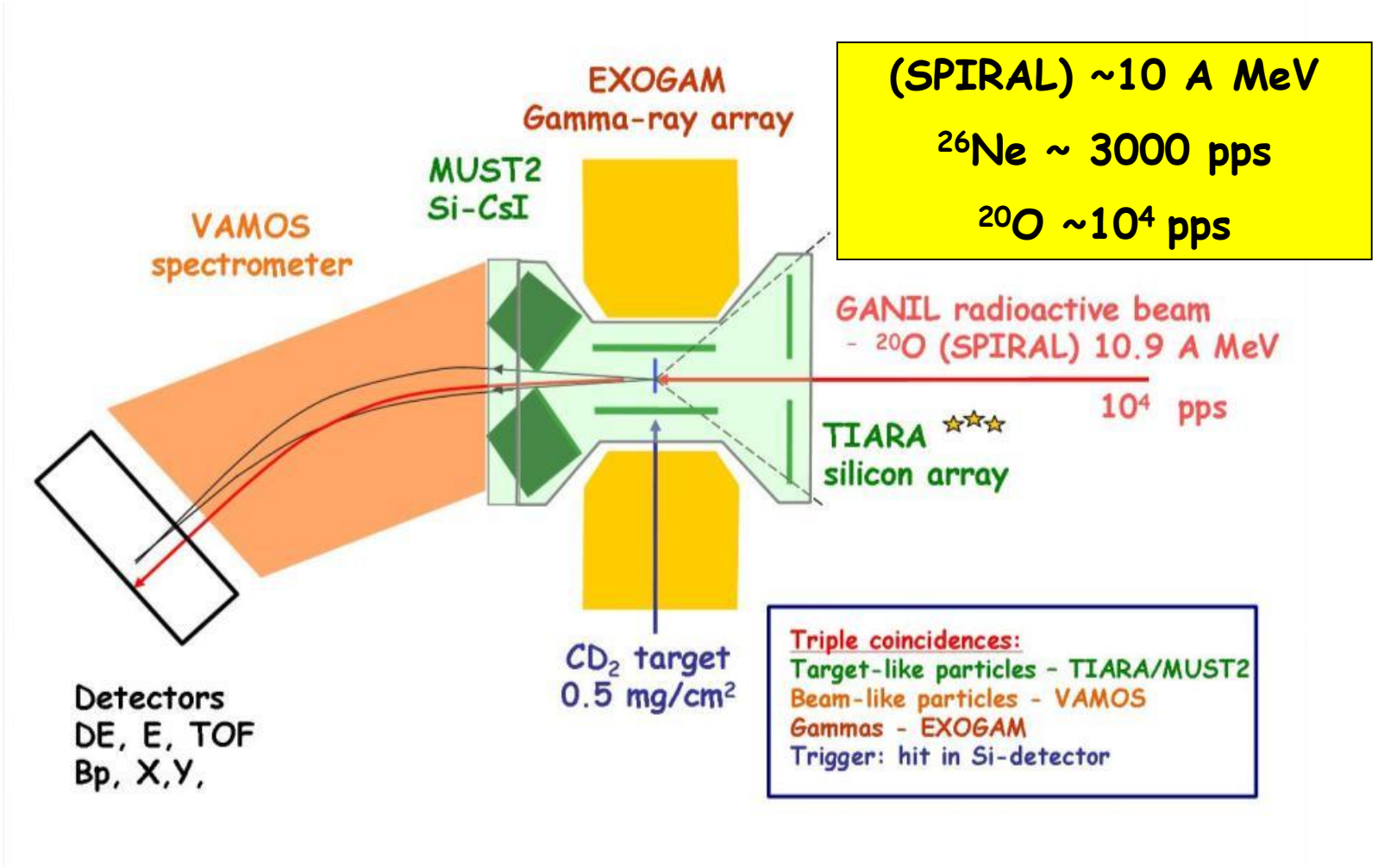
Excitation Energy Spectra from proton spectrum in VAMOS

Opportunities with SPIRAL 1 Beams

TIARA+MUST2+VAMOS+EXOGAM @ GANIL

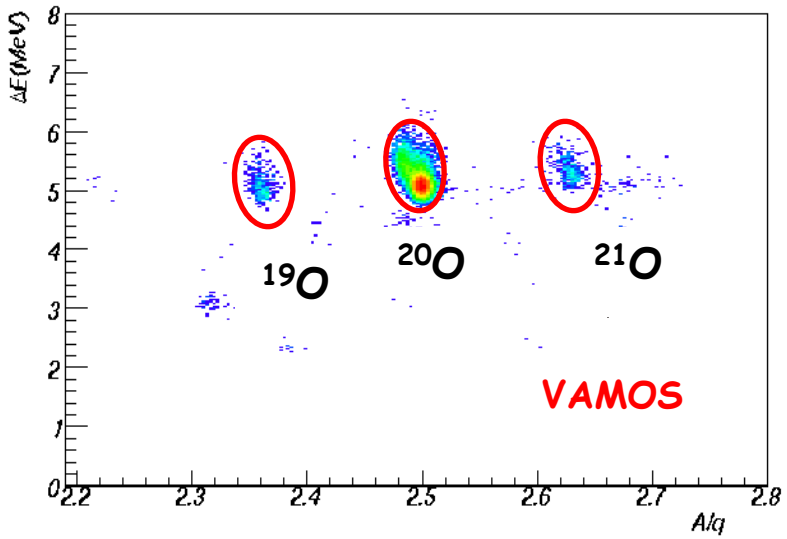
transfer reactions in inverse kinematics

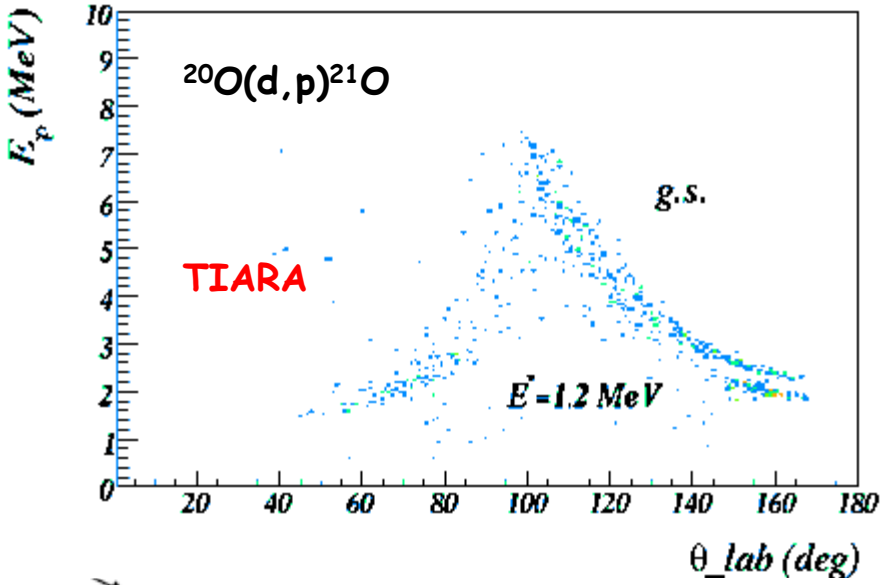
Inverse kinematics->(d,p),(d,t),(d,^{3}He),(d,d')

