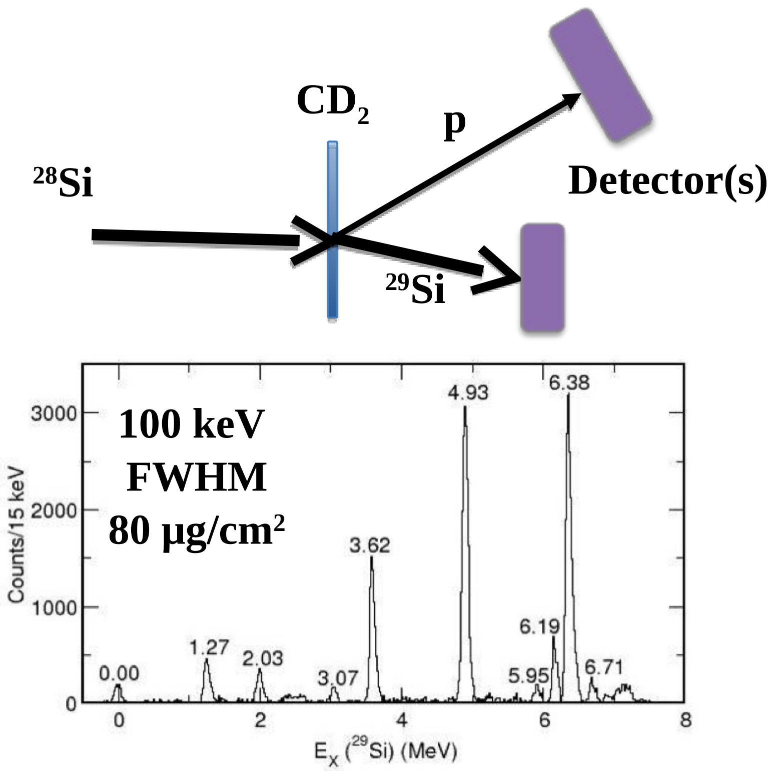
Active Targets and Time Projection Chambers for Nuclear Physics

Nuclear structure through transfer reactions

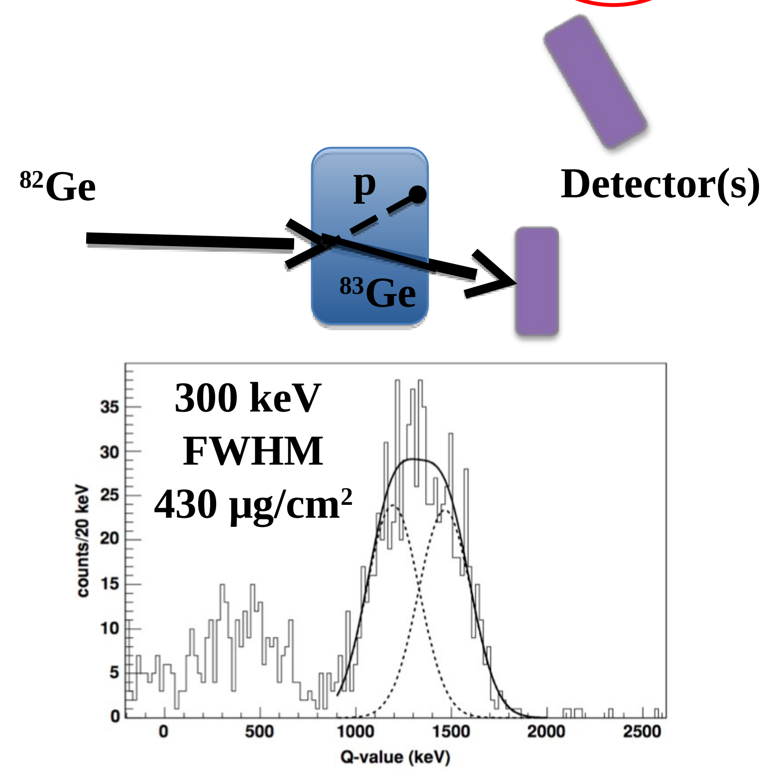
The quest of exoticity :

- Study of nuclei with short half-life → inverse kinematics
- Beam intensity decreases when exoticity increases

$$N_{reaction} = \sigma \times \Delta\Omega \times N_{beam} \times N_{target}$$



*J.C.Lighthall et al., NIM A **622** 97 (2010)*



*J.S. Thomas et al., PRC **71,** 012302 (2005)*

Need thick targets *and* excellent resolution

→ Need to be able to detect the reaction point (Vertexing)

Active targets: principle

Active target: (Gaseous) detector in which the atoms of the gas are used as a target

✓ Gas-filled active target and time projection chamber

- Gas = detector AND target
- Vertexing = resolution similar to thin solid target
- High effective thickness = up to 10^3 higher

➔ 1st difficulty: the choice of the gas is driven by the physics, not by its properties!

✓ Major advantages over conventional approaches

- Detection efficiency close to 4π
- Detection of low energy recoils (that stop inside the target)
- Event-by-event 3D reconstruction
- Compact, portable and versatile detector

➔ 2nd difficulty: Geometric efficiency has to be maximized though the target thickness is huge (tenth of cm)

✓ Physics programs

- Resonant scattering
- Inelastic scattering and giant resonances
- Transfer reactions
- Rare and exotic decays (2p, β2p, …)
- Transfer-induced fission, …

➔ 3rd difficulty: LARGE variety of experiments, involving “high energy” light particles and “low energy” heavy ions: LARGE detection dynamics required!

Time Projection Chambers

Active target: (Gaseous) detector in which the atoms of the gas are used as a target

✓ Drift region

- Homogeneous vertical drift electric field

✓ Amplification region

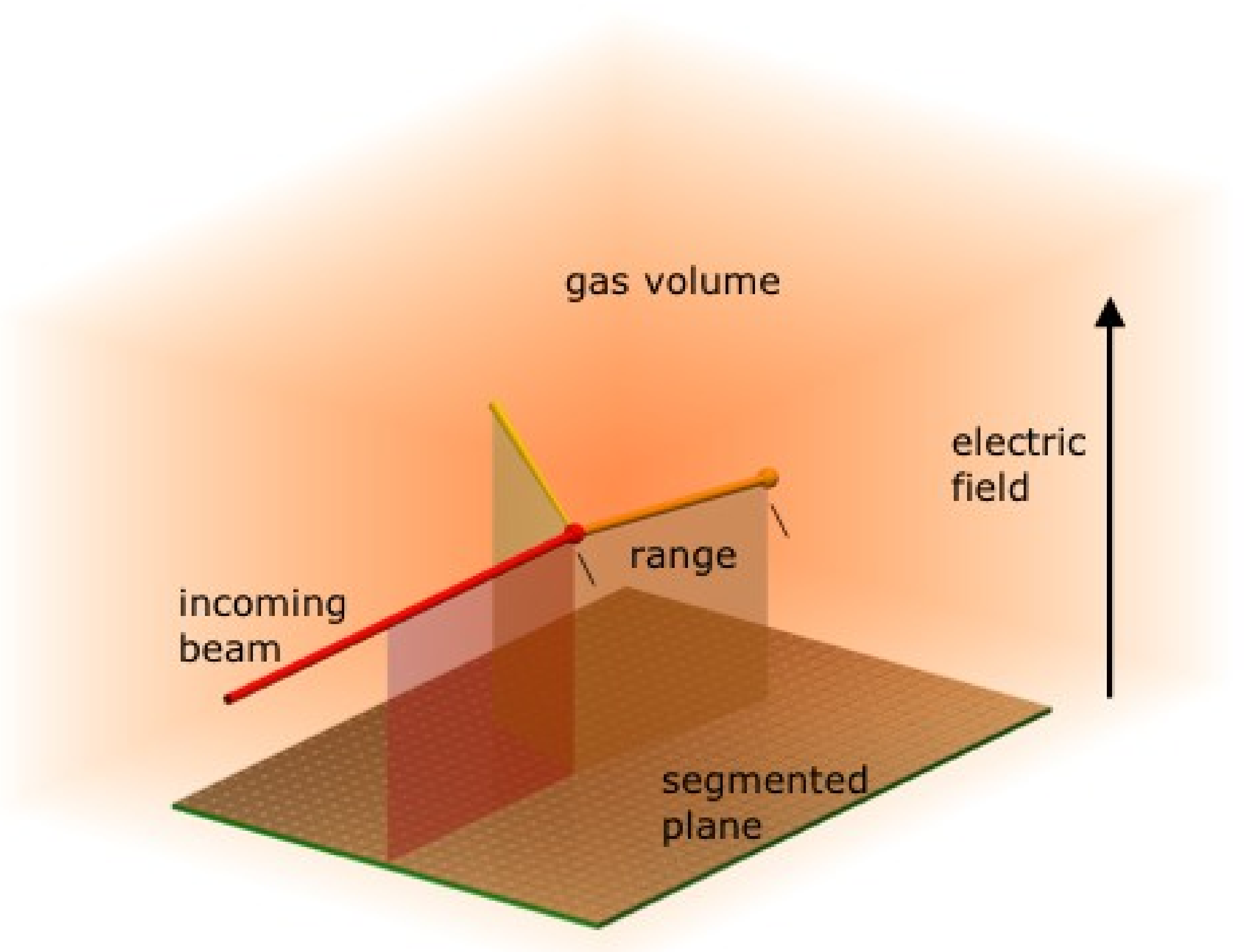
- Primary ionization signal too small

✓ Segmented pad plane

- Record tracks projections

✓ Electronics

- Need to record electron drift time for 3rd dimension



Time Projection Chambers

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- **Homogeneous vertical drift electric field**

✓ Amplification region

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- Record tracks projections

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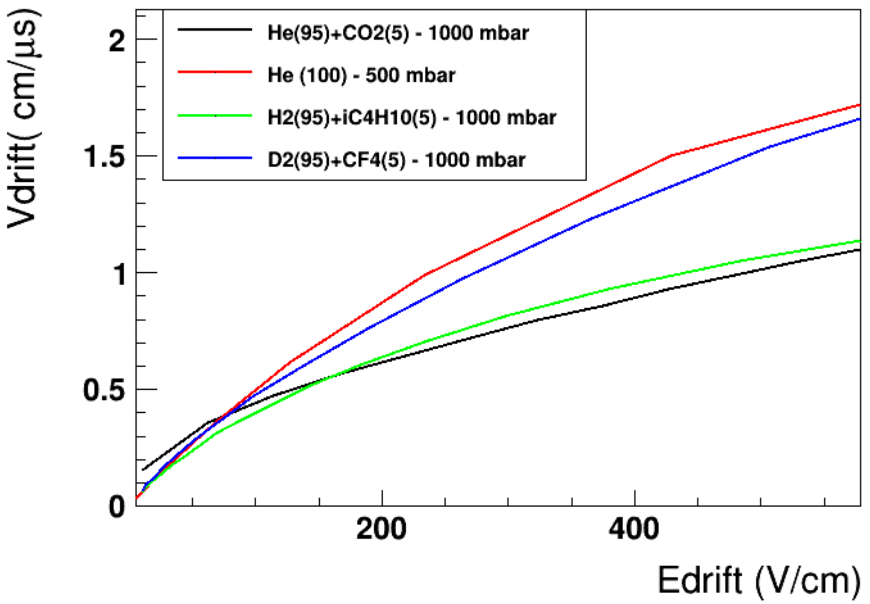
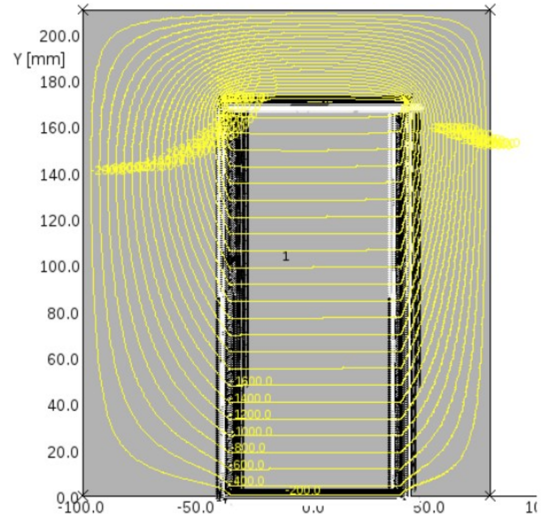
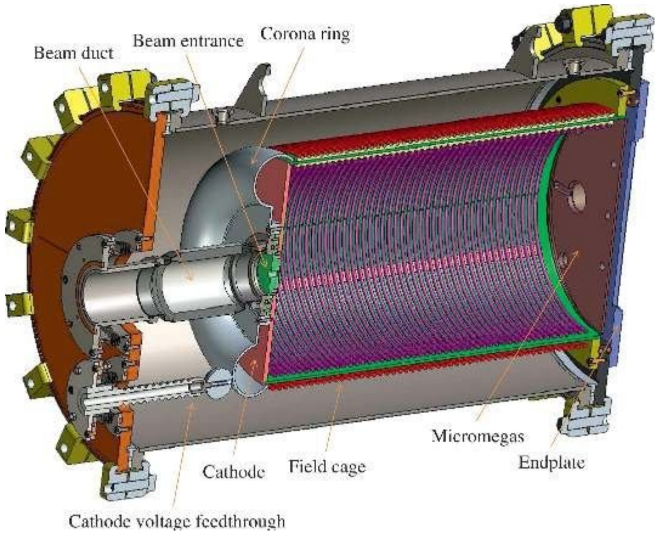
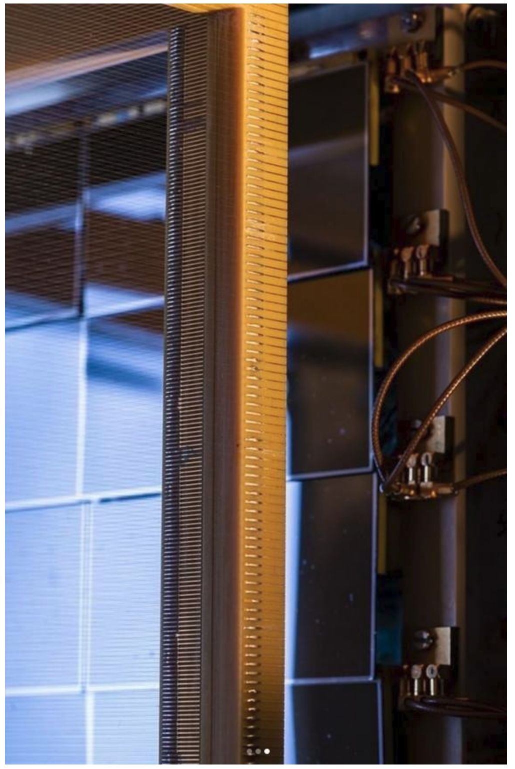




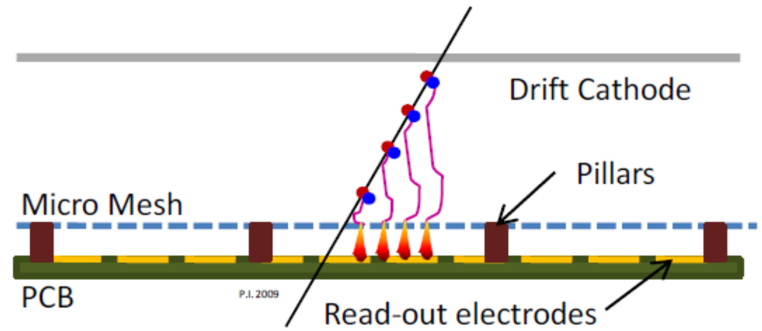




Time Projection Chambers

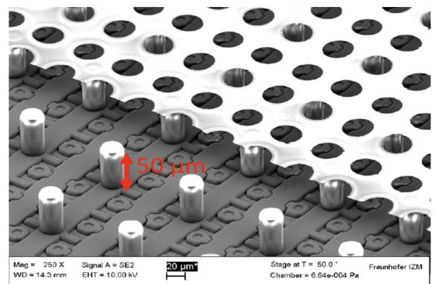
Active target: (Gaseous) detector in which the atoms of the gas are used as a target

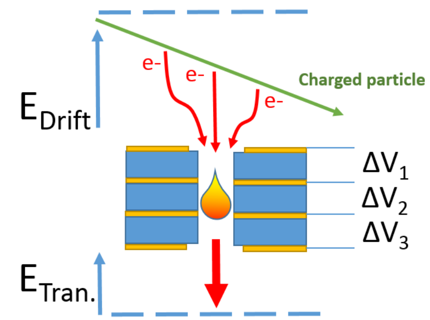
Micromegas



- ✓ Drift region
  - Homogeneous vertical drift electric field
- ✓ **Amplification region**
  - **Primary ionization signal too small**

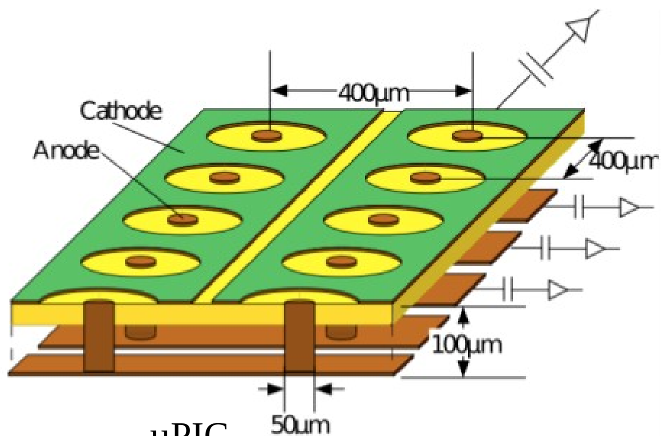
GridPix





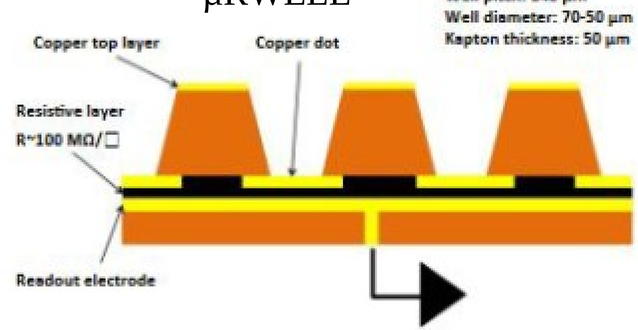
ML-ThGEM

- ✓ Segmented pad plane
  - Record tracks projections
- ✓ Electronics
  - Need to record electron drift time for 3rd dimension



μPIC

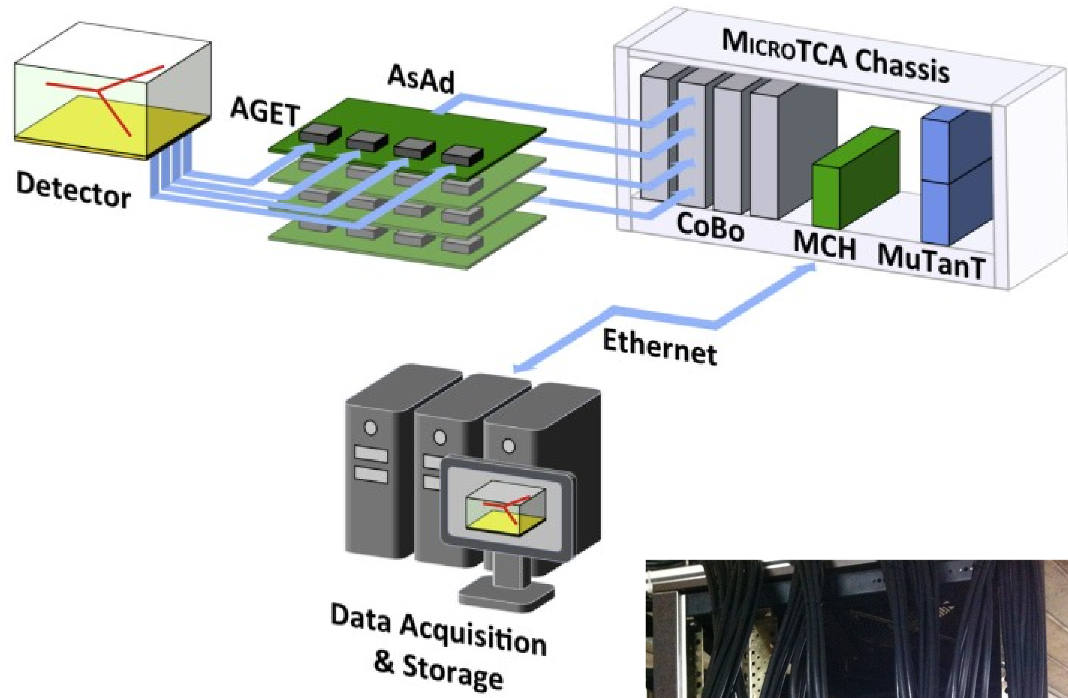
μRWELL

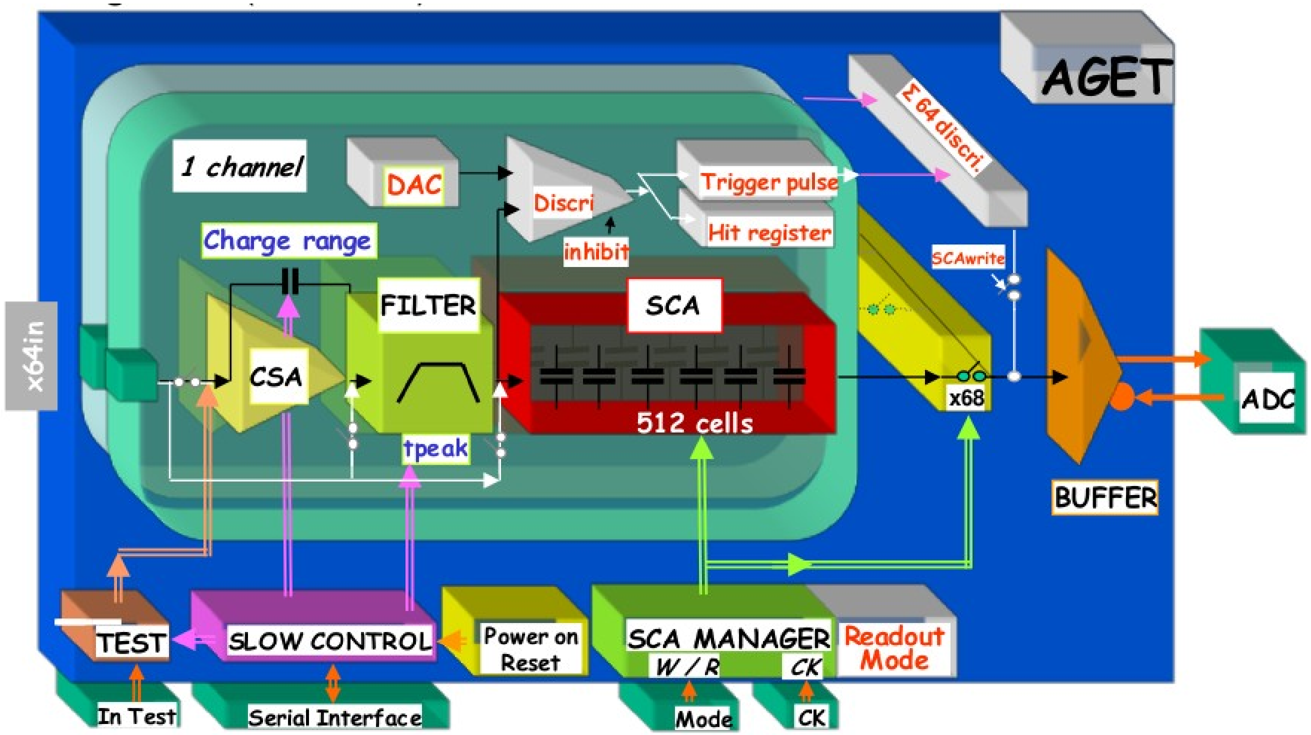


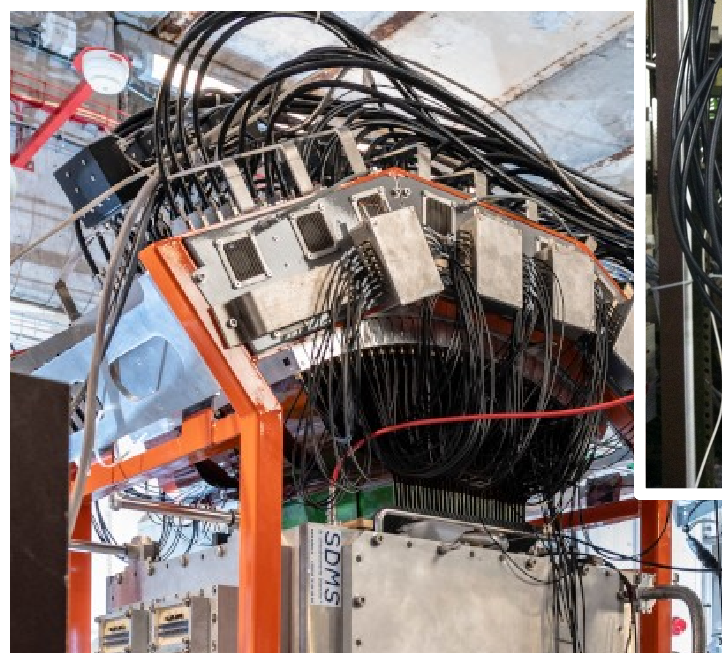
GET electronics

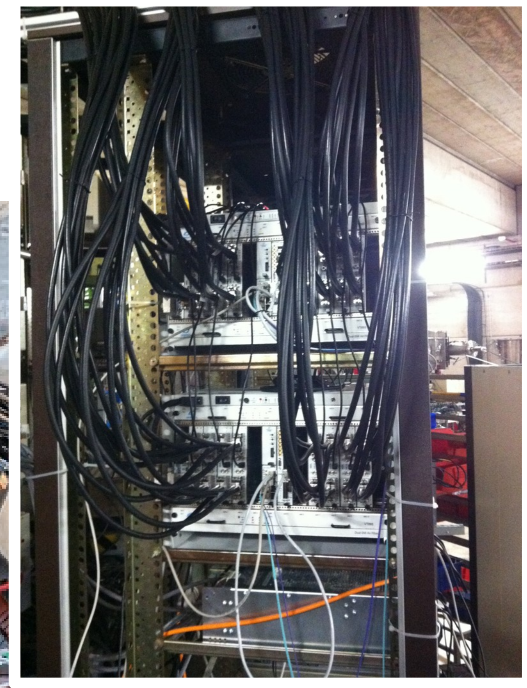
E.C. Pollacco et al., NIM A887, 81 (2018)

- ✓ Compact electronics
- ✓ Adjustable gain preamps (120 fC → 10 pC)
- ✓ Selectable peaking time
- ✓ Individual thresholds
- ✓ Adjustable sampling frequency (1 MHz → 100 MHz)
- ✓ Up to 512 cells signal digitization
- ✓ 12 bits ADCs, 64 channels
- ✓ Multi-level trigger (external, multiplicity, L2)
- ✓ Backend with uTCA standard, 10 Gb/s data transfer rate







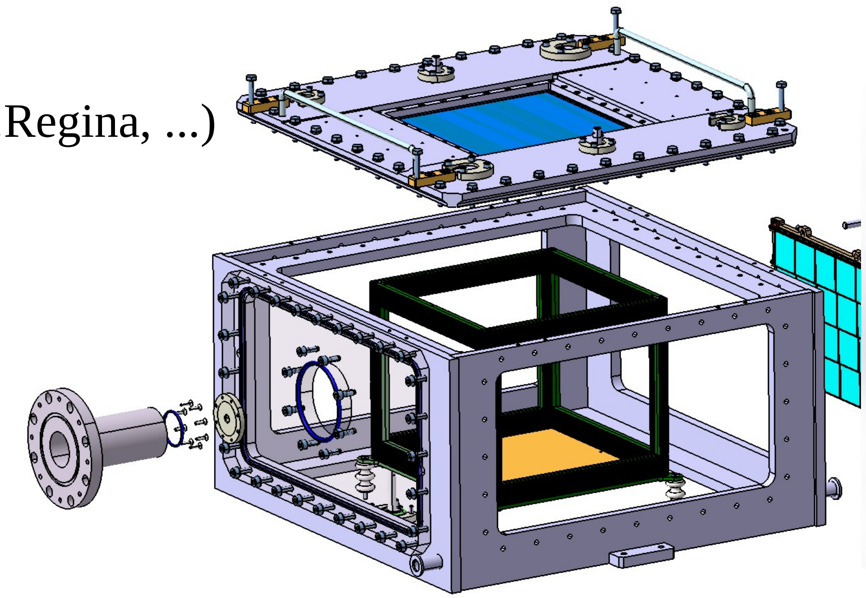


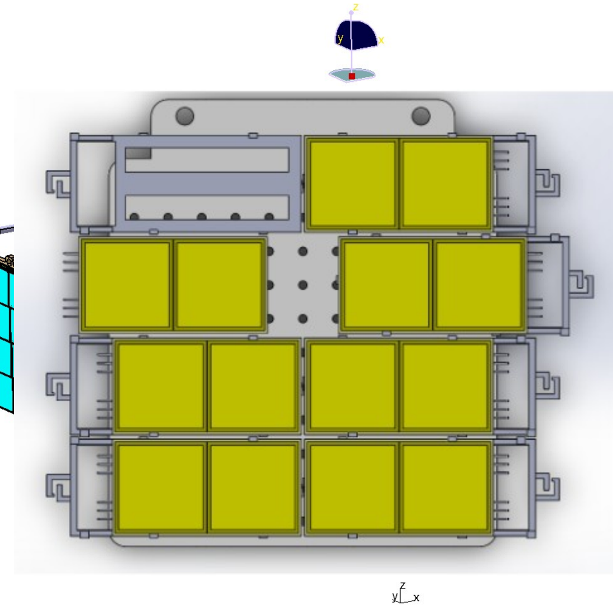
Maximizing geometric efficiency : auxiliary detectors (requires transparency on the sides!)

✓ ACTAR TPC (GANIL + USC/IGFAE, LP2IB, U.Regina, ...)