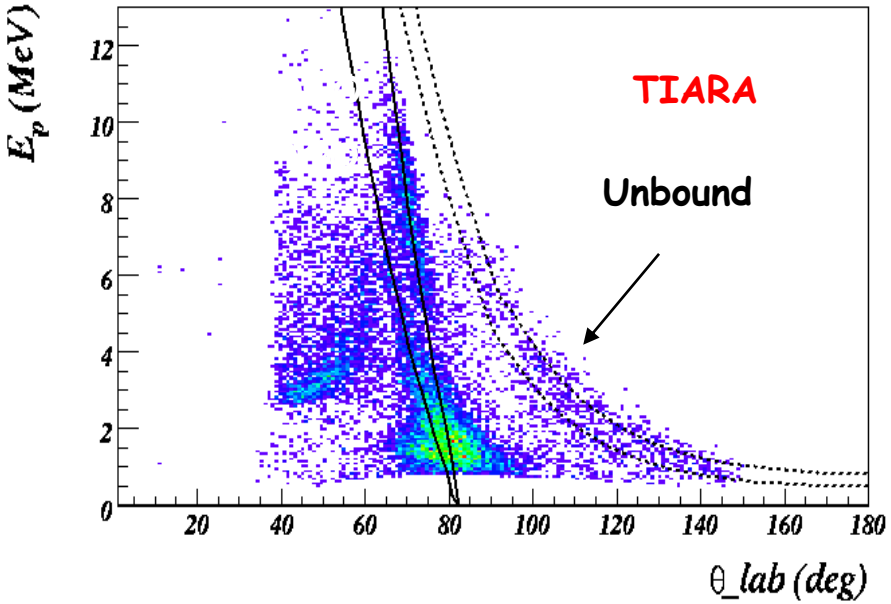


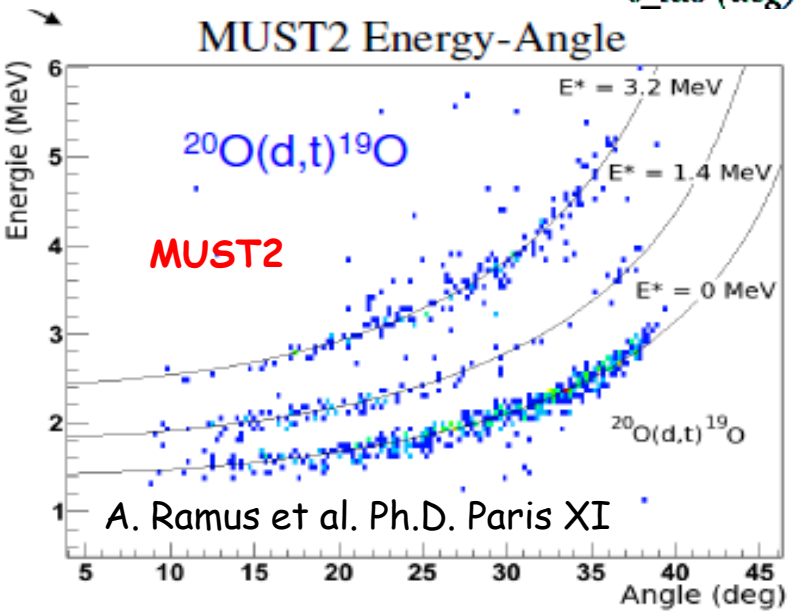
B. Fernandez-Dominguez et al, PRC 84, (2011), 011301

ANALYSIS : Example $d(^{20}O,p)^{21}O$

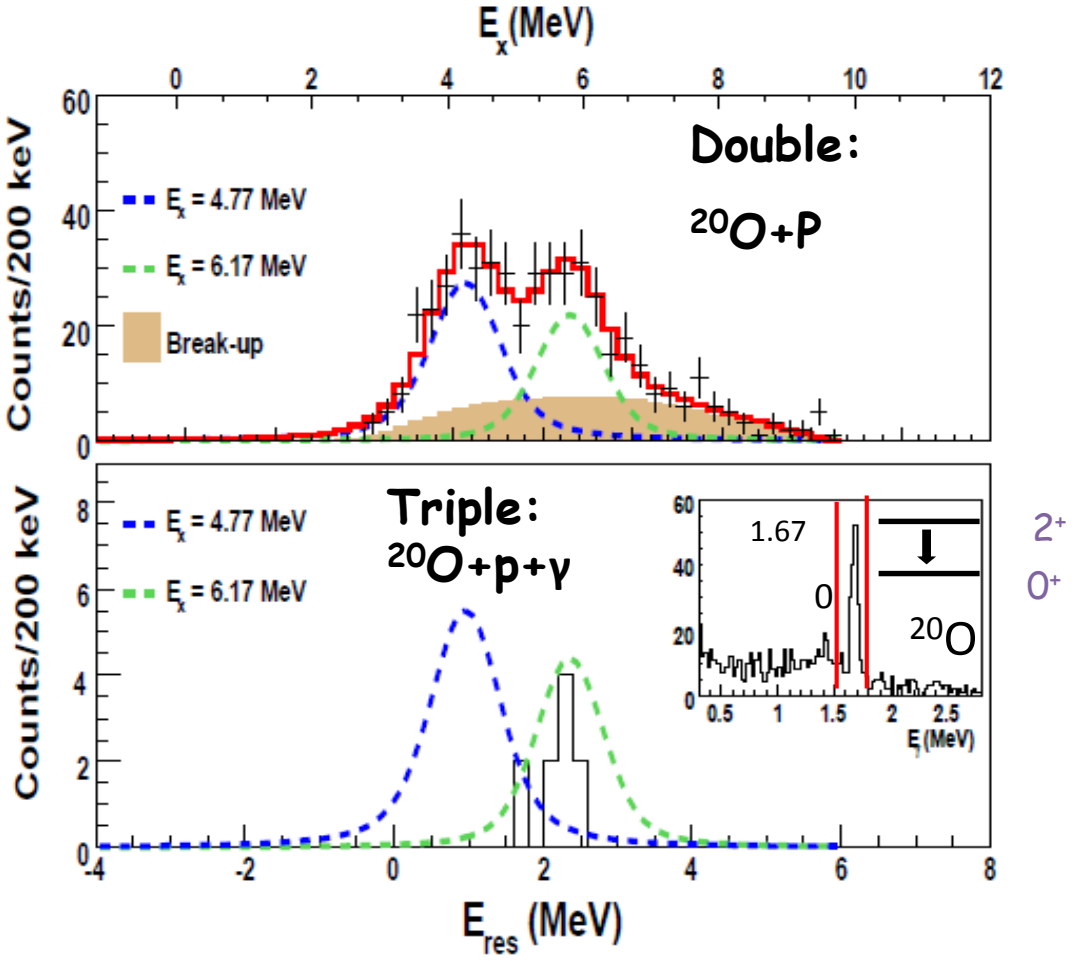


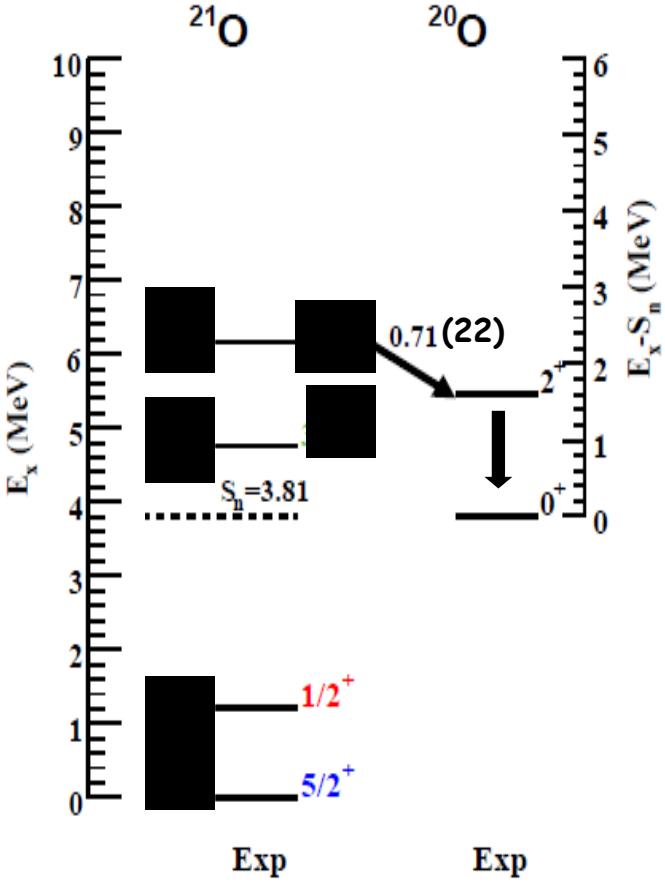






UNBOUND STATES: $d(^{20}O,p)^{21}O \rightarrow {}^{20}O + n$ (stripping)