T. Roger et al., NIM A895, 126 (2018)

→ Double wire field cage: 2 mm/1 mm pitch
→ 20 µm wires = 97% transparency
→ 4 sides equipped with Si detectors
(up to 60 5x5 cm^{2} from USC/IGFAE)
→ Readout: 128x128 pads (16384 total)
256x256 mm2 active surface, volume ~ 16 L

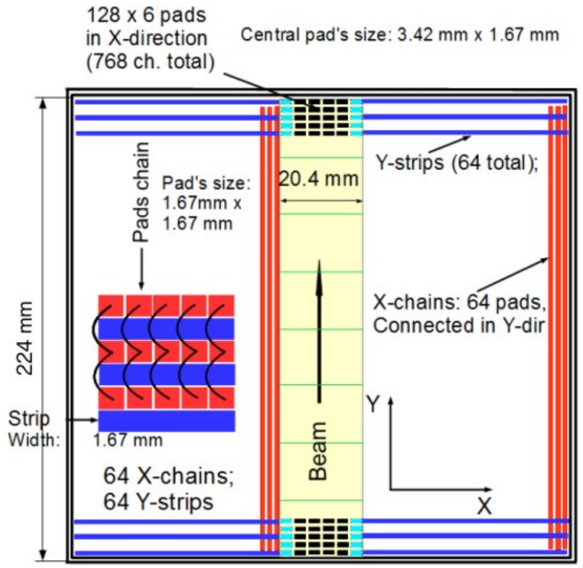


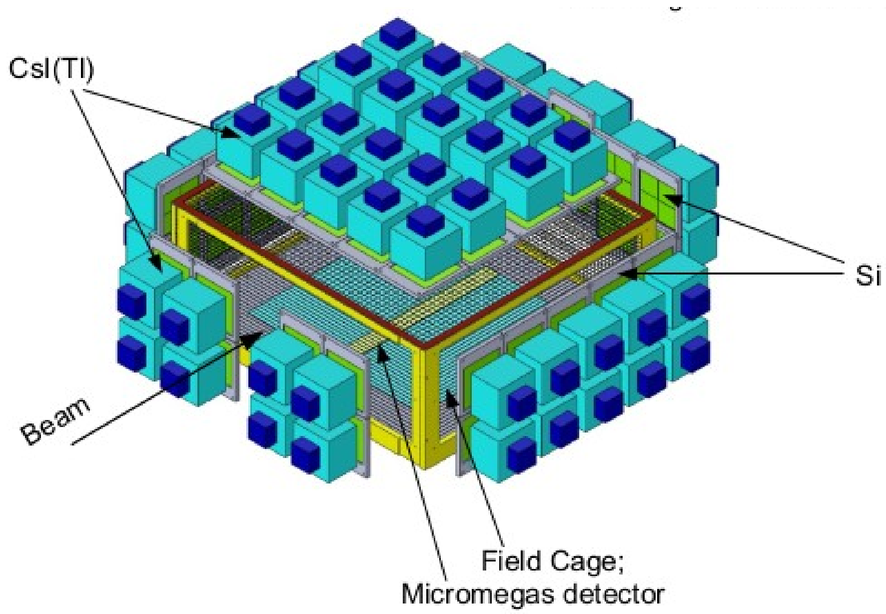


✓ TexAT (Texas A&M)

E. Koshchiy et al., NIM A957, 163398 (2020)

→ Double wire field cage: 5 mm/5 mm pitch
→ 50 µm wires = 98% transparency
→ Equipped with 58 Si+CsI telescopes
→ Readout: pads + strips (1024 channels total)
224x240 mm2 active surface, volume ~ 5 L



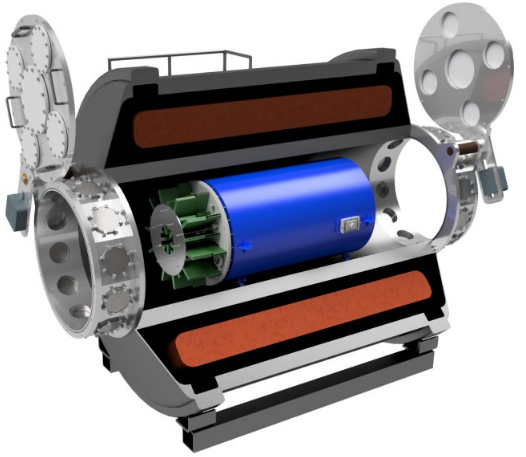


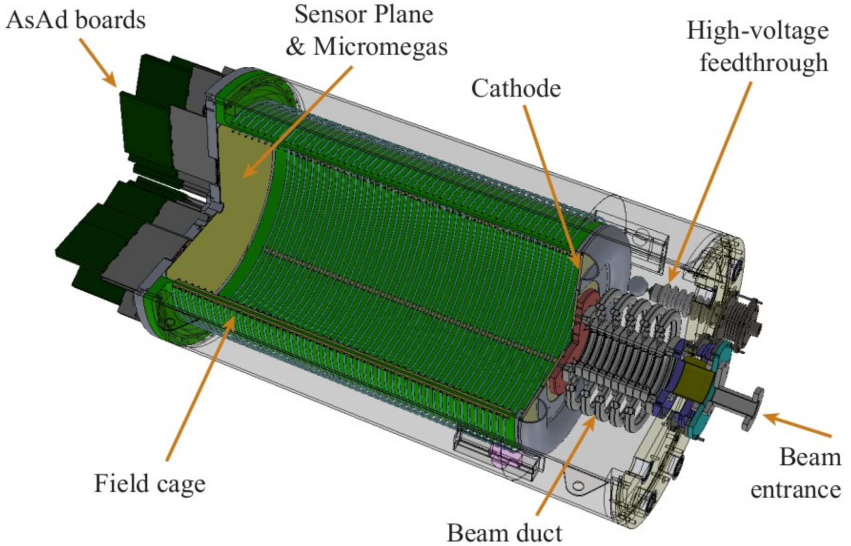
Maximizing geometric efficiency : Magnetic field

✓ AT-TPC (MSU)

J. Bradt et al., NIM A875, 65 (2017)

→ Solenoid magnet, 2 T max. field
→ Readout: 10240 triangular pads
Ø 29.2 cm active surface, 1 m long, volume ~ 67 L

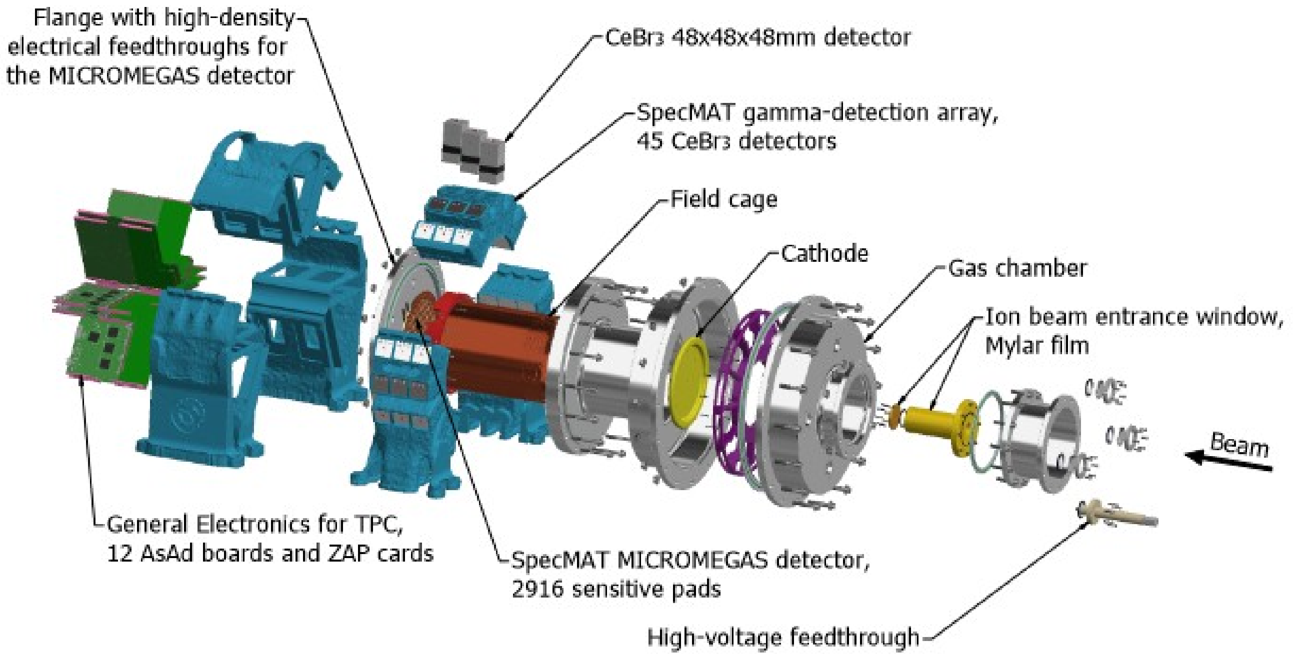




✓ SpecMAT (KU Leuven)

O. Poleshchuk et al., NIM A1015, 165765 (2021)

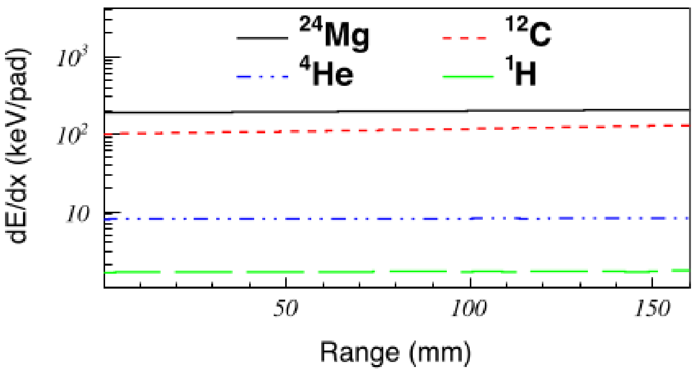
→ Solenoid magnet (ISS), ~2.5 T max. field
→ Readout: 2916 triangular pads
Ø 22.0 cm active surface, 32.3 cm long, volume ~ 12 L

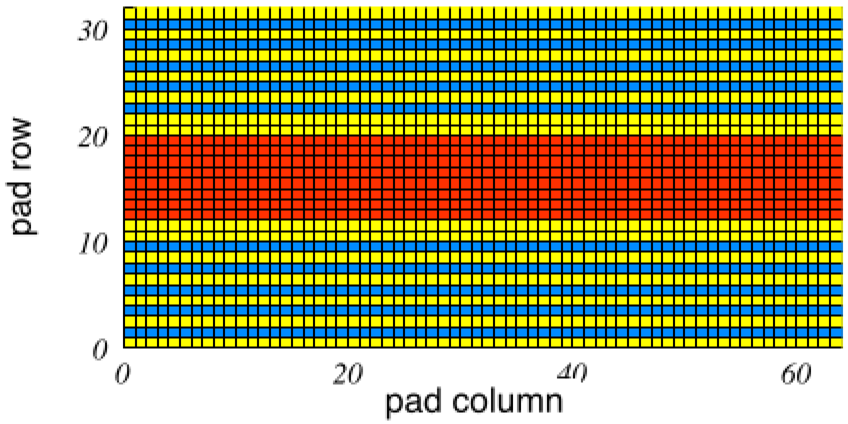


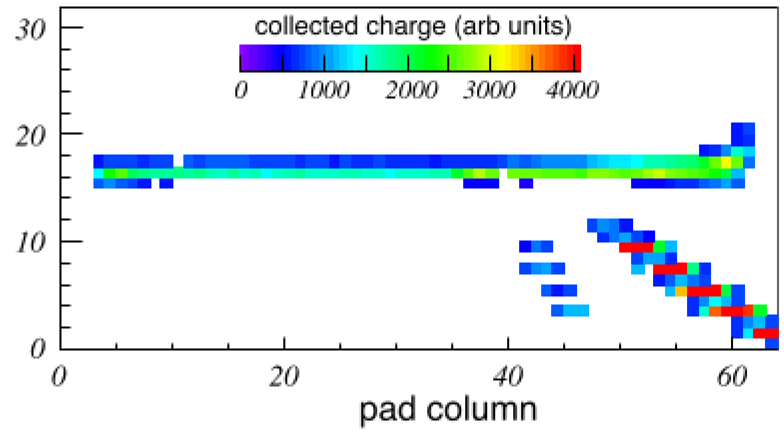
Increasing detection dynamics

✓GET electronics

→ Adjustable preamp gain (120 fC – 10 pC)



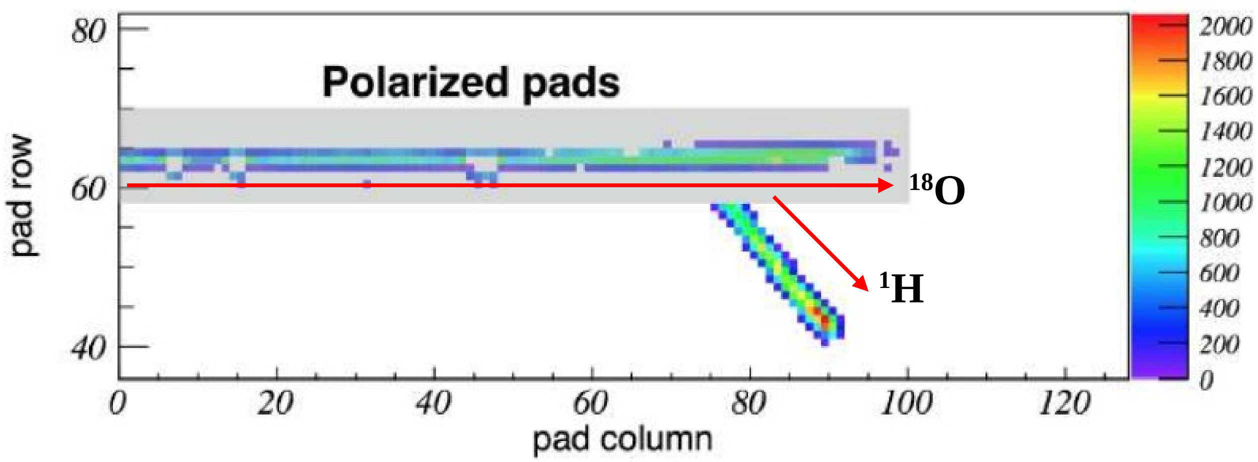


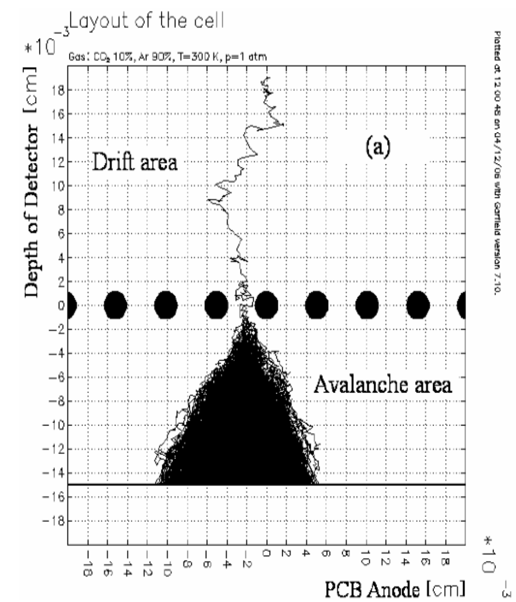


✓Pad polarization

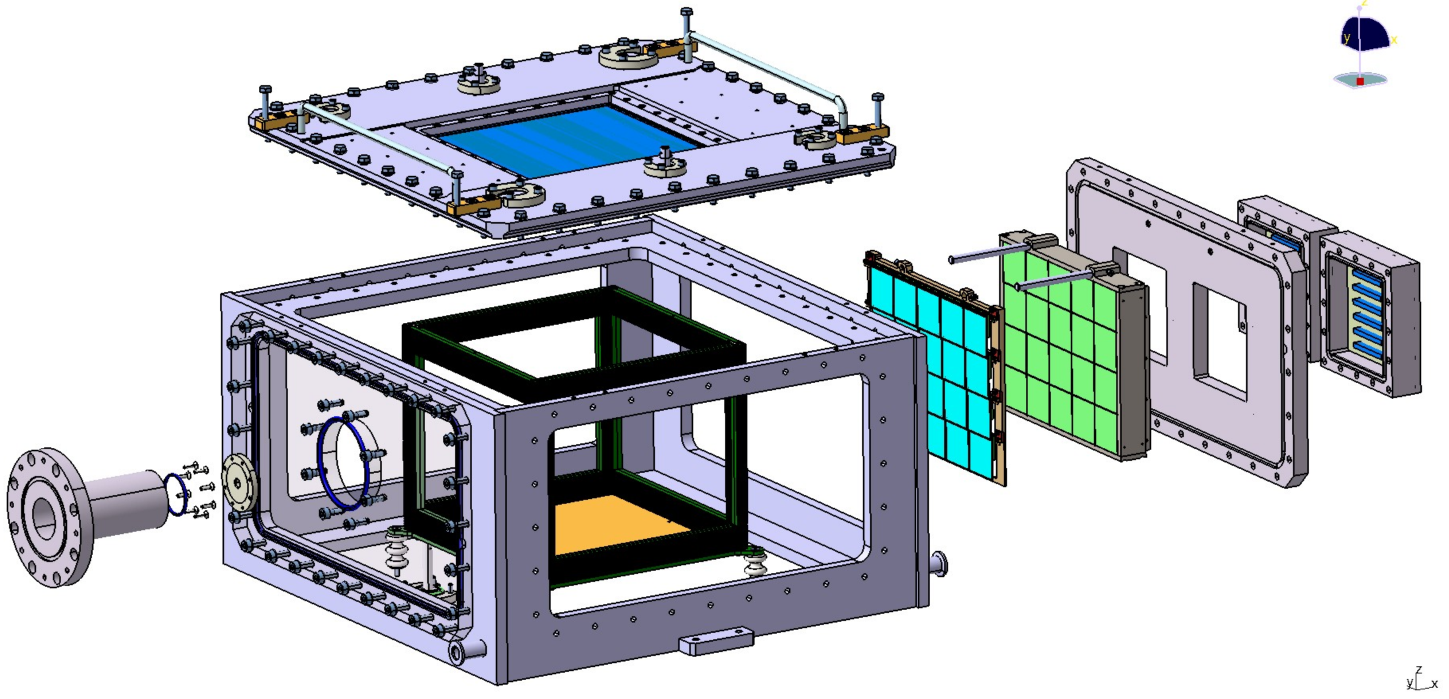
→ Micromegas: electron avalanche due to the high electric field between the mesh & the pad plane

→ Can be locally reduced (or increased) by polarizing the pads





Physics with ACTAR TPC at GANIL

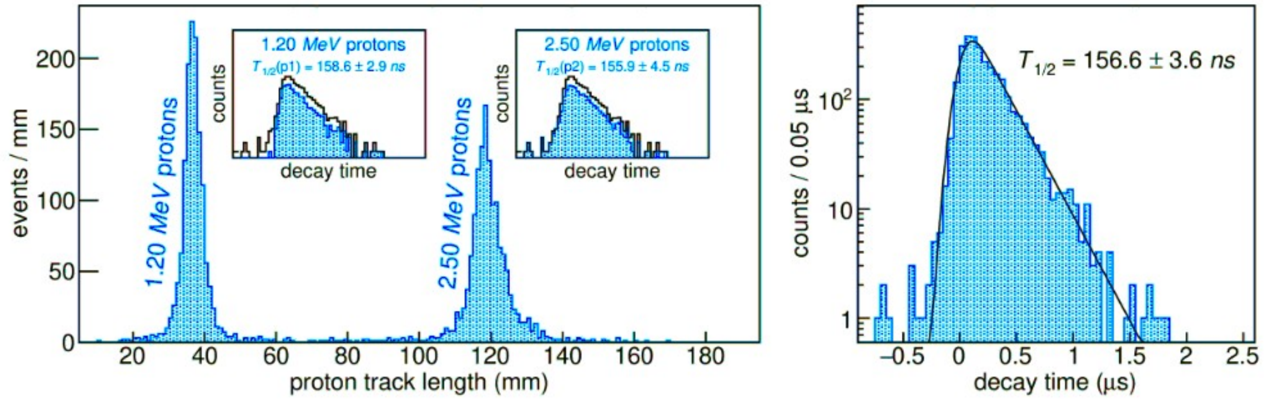


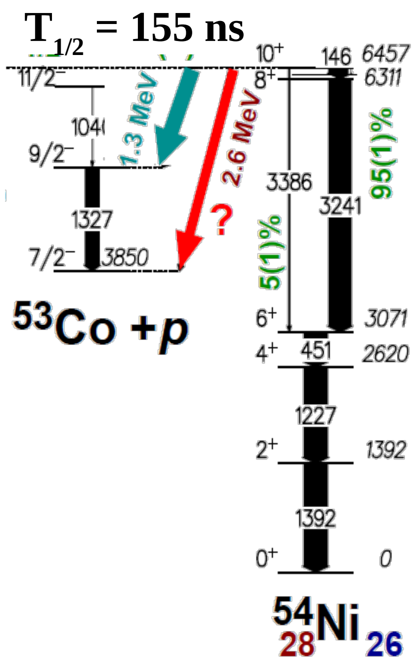
- ✓ Implantation / Decay: 1p & 2p decays (2 experiments)
- ✓ Transfer reactions: shell evolution (1 experiment)
- ✓ Inelastic scattering: giant resonances, shell evolution (2 experiments)
- ✓ Resonant scattering: cluster physics (2 experiments)

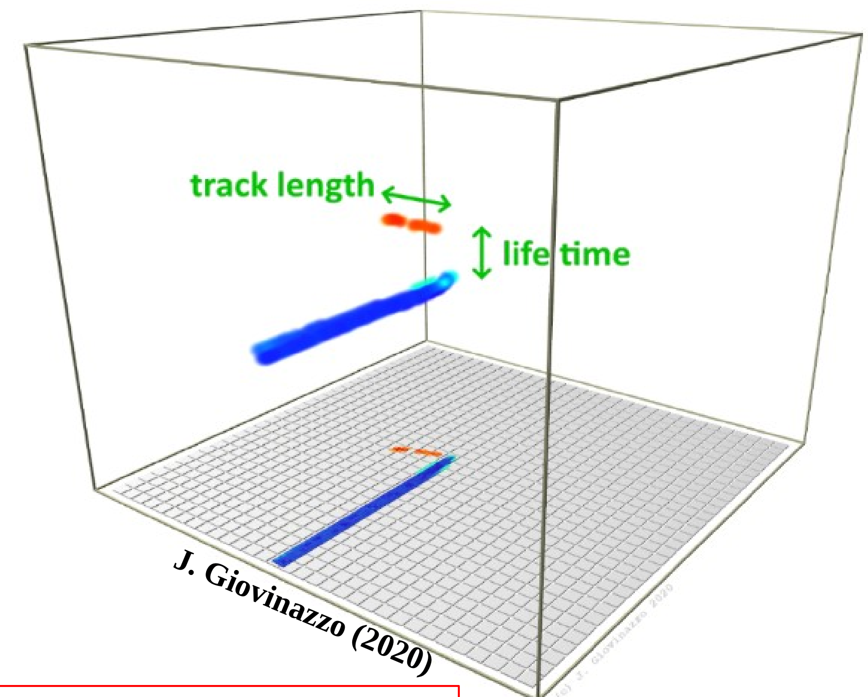
TPC mode : Implantation/Decay

✓ Proton-decay branches from the 10^+ isomer in ^{54}Ni and from the $19/2^-$ isomer in ^{53}Co (2019)

J. Giovinazzo et al., Nature communications 12, 4805 (2021)

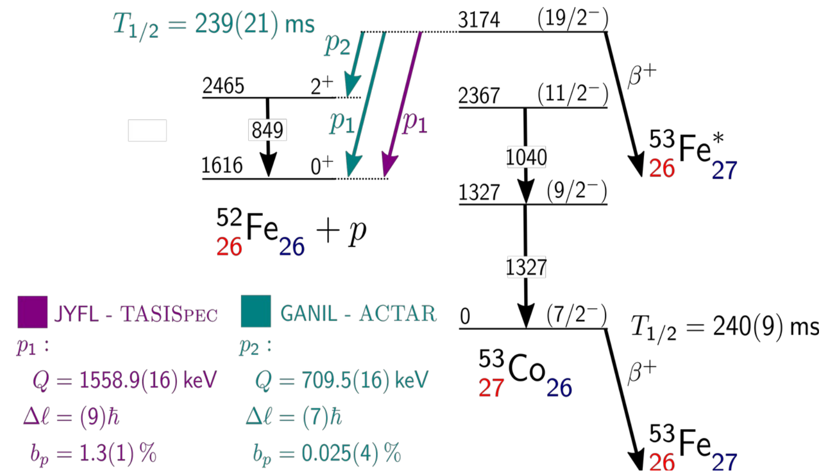


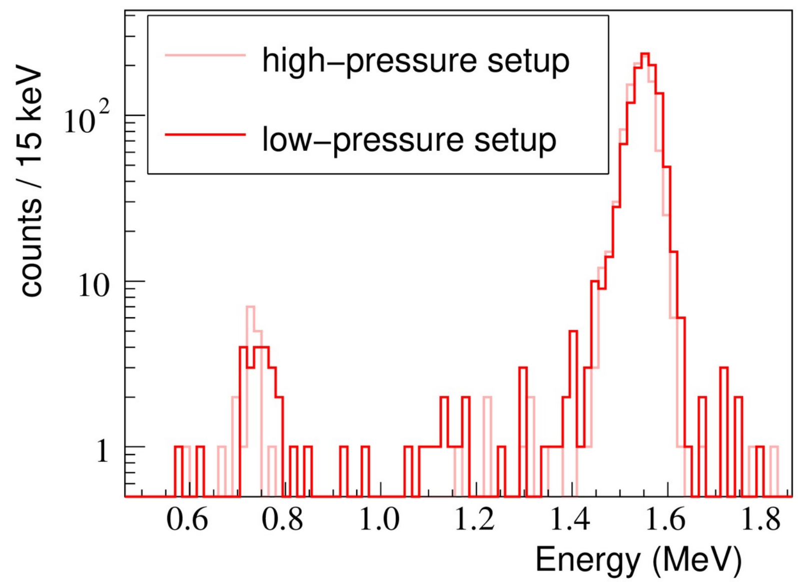




4D imaging of proton radioactivity

L. Sarmiento et al., Nature Communications 14, 5961 (2023)





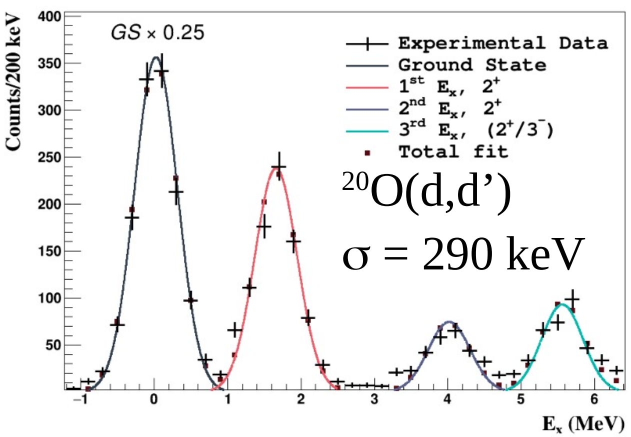
0.025 % branching ratio, no β background!

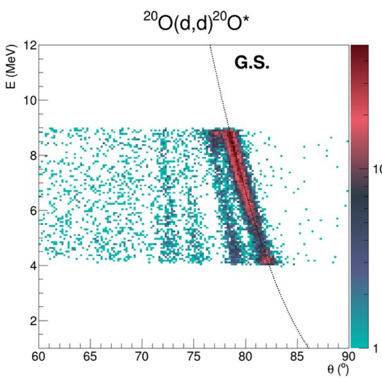
Transfer reactions (i.e. increasing target thickness)

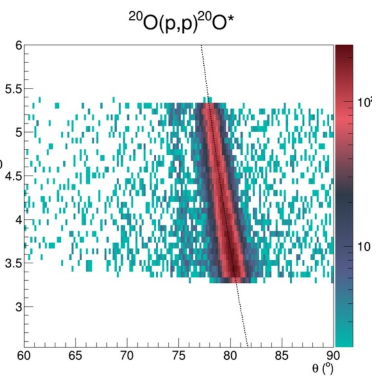
✓ Study of the $^{20}O(d,^{3}He)$ reaction (2022)

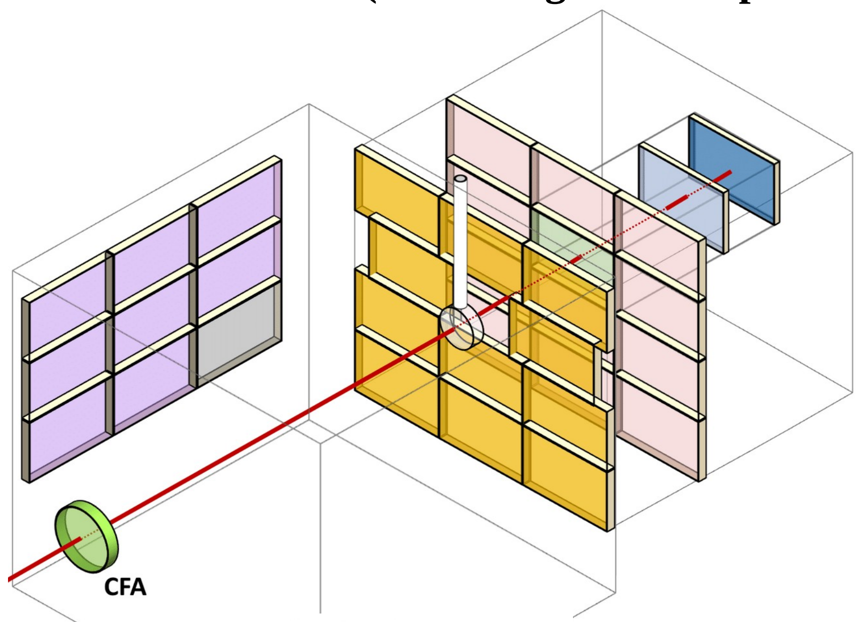
^{20}O at 30A MeV in 1 bar D_2(90%) + iC_4H_{10} (10%) → Equivalent **11 mg/cm²** CD_2 target + **5.4 mg/cm²** CH_2 target

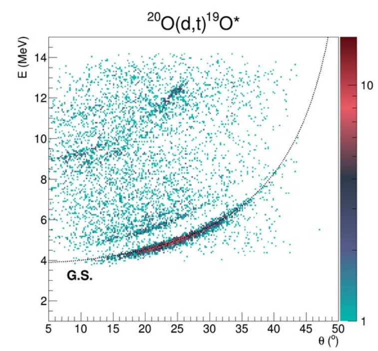
J. Lois Fuentes PhD thesis (U. Santiago de Compostela - 2023)

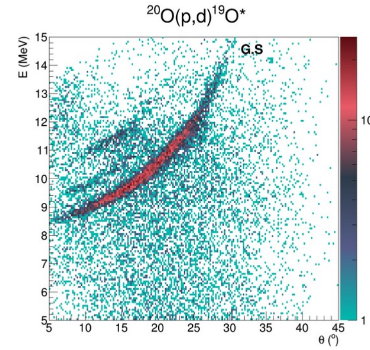


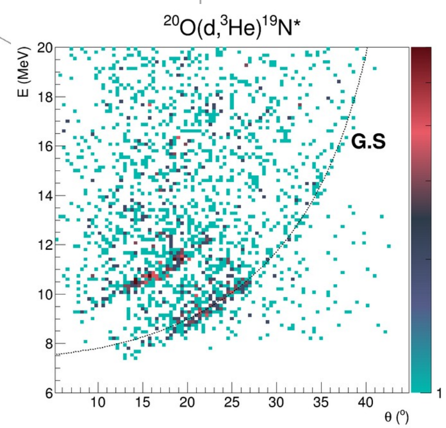


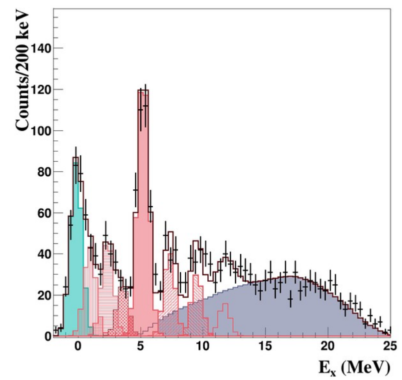


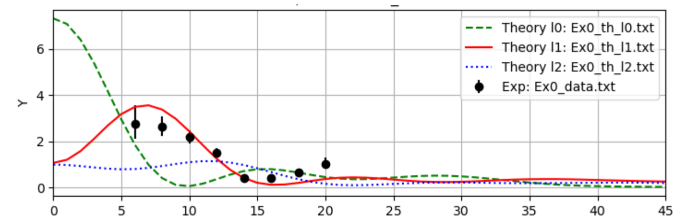


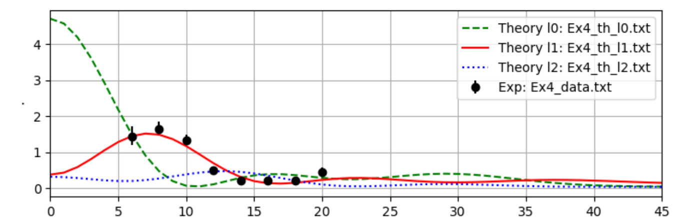












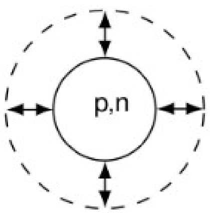
At equal E* resolution, a solid target should be 10 times thiner

Inelastic scattering (i.e. detection of low energy recoils)

✓ Study of the ^{58,68}Ni(α,α') reaction – June 2019

^{58,68}Ni @ 49*A* MeV in 400 mbar He(98%) + CF_4(2%) → **tracking of 400 keV alphas**