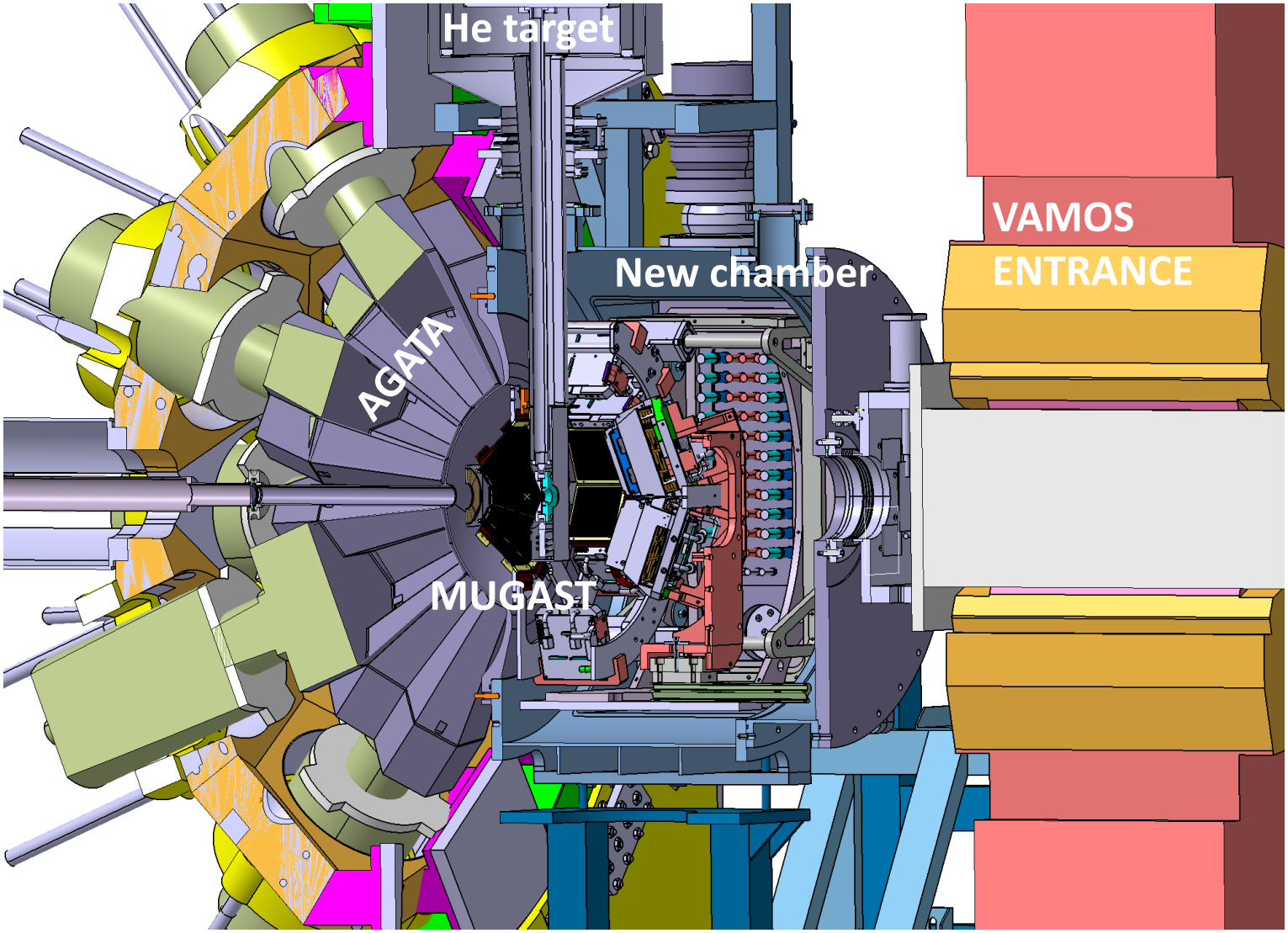




Triple coincidence: particle+γ+recoil

And more from Freddy Flavigny on Thursday
VAMOS + MUST with ^{14}O and ^{18}Ne

MUGAST-AGATA @VAMOS



Detectors, FEE and new chamber are available

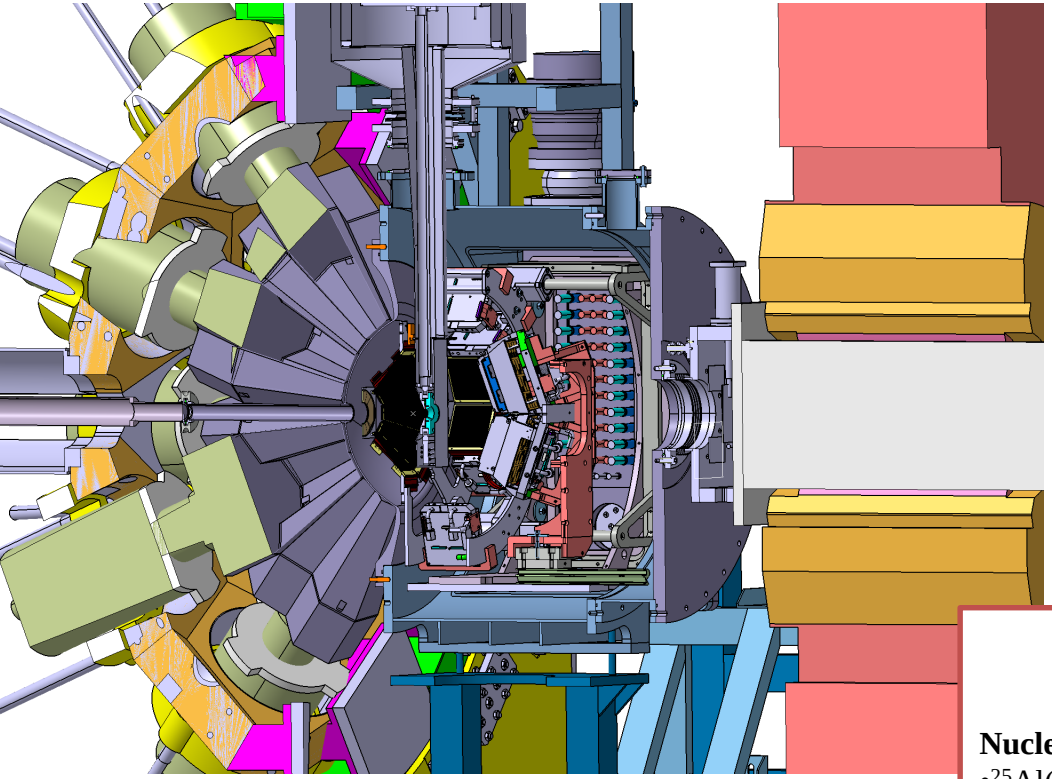
Courtesy D. Beaumel

MUGAST

MUst2 - **Ga**spard - **T**race

An intermediate step to high resolution Direct reaction studies with AGATA

AGATA MUGAST VAMOS



Transfer in inverse kinematics

Triple coincidences :

MUGAST (p,d,t,^{3}H) – AGATA (γ)– VAMOS

Improvements :

-> MUST2 + New det. Gaspard / Trace

-> Possibility of cryogenic target

-> SPIRAL 1 Upgrade beams

Some questions … as todays BTD/CATS do not fit in

1) Beam normalisation ?
   Focal Plane - Plastic / Diamant (I> 10^{5})?
2) Beam Spot / Doppler Correction in AGATA
   10^{5}pps Drift Chambers 2x (X,Y) ?

Letters of Intent

Nuclear astrophysics:

- ^{25}Al(3He,d) *(N.de Séréville, F. Hammache, IPNO)*
- ^{30}P(3He,d) or (d,p) *(N.de Séréville, F.Hammache, IPNO)*
- ^{79}Se(d,p)^{80}Se *(G. de Angelis, INFN-LNL)*

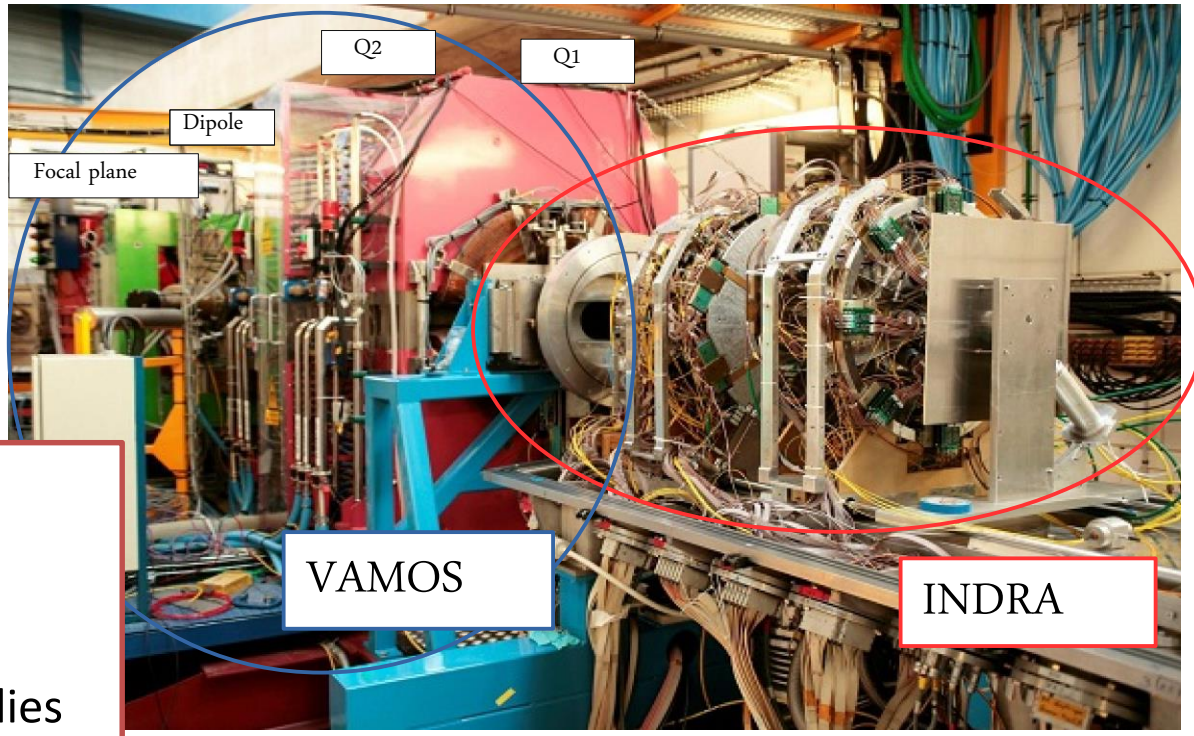
Shell evolution:

- ^{56}Ni(d,p)(d,t) *(F.Flavigny, IPNO, O.Sorlin, GANIL)*
- ^{28}Mg(d,p) *(A.Matta,LPC, W.Carford, University of Surrey)*
- ^{46,48}Ar(t,p) *(D.Mengoni, University of Padova)*
- ^{67}As(3He,d) *(D. Mengoni, A. Goasduff,University of Padov)*

Clusters, pairing, correlations & others

- ^{56}Ni(3He,p)(6Li,α) *(M.Assie, IPNO)*

Nuclear Dynamics



- Fission Dynamics :
  M. Caamano Tomorrow
- VAMOS + INDRA :
  P. Saint Onge Yesterday
- Deep Inelastic Collisions studies
  - Pathway to N=126
  - Zero degree I. Stefan yesterday

PRL 115, 172503 (2015) PHYSICAL REVIEW LETTERS week ending 23 OCTOBER 2015

Pathway for the Production of Neutron-Rich Isotopes around the $N = 126$ Shell Closure

Y. X. Watanabe,[1,*] Y. H. Kim,[2,3,†] S. C. Jeong,[1,‡] Y. Hirayama,[1] N. Imai,[1,§] H. Ishiyama,[1,‡] H. S. Jung,[1] H. Miyatake,[1] S. Choi,[2,3] J. S. Song,[2,3,4] E. Clement,[5] G. de France,[5] A. Navin,[5,‖] M. Rejmund,[5] C. Schmitt,[5] G. Pollarolo,[6] L. Corradi,[7] E. Fioretto,[7] D. Montanari,[8] M. Niikura,[9,¶] D. Suzuki,[9,**] H. Nishibata,[10] and J. Takatsu[10]

Fission Dynamics

Uniqueness of GANIL

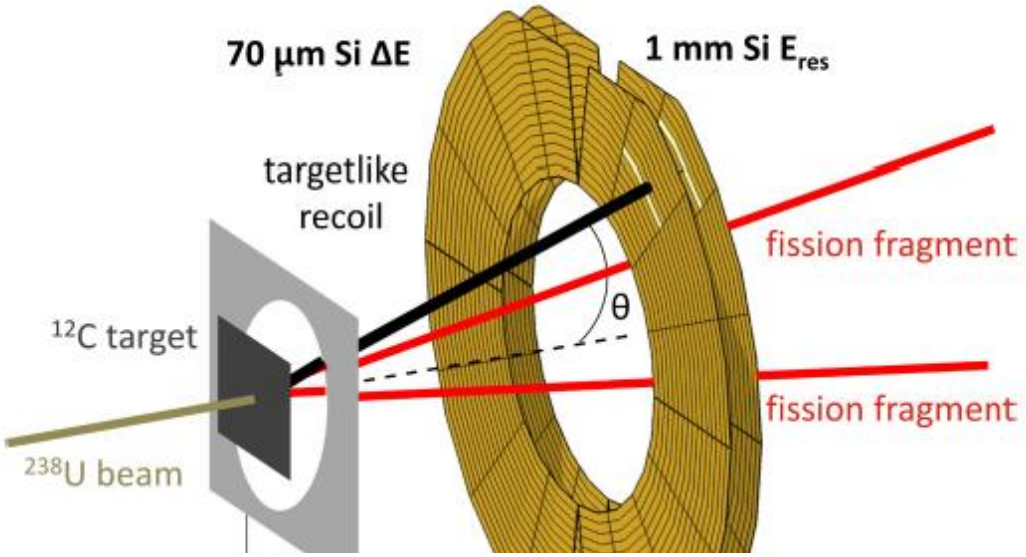
^{238}U beams

VAMOS = > Isotopic identification event by event

Fission Yields

Isotopic distributions

^{238}U (6.1 MeV/u) + 12C



SPIDER:

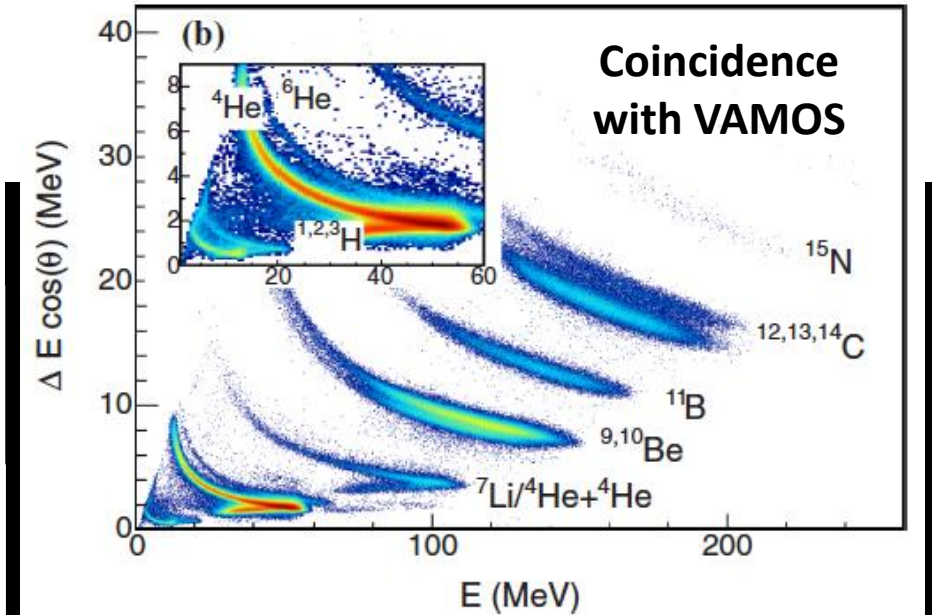
- target-like nuclei (30°-47°)
- identification of fissionning system
- control of the the excitation energy

VAMOS:

- fission fragments

EXOGAM:

- gamma rays



PHYSICAL REVIEW C **92**, 034606 (2015)

Characterization of the scission point from fission-fragment velocities

M. Caamaño,[1,2,*] F. Farget,[1,2,†] O. Delaune,[1,‡] K.-H. Schmidt,[1] C. Schmitt,[1] L. Audouin,[3] C.-O. Bacri,[3] J. Benlliure,[2] E. Casarejos,[4] X. Derkx,[1,§] B. Fernández-Domínguez,[5] L. Gaudefroy,[6] C. Golabek,[1,‖] B. Jurado,[7] A. Lemasson,[1] D. Ramos,[2] C. Rodríguez-Tajes,[2,1] T. Roger,[†] and A. Shrivastava[1,8]

PHYSICAL REVIEW C **89**, 024614 (2014)

Transfer reactions in inverse kinematics: An experimental approach for fission investigations