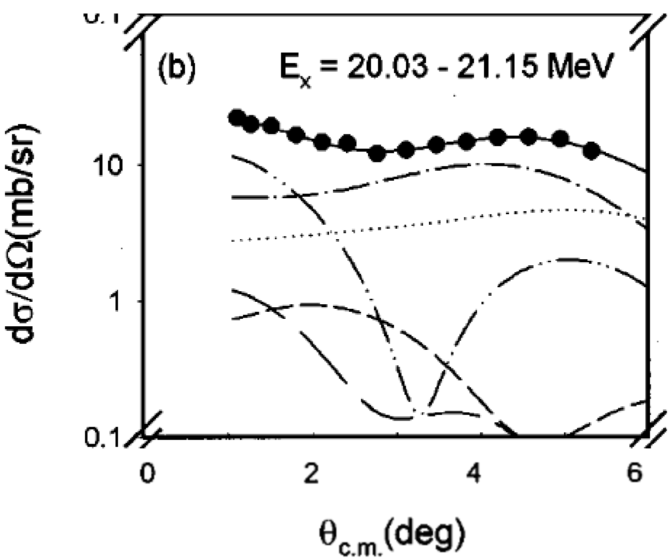
D. Thisse (IRFU/DphN) → work in progress



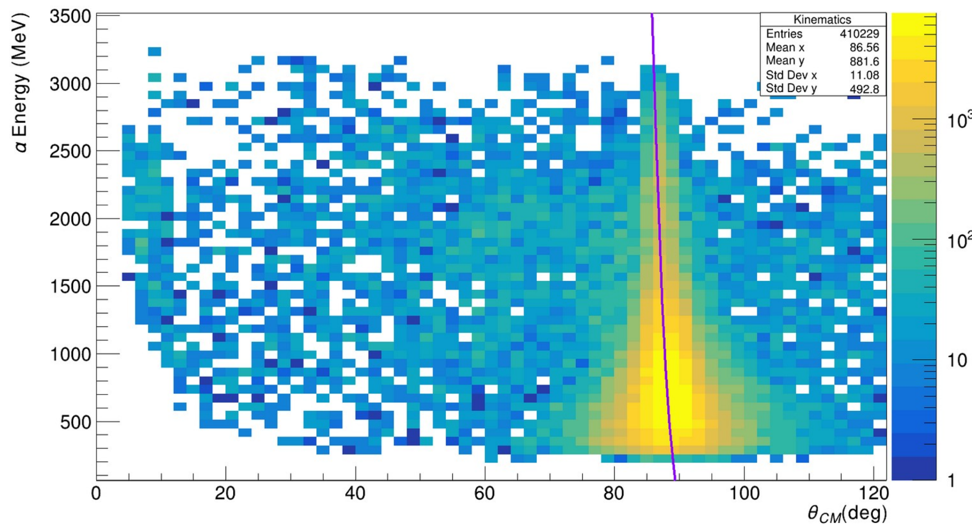
ISGMR

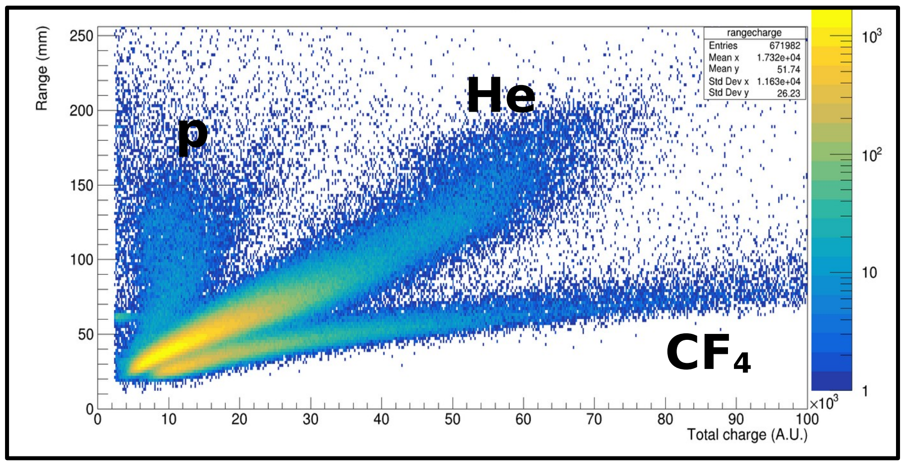
ΔT = 0

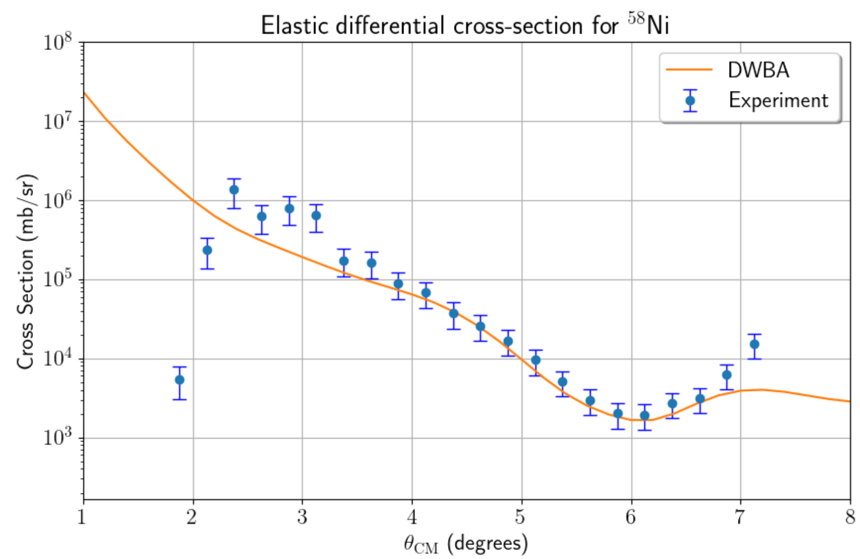
ΔS = 0



Y. W. Lui *et al.* PRC 61, 067307 (2000)







Resonant scattering : excitation functions

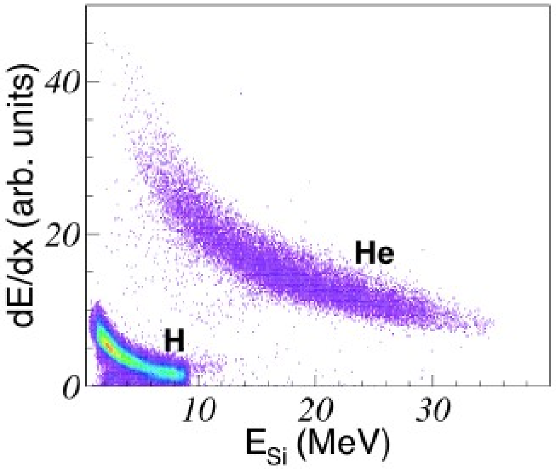
- "Classic" TTIK method (thick solid target, beam stopped inside):
  - 3 unknown: E_{CM}, θ_{CM}, E^* but only 2 observables (θ_{light}, E_{light})

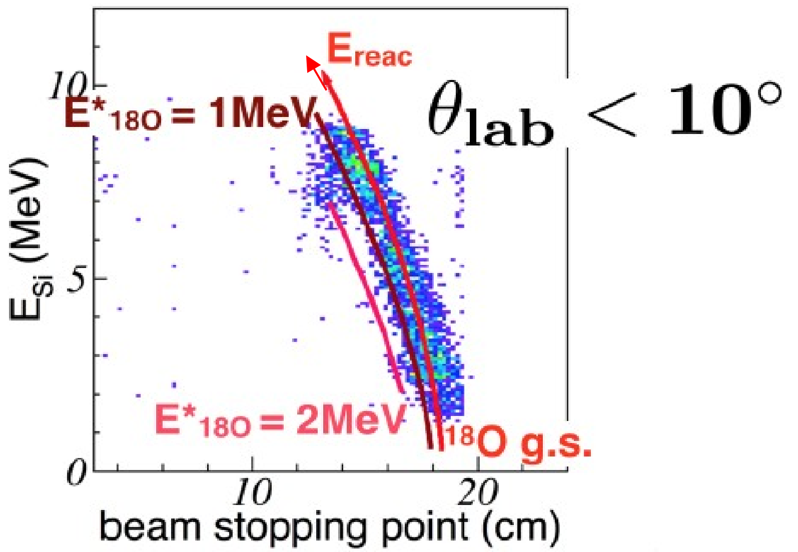
    → unable to disentangle elastic and inelastic channels (no info on E^*)
- Active Target: one more kinematic parameter (stopping point of the beam-like particle)

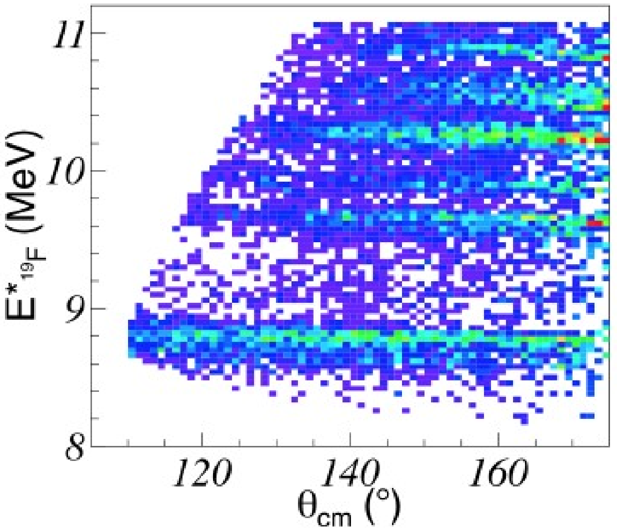
  → full identification of the reaction

  + reconstruction of double differential cross section ($d^2\sigma/d\Omega dE$)

B. Mauss, PhD thesis (GANIL)





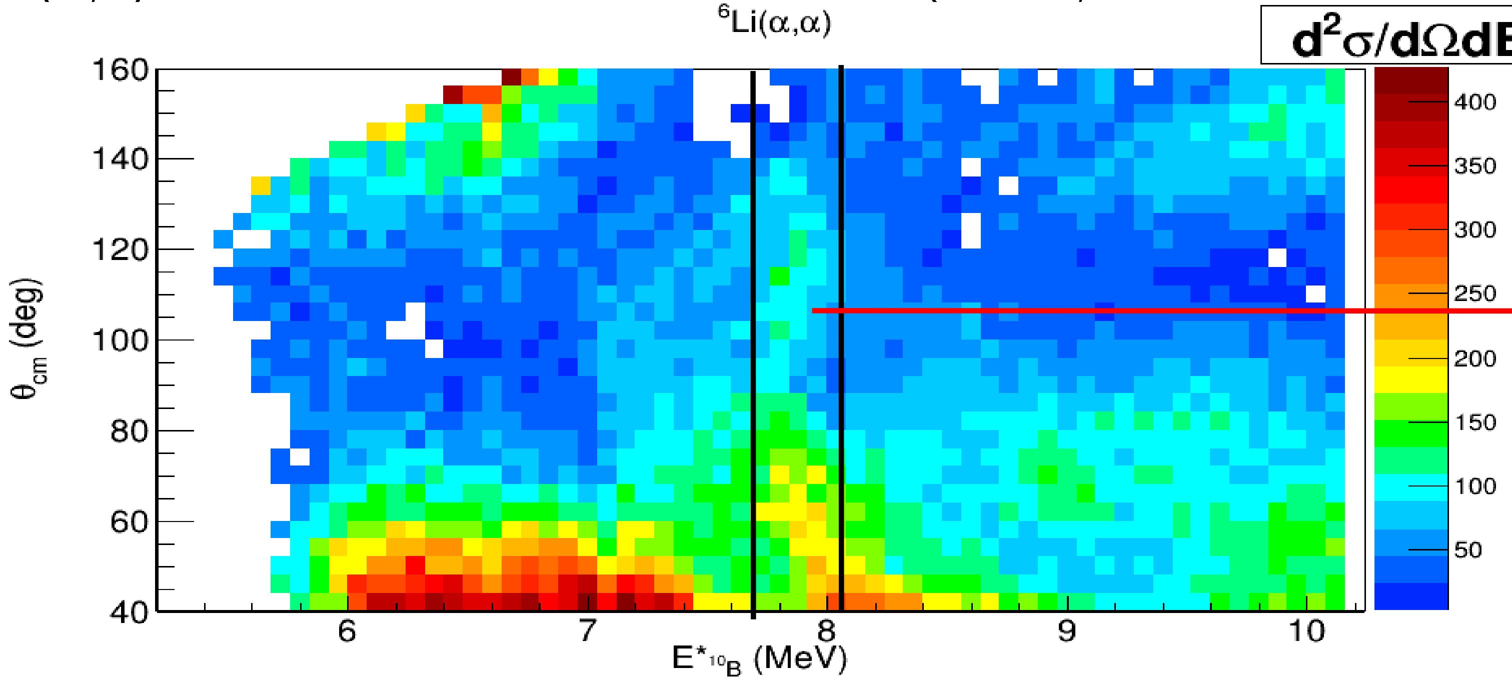


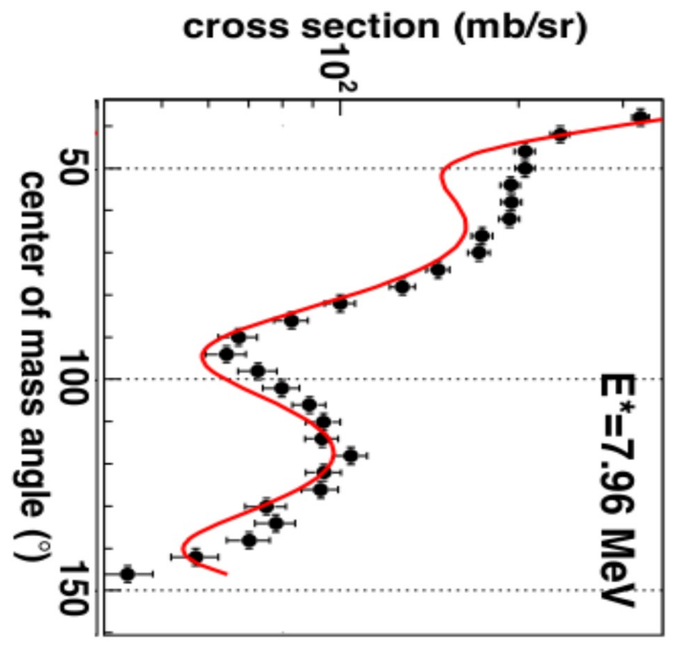
Particle identification → Tracking algorithm → Channel selection → Reaction kinematics + energy loss tables → Double differential cross section

Resonant scattering : an example

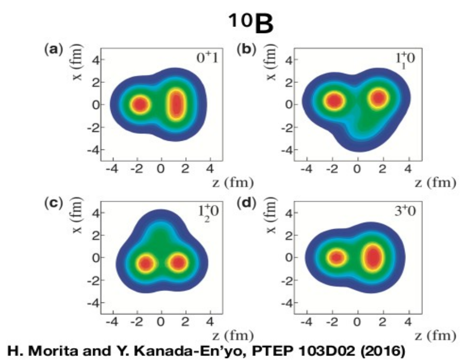
✓ Search for α-cluster states in ^{10}B (B. Mauss, PhD thesis – to be published)

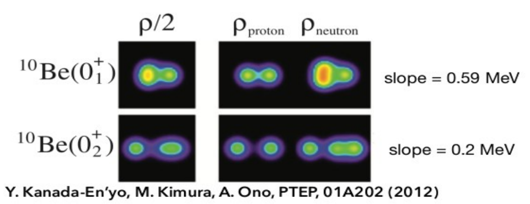
$^{6}Li(\alpha,\alpha)$ elastic and inelastic excitation functions @ LNS, Catania