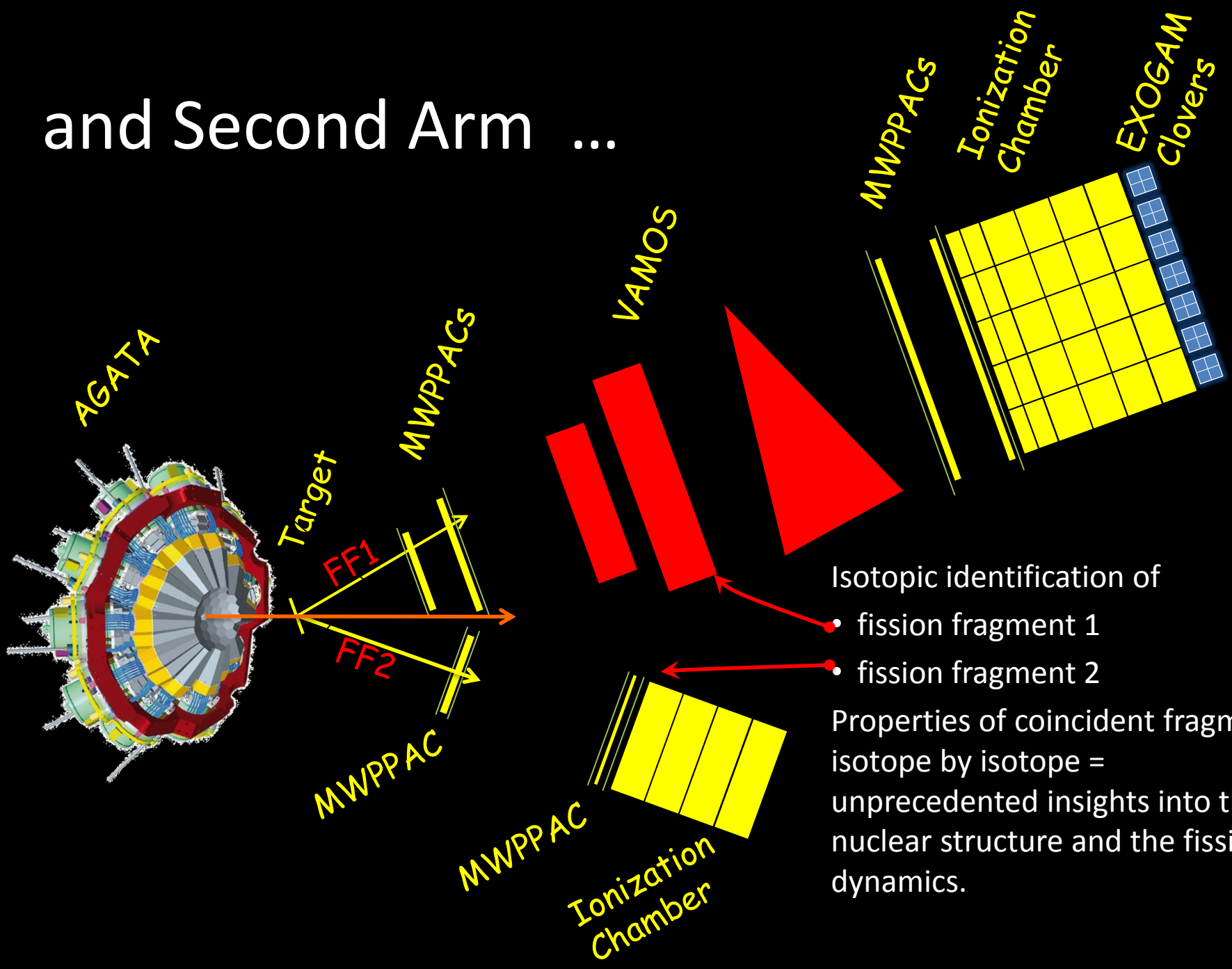
C. Rodríguez-Tajes,[1,2,*] F. Farget,[1,†] X. Derkx,[1,3,‡] M. Caamaño,[2] O. Delaune,[1,§] K.-H. Schmidt,[1] E. Clément,[1] A. Dijon,[1,§] A. Heinz,[4] T. Roger,[1] L. Audouin,[5] J. Benlliure,[2] E. Casarejos,[6] D. Cortina,[2] D. Doré,[7] B. Fernández-Domínguez,[2] B. Jacquot,[1] B. Jurado,[8] A. Navin,[1] C. Paradela,[2] D. Ramos,[2] P. Romain,[9] M. D. Salsac,[7] and C. Schmitt[1]

PHYSICAL REVIEW C **88**, 024605 (2013)

Isotopic yield distributions of transfer- and fusion-induced fission from ^{238}U + ^{12}C reactions in inverse kinematics

M. Caamaño,[1,2,*] O. Delaune,[1,†] F. Farget,[1,‡] X. Derkx,[1,§] K.-H. Schmidt,[1] L. Audouin,[3] C.-O. Bacri,[3] G. Barreau,[4]

and Second Arm …

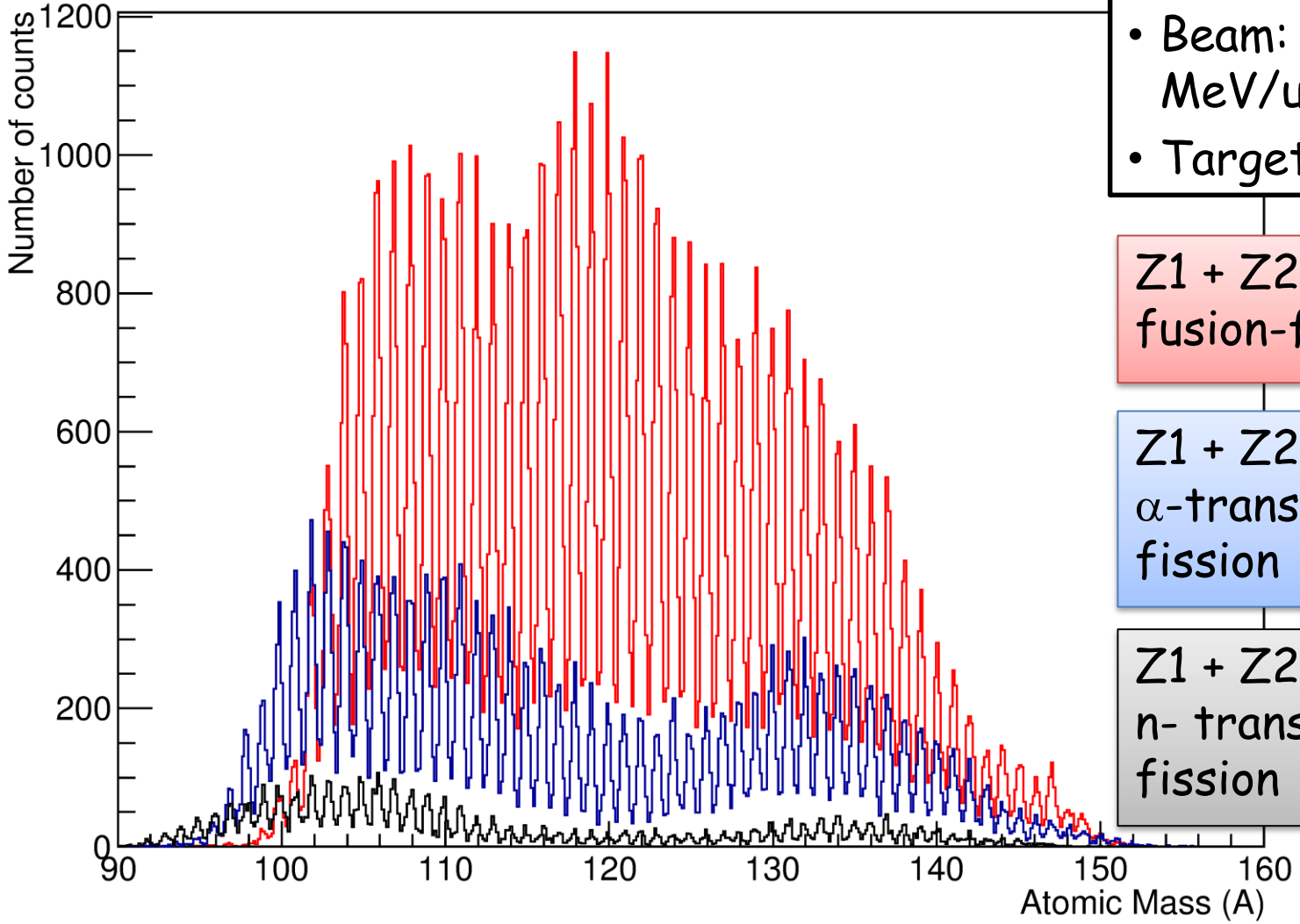


Isotopic identification of

- fission fragment 1
- fission fragment 2

Properties of coincident fragments isotope by isotope = unprecedented insights into the nuclear structure and the fission dynamics.

Processes



System studied

- Beam: ^{238}U at 6.2 MeV/u
- Target: ^{9}Be

Z1 + Z2 = 96 (Cm): fusion-fission

Z1 + Z2 = 94 (Pu): α-transfer induced fission

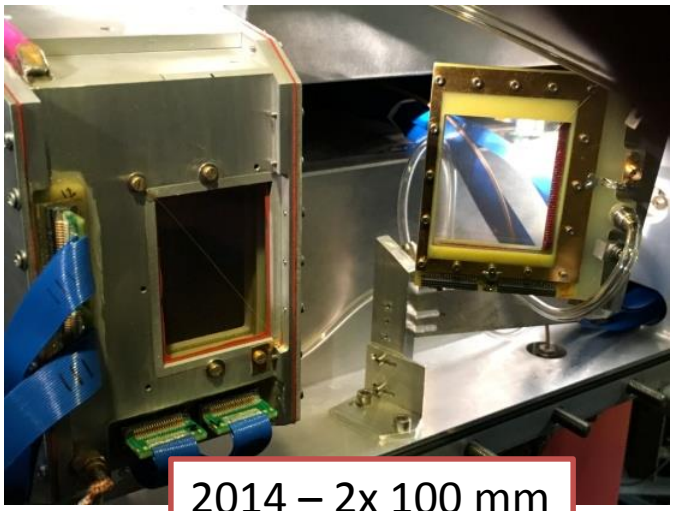
Z1 + Z2 = 92 (U): n- transfer induced fission

Open opportunities
in a deeper understanding of the fission process

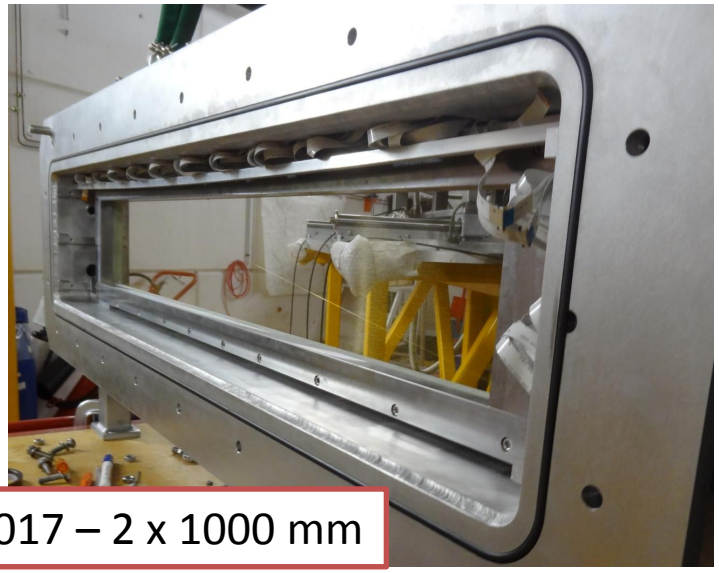
Opportunities with VAMOS

- detection from protons to the heaviest nuclei
- already covering a large physics program

Your new dreams or crazy ideas will extend it further !



2014 – 2x 100 mm

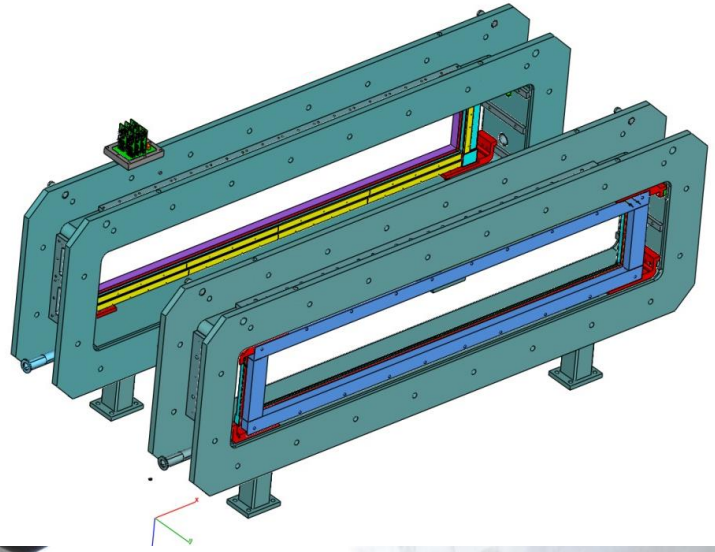


2017 – 2 x 1000 mm

VAMOS

VARIABLE MODE SPECTROMETER

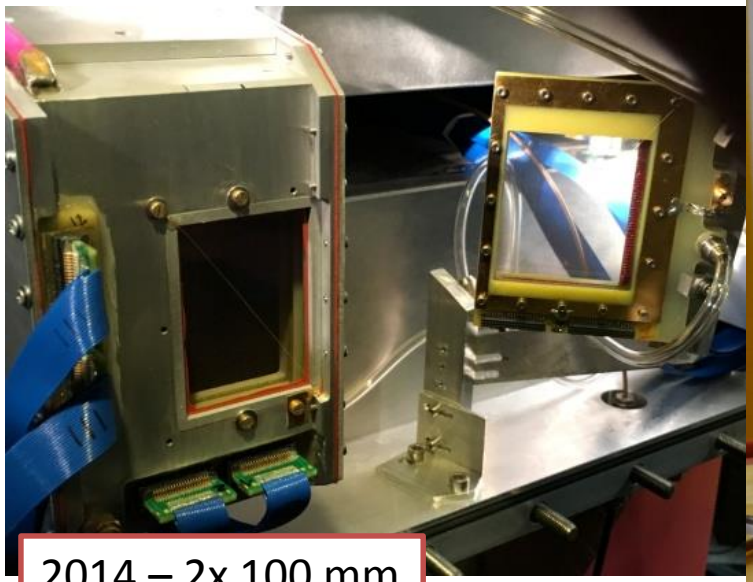
Grand DPS-MWPC



1 détecteur

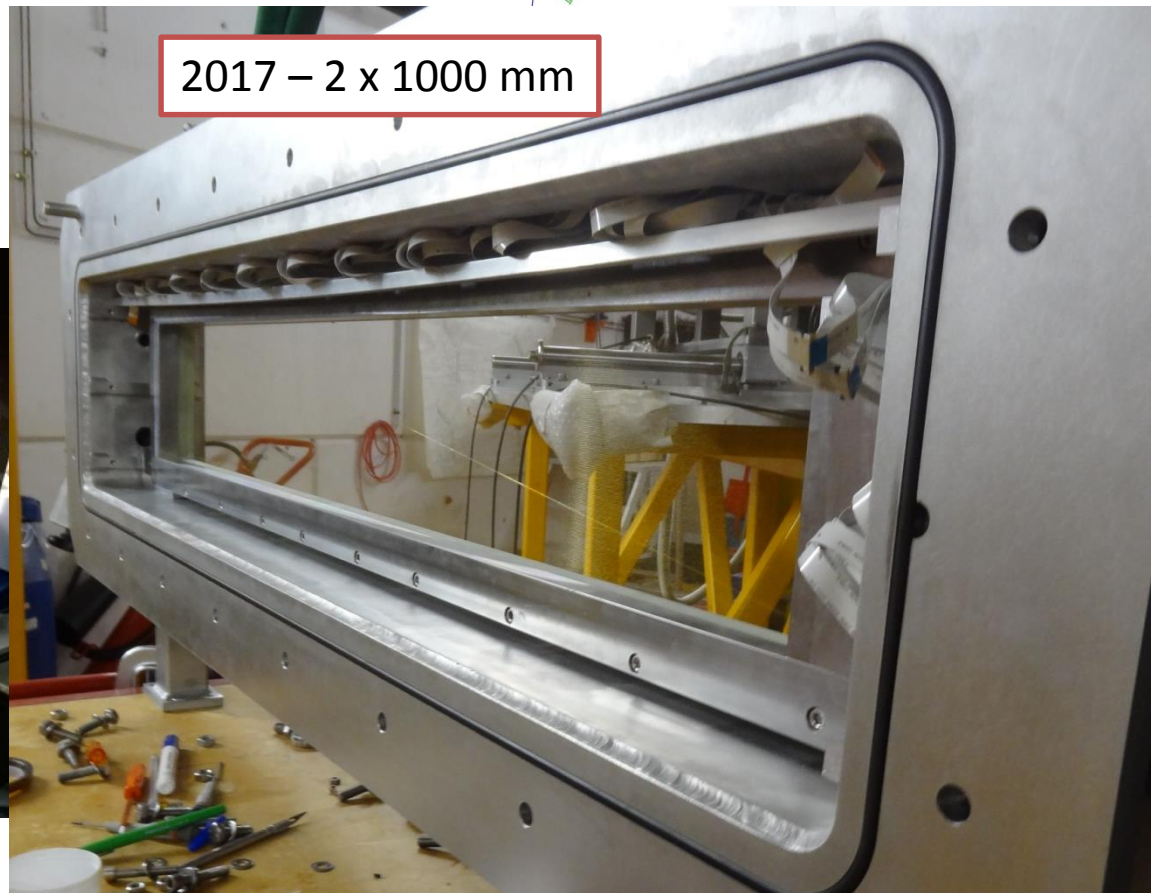
- 1000 fils X et 150 fils Y
- 2000 fils de temps
  - 3150 fils de 20 µm tissés
- 1150 signaux a traiter
- Mesure les positions et le temps des noyaux au plan focal