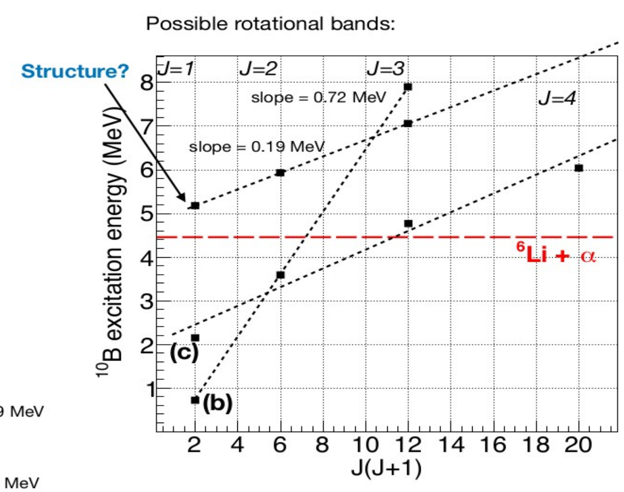




3+ state @ 7.9 MeV,
large alpha decay width



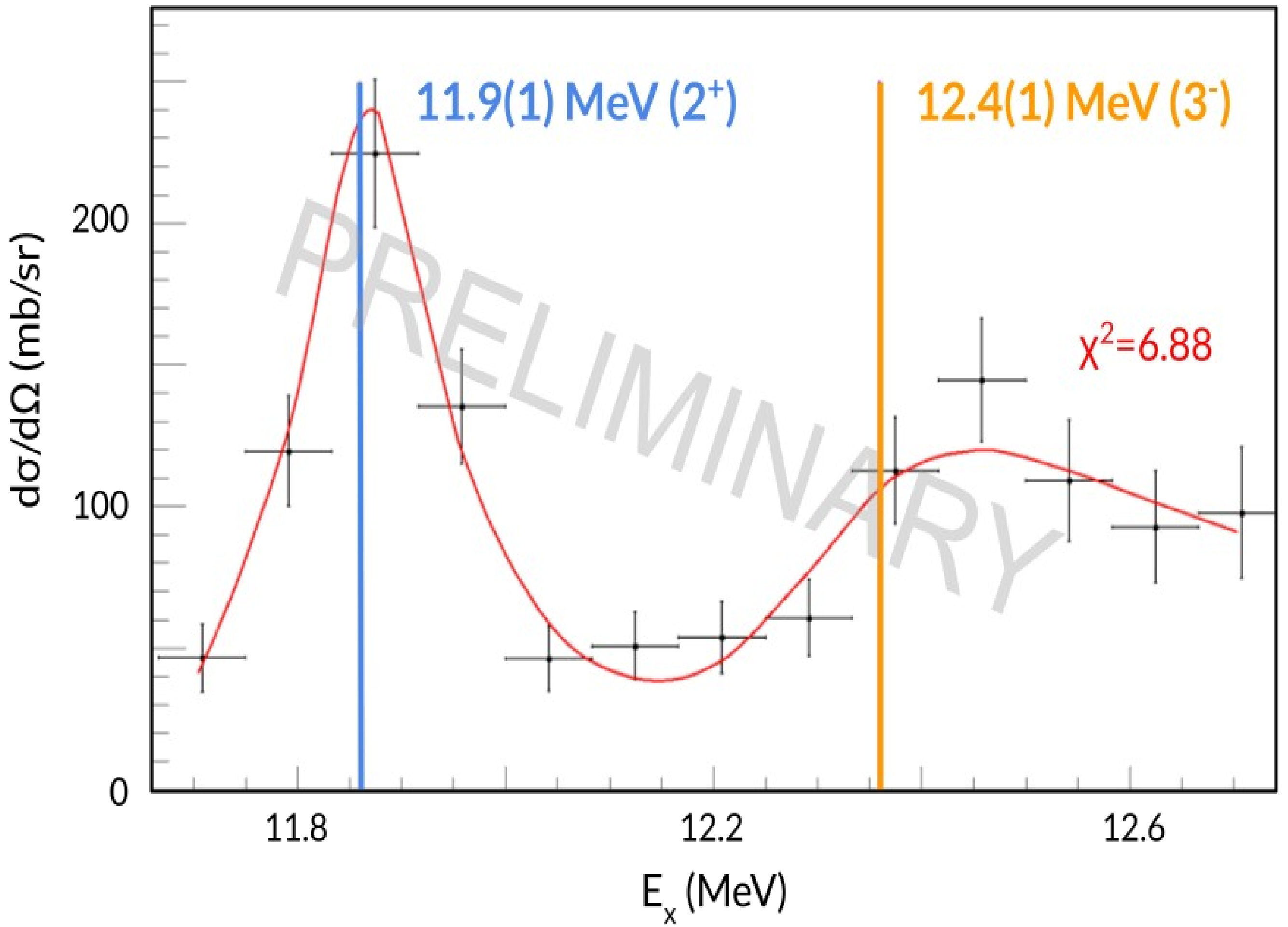




Preliminary work, B. Mauss (GANIL/RIKEN)

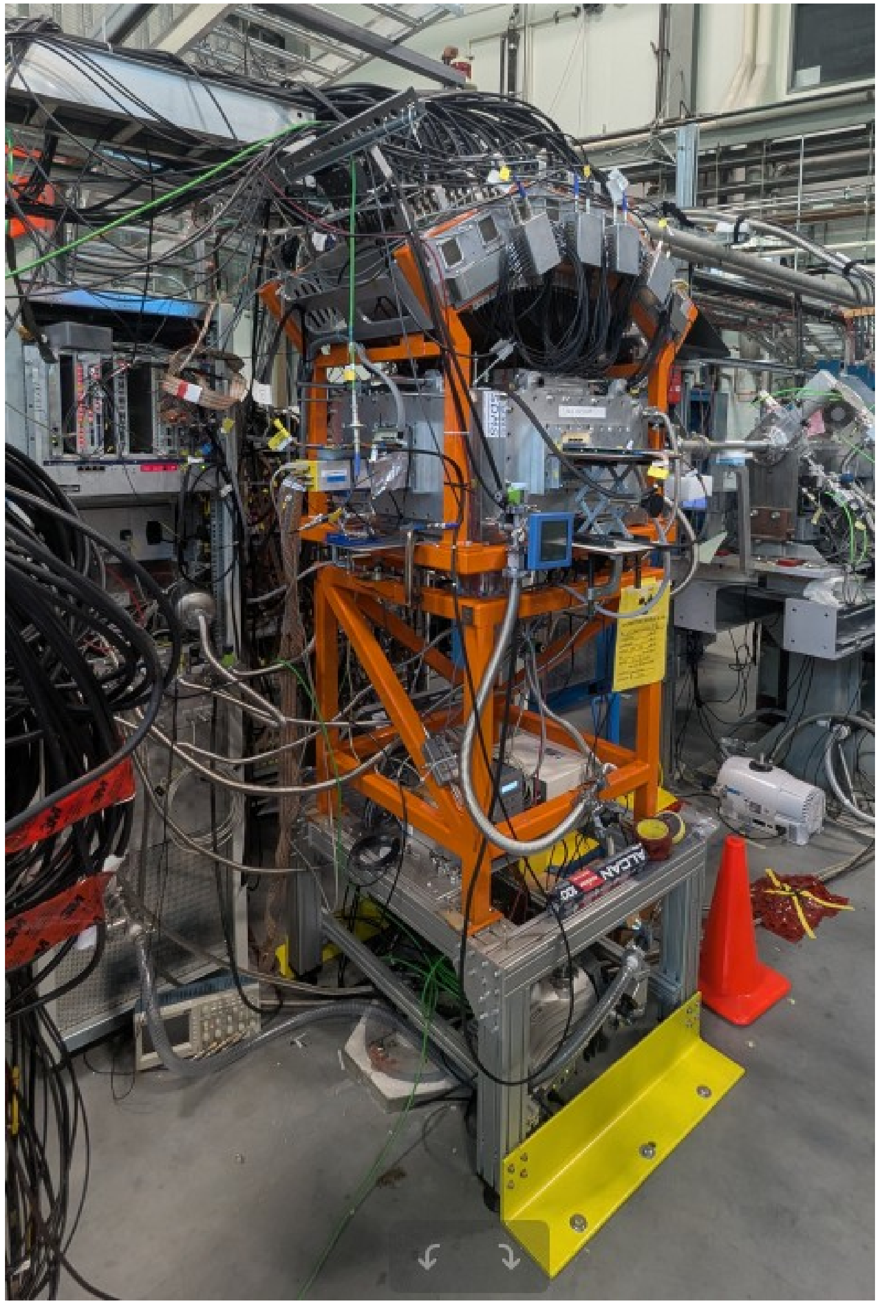
ACTAR 2024 campaign : study of ^{12}Be structure in multi-threshold vicinity

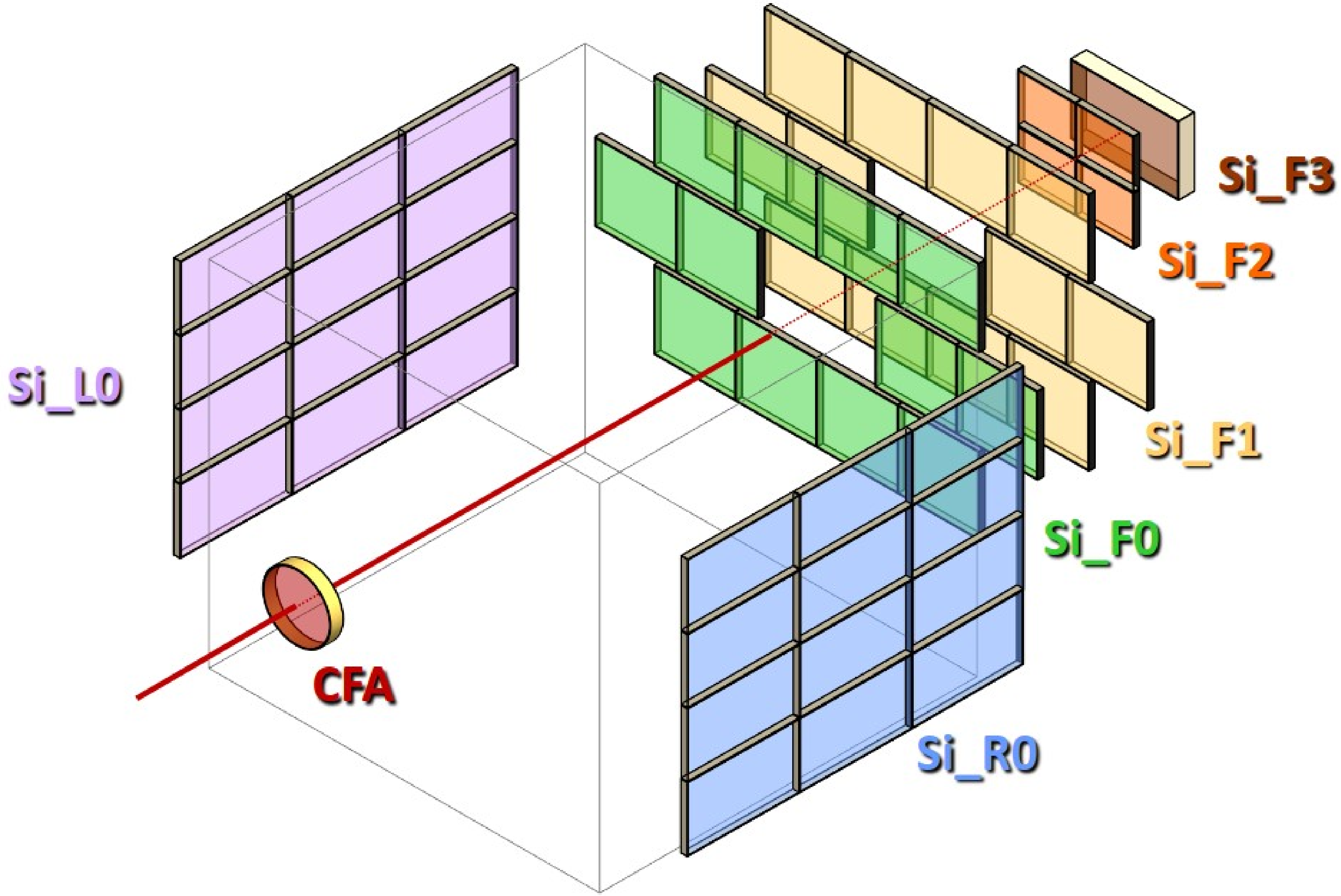
- Two alpha cluster states measured in ^{12}Be (via ^{8}He+^{4}He) with new spin assignments



→ see Laurie's poster for more information

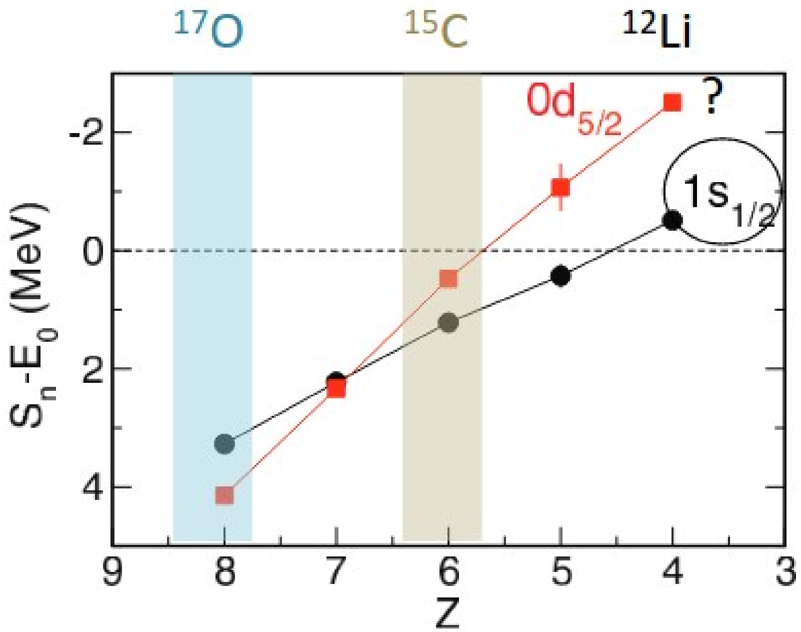
Experiments proposed at TRIUMF





Experiments proposed at TRIUMF

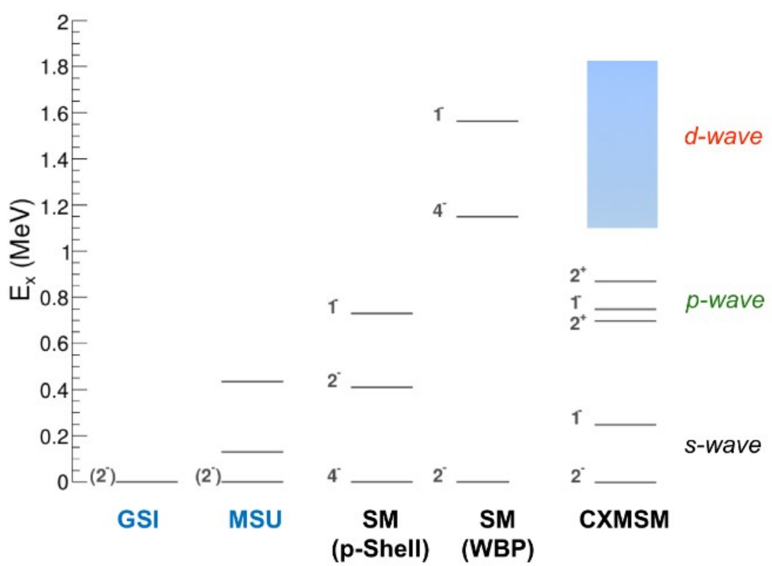
⇨ S2384 : Detailed spectroscopy of ^{12}Li (B.F.D., W. Catford, T.R.)