2011 – 1 x 50 mm



2014 – 2x 100 mm

2017 – 2 x 1000 mm

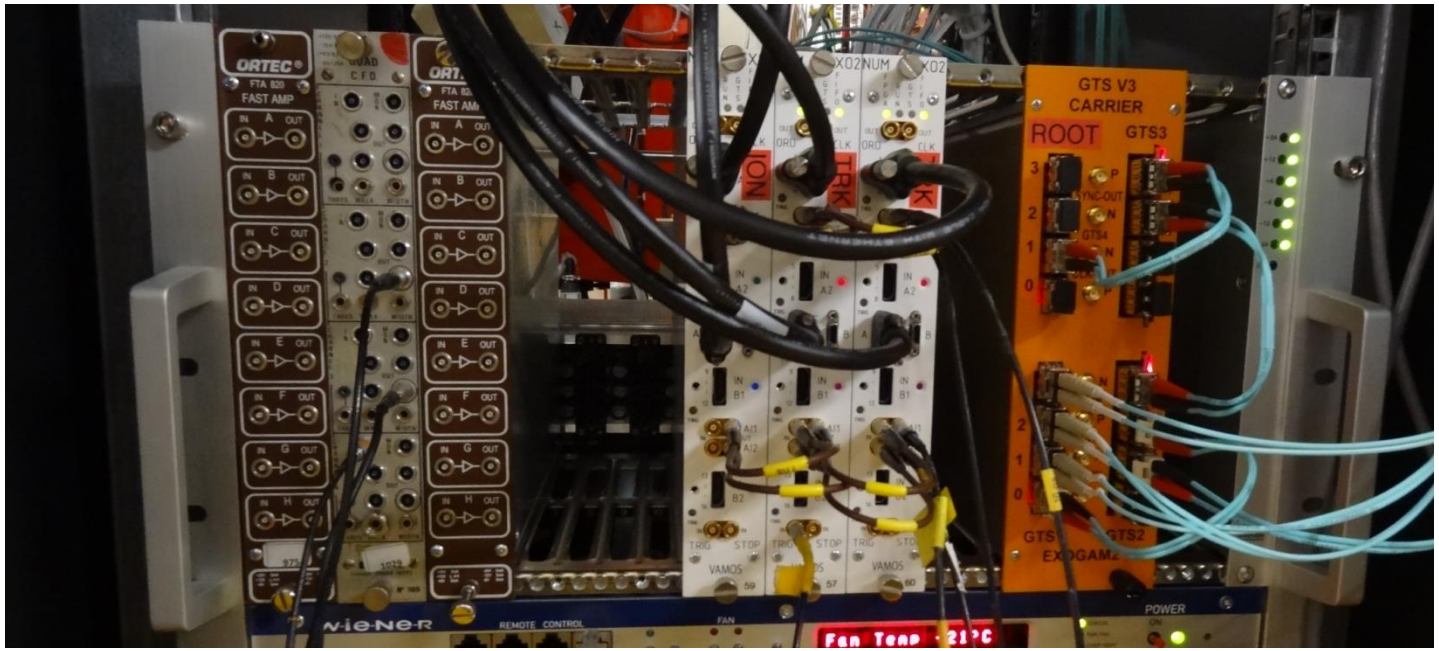


NUMEXO 2 @ VAMOS

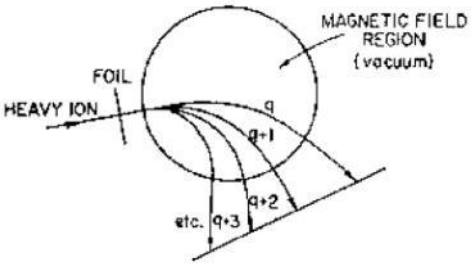
- Electronique Numérique – Numériseurs NUMEXO2
- S'appuie sur les développements importants fait pour EXOGAM2 au GANIL
- Modifications pour VAMOS pour la mesure :

  $\Rightarrow$ de l'énergie de Chambre à Ionisation

  $\Rightarrow$ des positions avec les nouvelles chambres à fil

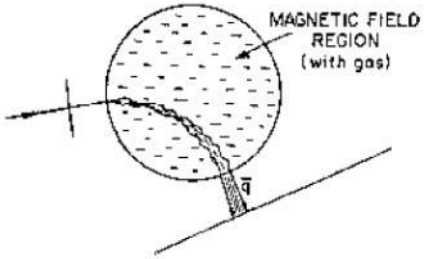


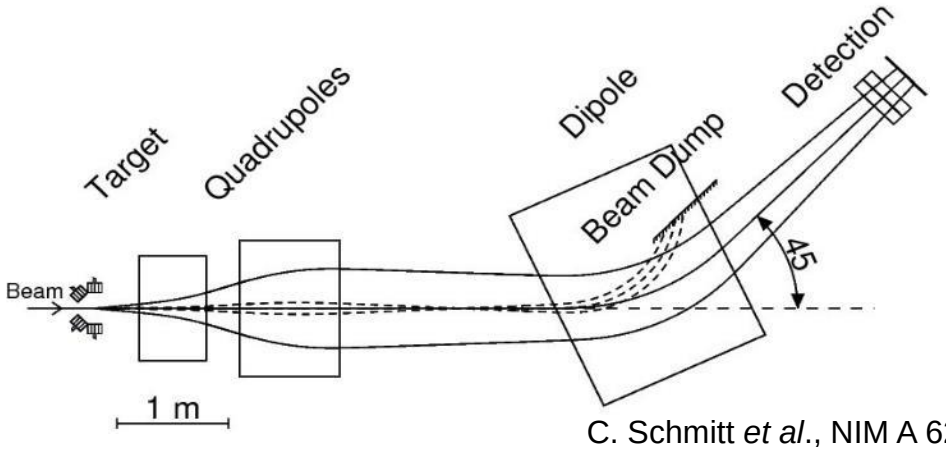
VAMOS-GFS test 2009



Proof of principle established in 2009: test experiment

^{40}Ca (196MeV) + $^{150}Sm \rightarrow {}^{190}Pb^*$ ($\sigma_{ER} \sim 50$mb)



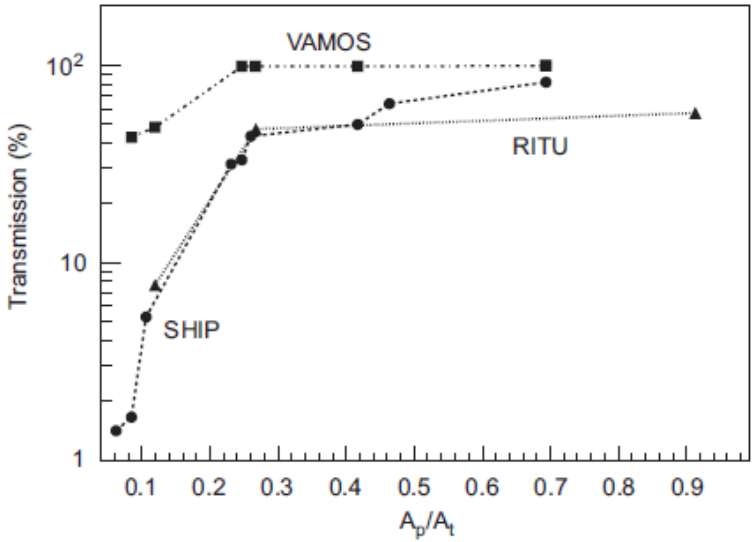


C. Schmitt *et al.*, NIM A 621 (2010) 558

Transmission :

- 95 % for *x*n channels
- 80% for α, p channels

Rejection > 10^{10}

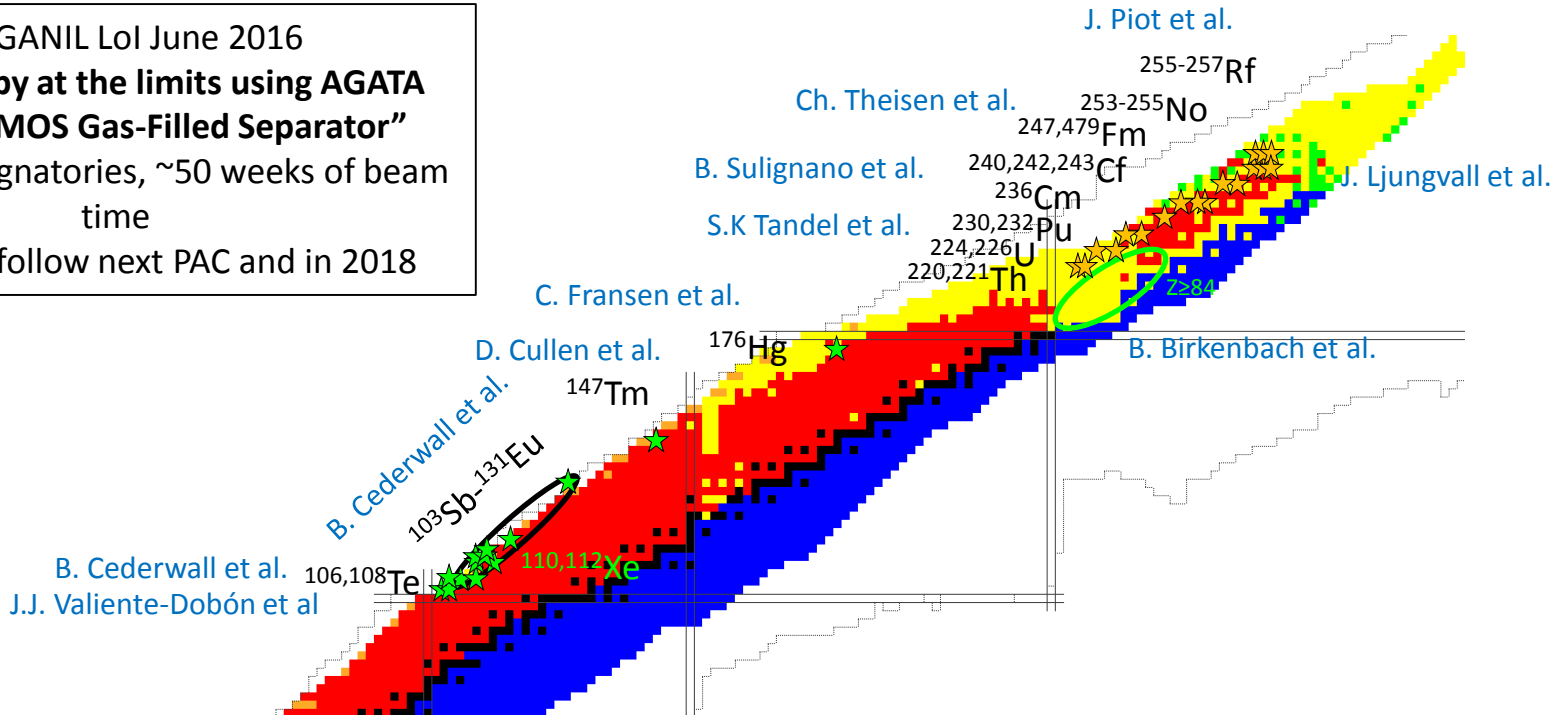


- Up to Bρ = 2.1 - 2 .2 Tm if VAMOS pushed back

What for ?

- Prompt g-ray spectroscopy
- Fusion evaporation reactions
- Low cross-sections → separator + tagging techniques
- Regions of interest : VHE/SHE, ^{100}Sn region, proton drip-line, neutron-deficient Pb
- Note: no other place foreseen for the coupling of AGATA with a zero degree separator

PAC GANIL LoI June 2016
"Spectroscopy at the limits using AGATA and the VAMOS Gas-Filled Separator"
31 labs, 180 signatories, ~50 weeks of beam time
Proposal to follow next PAC and in 2018



Physics with MUGAST

2 dedicated workshops organized at Orsay and Padova

- **Shell evolution & deformation**
  - Mapping of neutron orbitals around N=28 — *F.Flavigny, O.Sorlin et al.*
  - Oblate driving force in n-deficient nuclei above ^{56}Ni — *A.Goasduff, D.Mengoni, et al*.
  - Shape transition along and across N=28 — *L.Fortunato, D.Mengoni et al.*
  - Interplay of single-part and collective structures in ^{46}Ca — *S.Leoni et al.*
  - Shell evolution toward the island of inversion — *A.Matta, W.Catford, N.Orr, et al.*
  - Shape coexistence in Kr isotopes — *A.Matta, W.Catford, et al.*
  - Island of Inversion and shape coexistence in ^{30,31}Mg — *B.Fernandez-Dominguez et al.*

- **Neutron-proton pairing**
  - np-pairing in fp-shell — *M. Assie et al.*

- **Astrophysics**
  - Breakout from hot CNO to rp process — *C.Diget et al.*
  - Explosive H-burning in Novae — *N.de Sereville, F.Hammache et al.*
  - Surrogate method for s-process reactions — *G.de Angelis et al.*
  - ^{60}Fe — *A.Matta, W.Catford, et al.*

- **Reaction dynamics**
  - Space-time characterization of emitting sources in HI collisions — *G. Verde, A.Chbihi, Q.Fable et al*

Courtesy D. Beaumel

Mainly *stripping* reactions

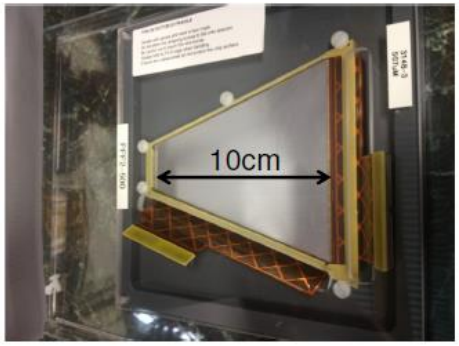
MUGAST

MUst2 - **Ga**spard - **T**race

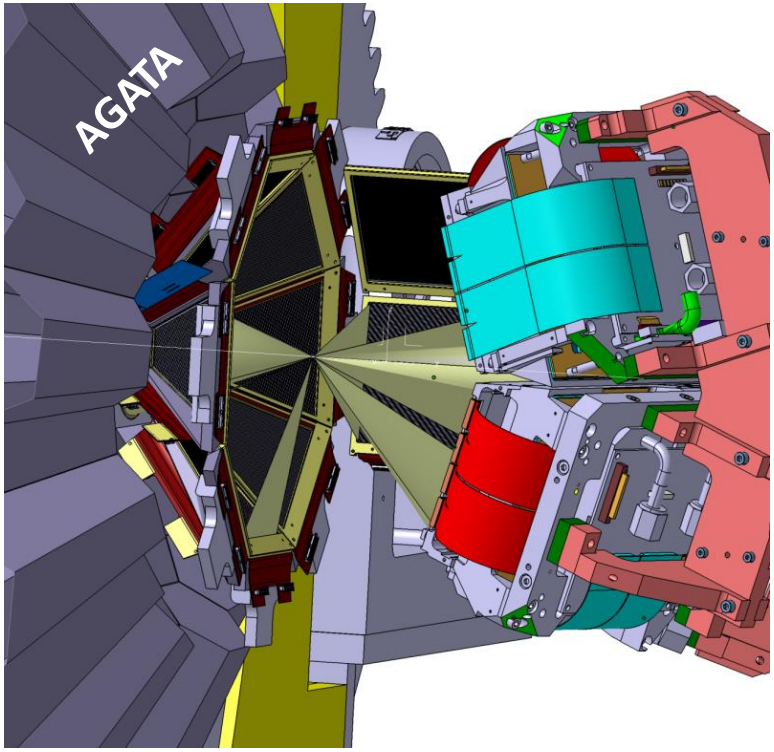
An intermediate step to high resolution Direct reaction studies with AGATA

- ***New detectors developed for GASPARD/TRACE***
- ***few MUST2 detectors at forward angle***
- ***MUST2 electronics***

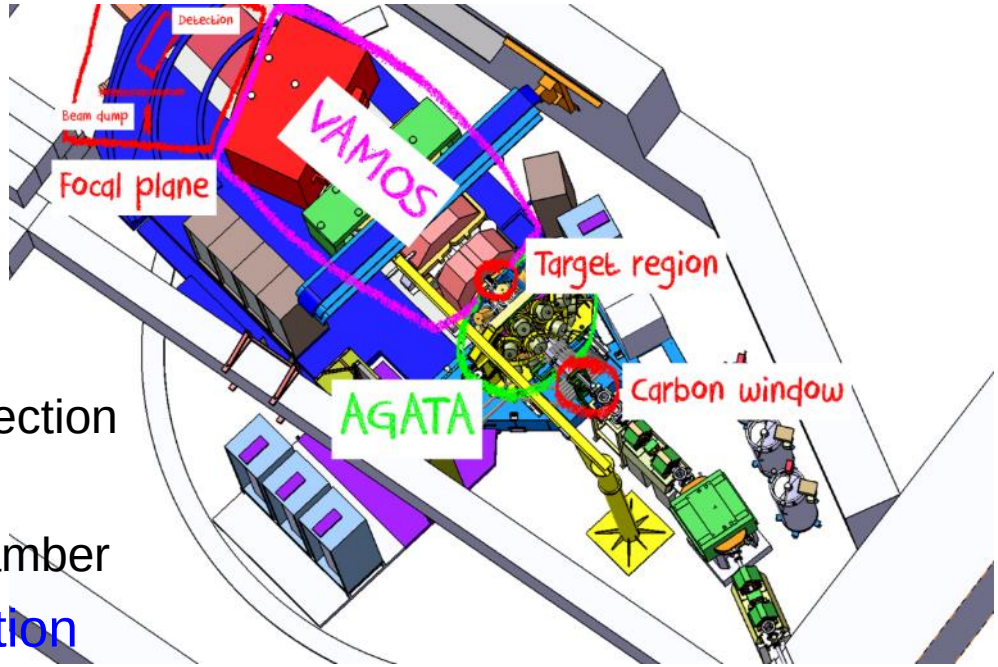
New detectors



- New geometries
- New packaging: thin frame Kapton at 90°
- NTD, random cut, reverse mounting
- Thin and thick



The VAMOS-GFS upgrade



1. Focal plane
   - Beam dump
   - MUSETT & ToF detection
   - Detection shielding
   - → New focal plane chamber
2. Low pressure regulation
3. Transition He - vacuum
   - C Window
4. Adaptation of AGATA target chamber