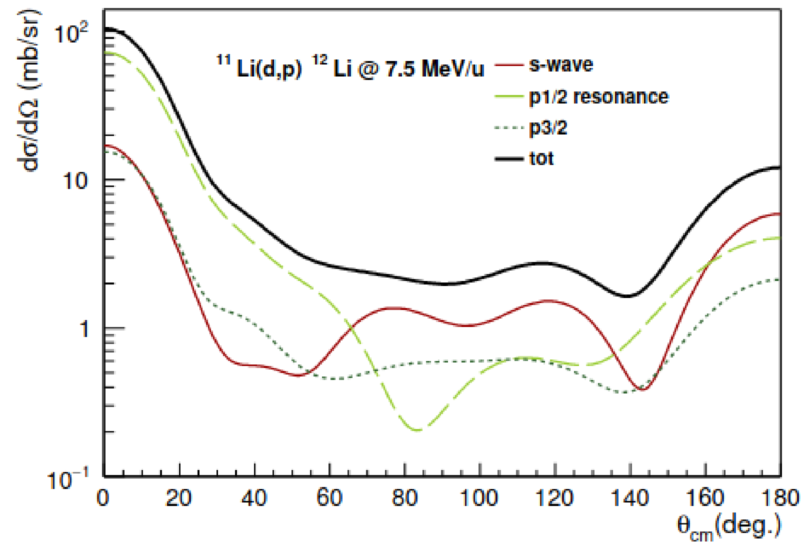


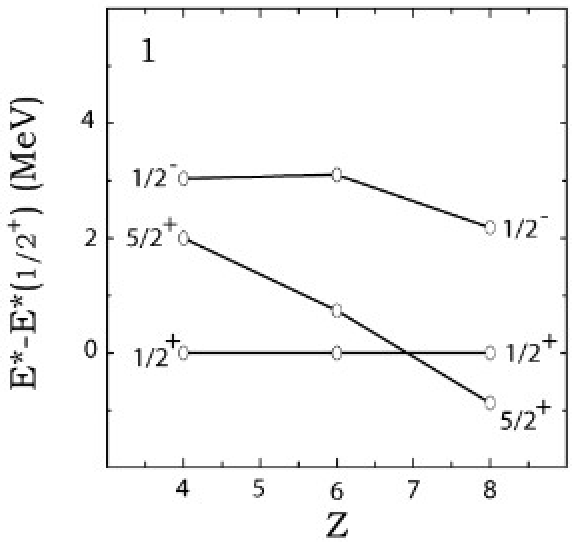
⇨ Neutron $2s_{1/2}$ orbital is going down in energy in the N=9 isotones

⇨ Trend confirmed with l=0 ground state found for ^{12}Li

⇨ Simultaneously, neutron $1p_{1/2}$ is going down in energy. Could even go below $1d_{5/2}$ in ^{12}Li







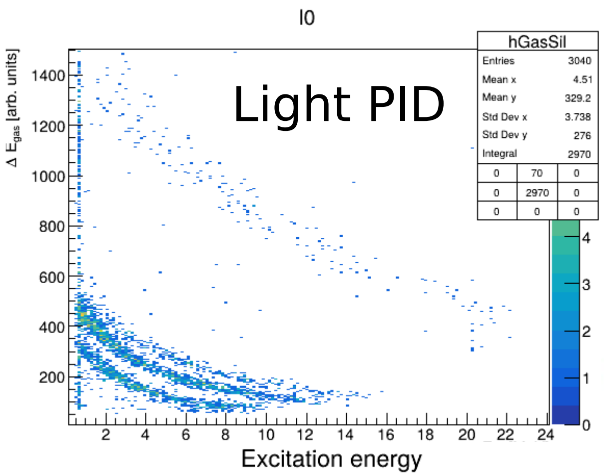
⇨ ^{11}Li(d,p) in order to locate the p- and d- wave resonances in ^{12}Li and deduce the nature of the low-lying states in ^{12}Li

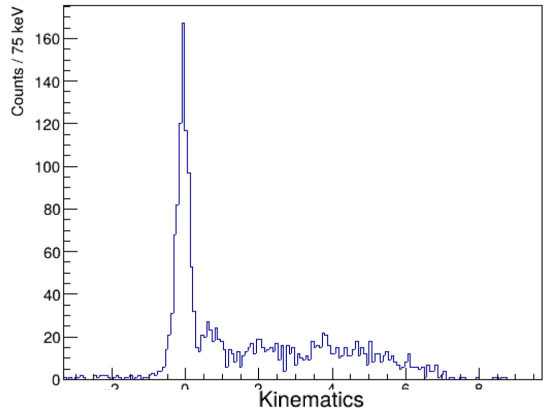
⇨ ^{11}Li beam @ 7.5*A* MeV, I > 2000 pps

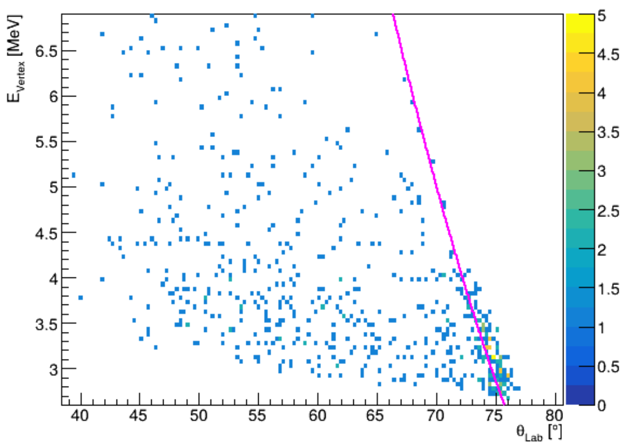
Experiments proposed at TRIUMF

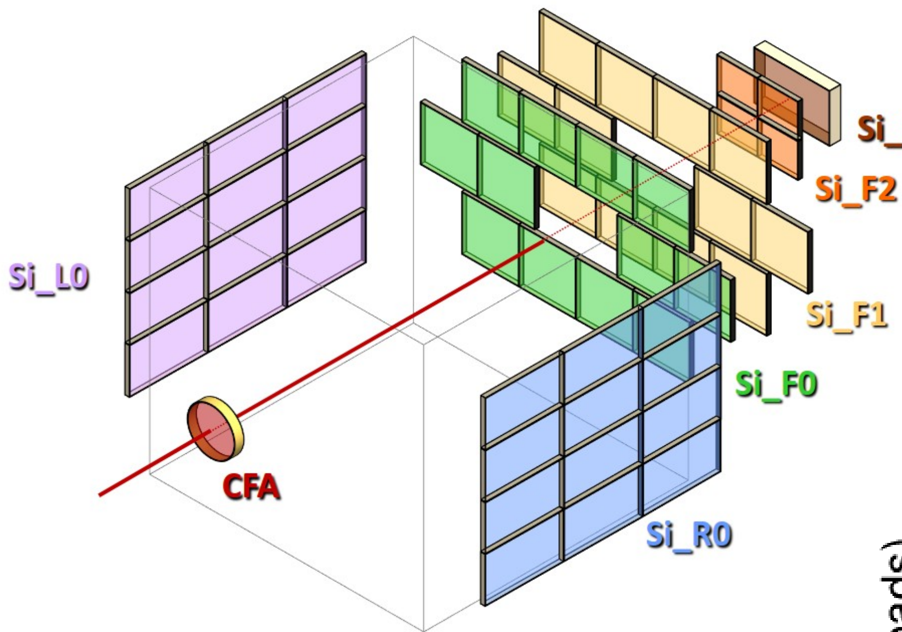
⇨ S2384 : Detailed spectroscopy of ^{12}Li (B.F.D., W. Catford, T.R.)

PhD thesis I. Blanco (USC)

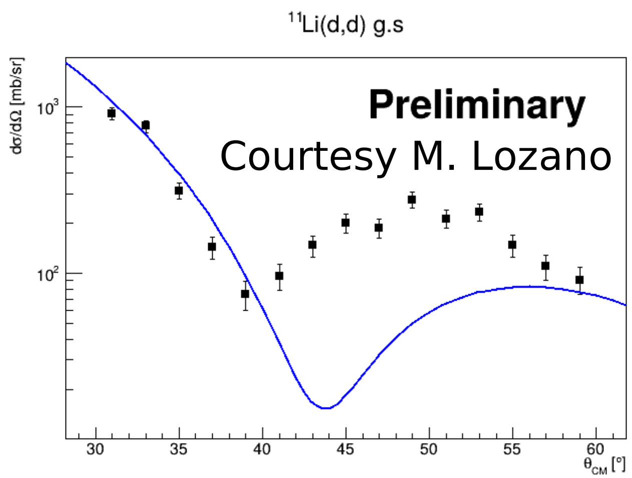


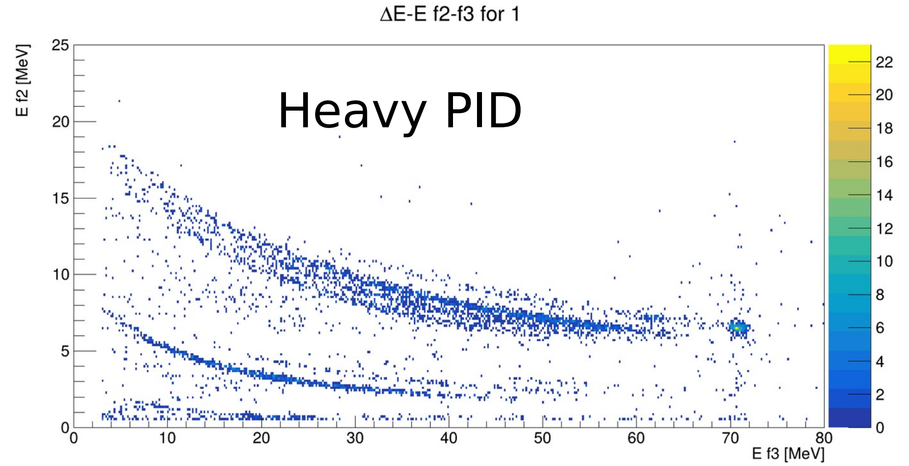


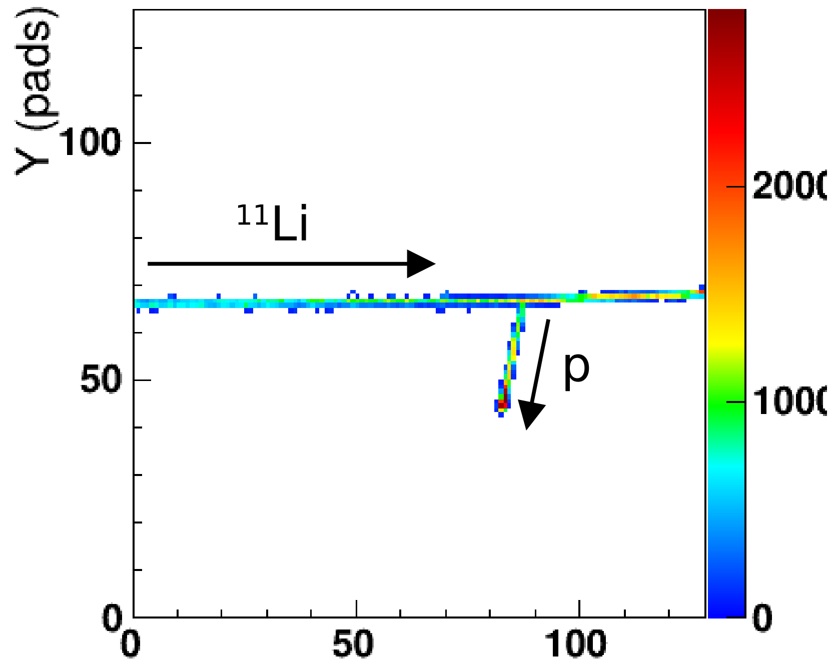




Elastic scattering





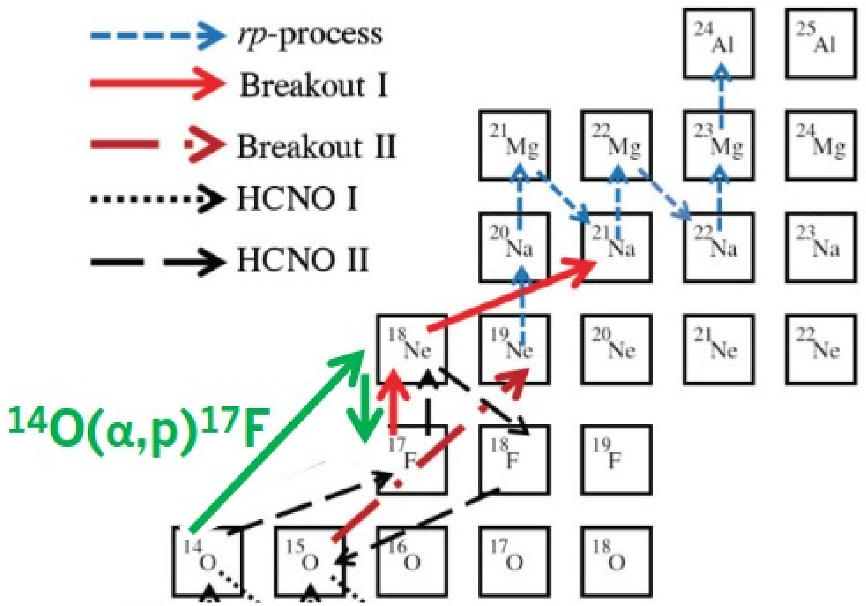


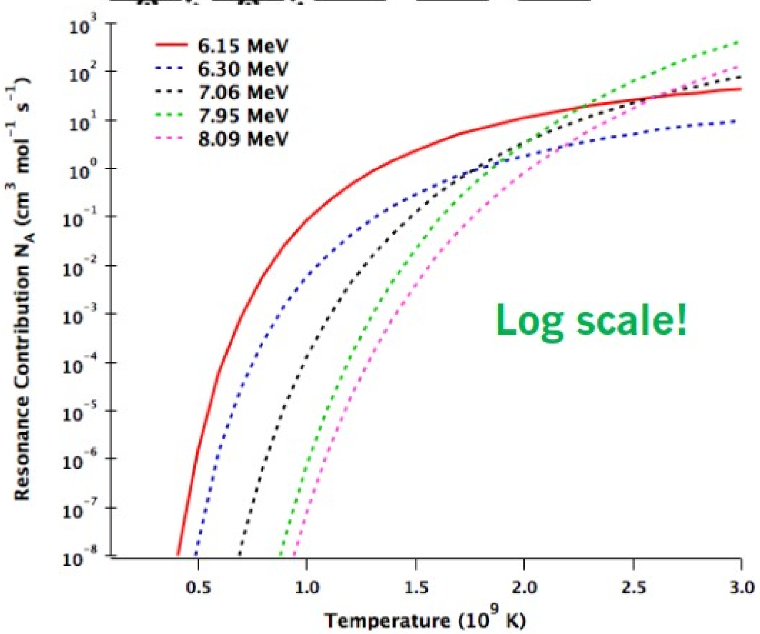
Experiments proposed at TRIUMF

⇨ S2029 : Resonant proton elastic scattering on ^{17}F (G.F.G., T.R.)

MSc thesis Fatima Aljarrah (Regina)

Pdf : Artemis Tsantiri (Regina)





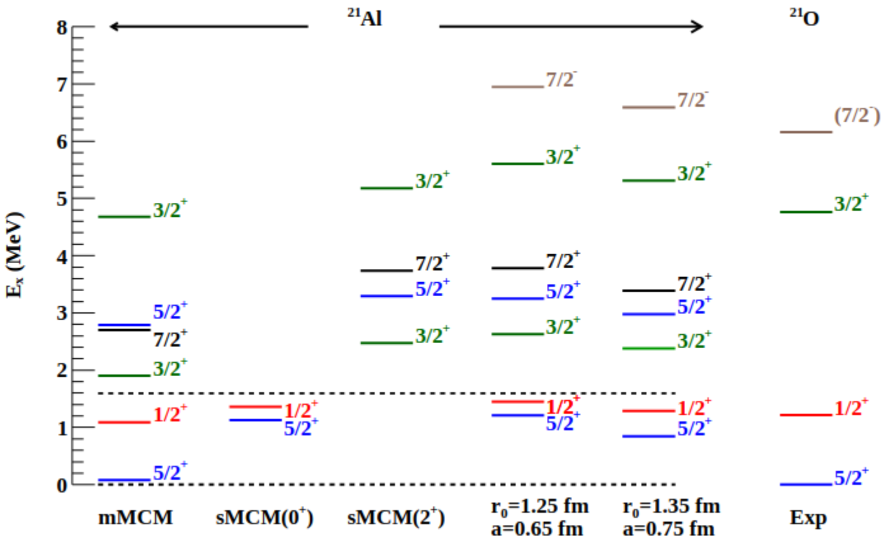
- ⇨ ^{14}O(α,p) is one of the two break-out pathways from the HCNO cycle
- ⇨ This reaction is dominated by the 6.15 MeV (1^-) resonance in ^{18}Ne
- ⇨ The 1^- state is known to decay by single proton, but 2p and α channels are opened
- ⇨ Γ_{2p} has been experimentally measured (indirectly) to be ~ 27%, but theoretical estimates are about 10000 times smaller!
- ⇨ Γ_α has never been measured.

- ⇨ ^{17}F+p resonant scattering to populate 6.15 MeV state in ^{18}Ne
- ⇨ $^{17}F^{9+}$ beam @ 4.5*A* MeV in H_2(95%)+iC_4H_{10}(5%) @ 700 mbar, I > 5000 pps

Γ_{2p}/Γ_{tot} (%)	2p yield (counts/day)
< 27.0	$< 7\times10^4$
0.03 to 0.11	70 to 280
0.001 to 0.006	2 to 14

Experiments proposed at TRIUMF

⇨ S2008 : Study of the unbound states in ^{21}Al using an active target (B.F.D, O. Tengblad, T.R.)



⇨ Only experimental information on ^{21}Al: $T_{1/2}$<13 ns

→ Theoretical predictions in disagreement

⇨ Mirror nuclei ^{21}O

→ Largest known TES predicted (according to sMCM)

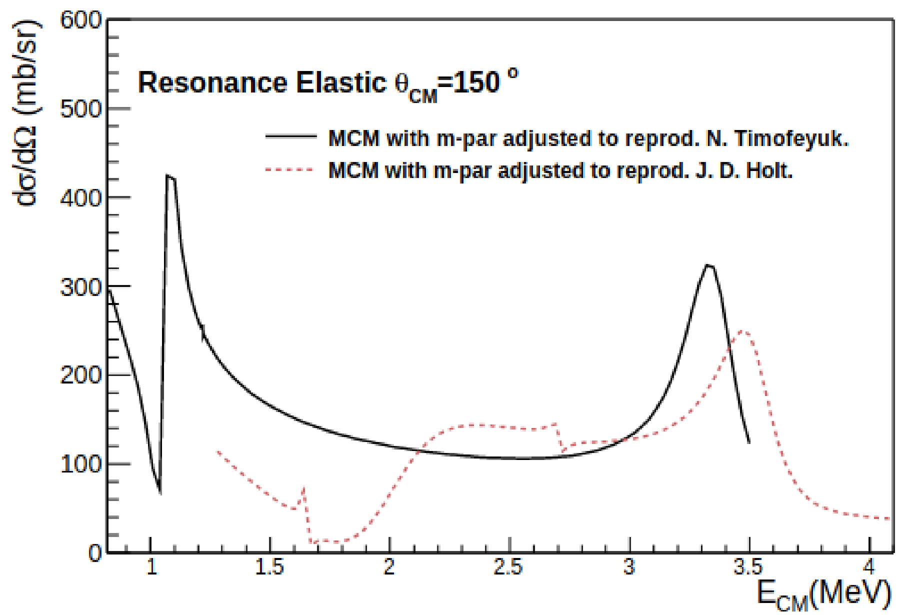
⇨ Nuclei located at the N=8 gap and just below the Z=14 gap

→ Is the modification of the Z=14 gap due to combined action of the central component and the tensor part of the effective nucleon-nucleon (NN) like on the neutron rich side?

⇨ Proton resonant scattering to probe proton states

⇨ ACTAR TPC to disentangle elastic v.s. inelastic channels (probes core excitations in ^{21}Al)

⇨ ^{20}Mg beam @ 2*A* and 6*A* MeV – min. I expected: 1000 pps



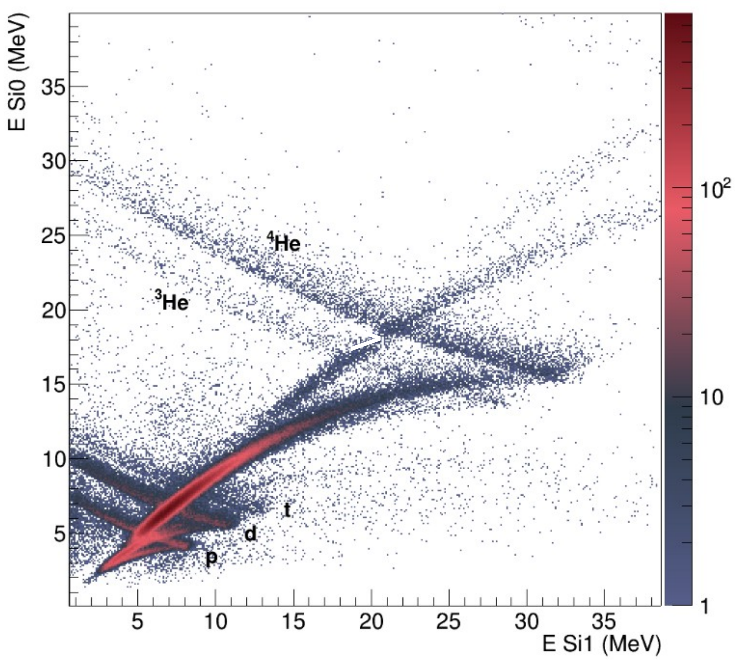
Data analysis : Particle identification w/o B field

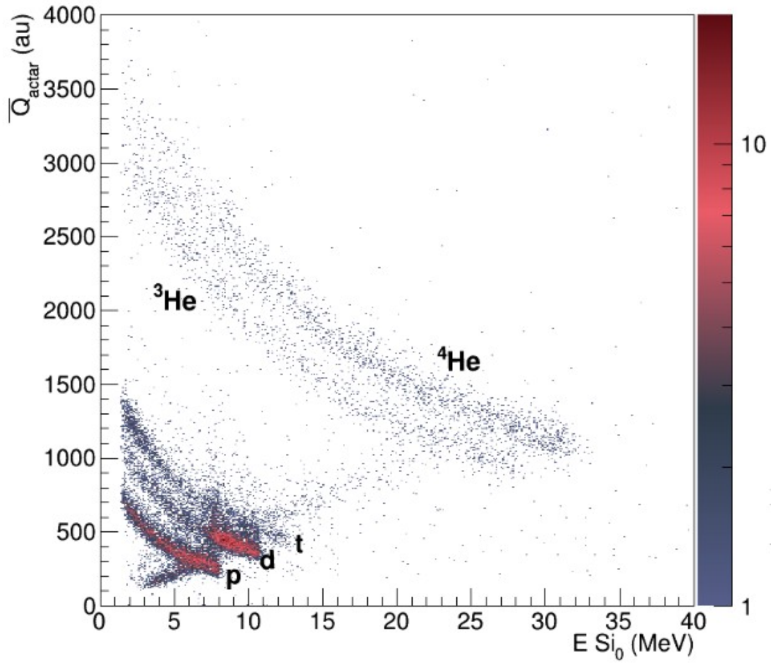
Particle energy

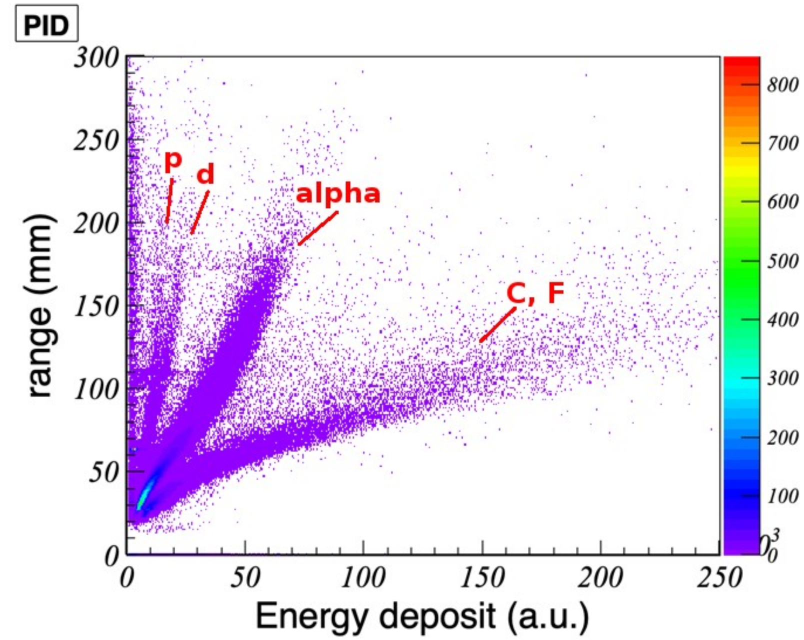
- Range / Q_{tot}
- Charge profile, Line shape analysis

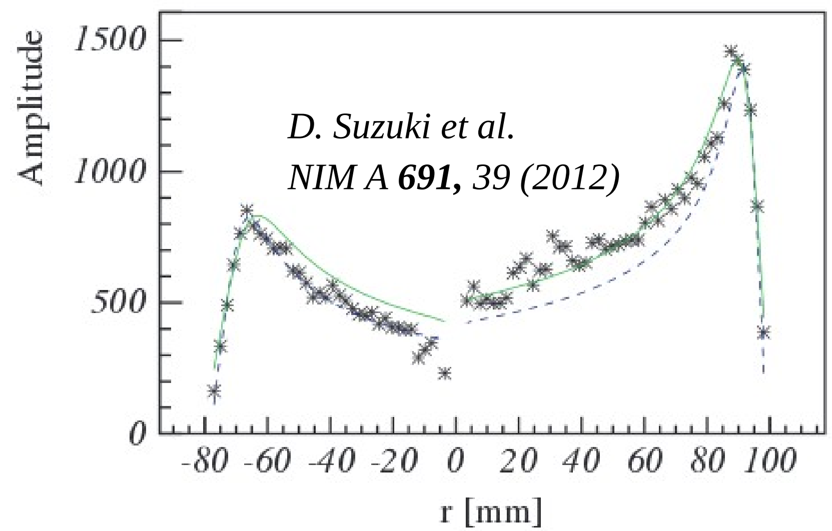
- ΔE / E
(gas v.s. solid state detector)
- Silicon PSA

ΔE / E
(solid state detectors)







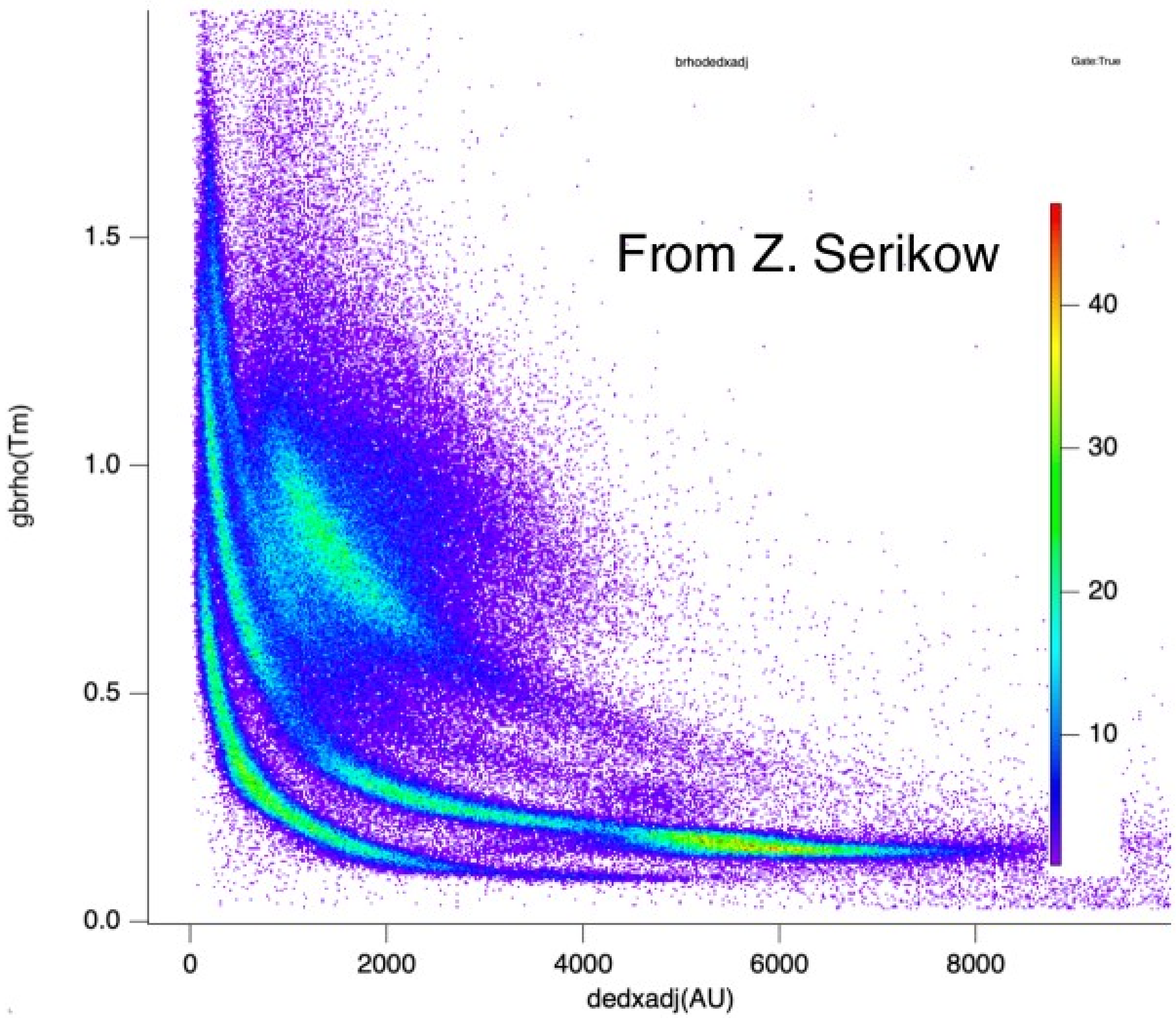


D. Suzuki et al.
*NIM A **691,** 39 (2012)*

Data analysis : Particle identification with B field

Particle energy

PID from Brho and dedx



Data analysis : Signal processing & Tracking

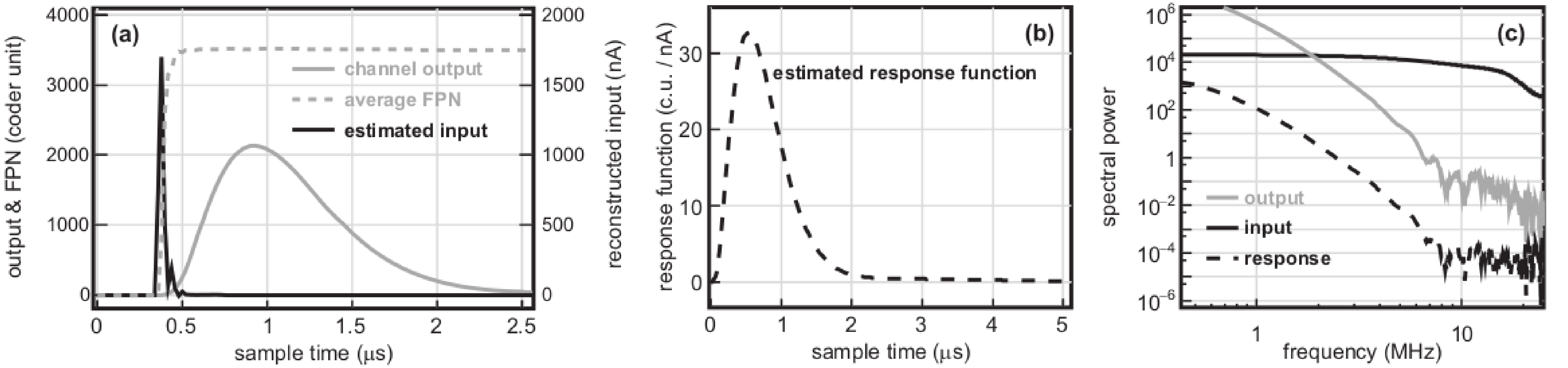
Unlike other “classic” setups, getting particles angles with an active target requires some work!

→ Starting with raw signal treatment (see e.g. J. Giovinazzo et al., *NIM A953, 163184 (2020))*

Time signal is distorted by the electronics (mostly shaper)

→ Tracks going towards the pad plane are strongly affected!

→ Requires response function deconvolution



Construction of the experimental response function
using GET internal pulser

Data analysis : Signal processing & Tracking

Unlike other “classic” setups, getting particles angles with an active target requires some work!

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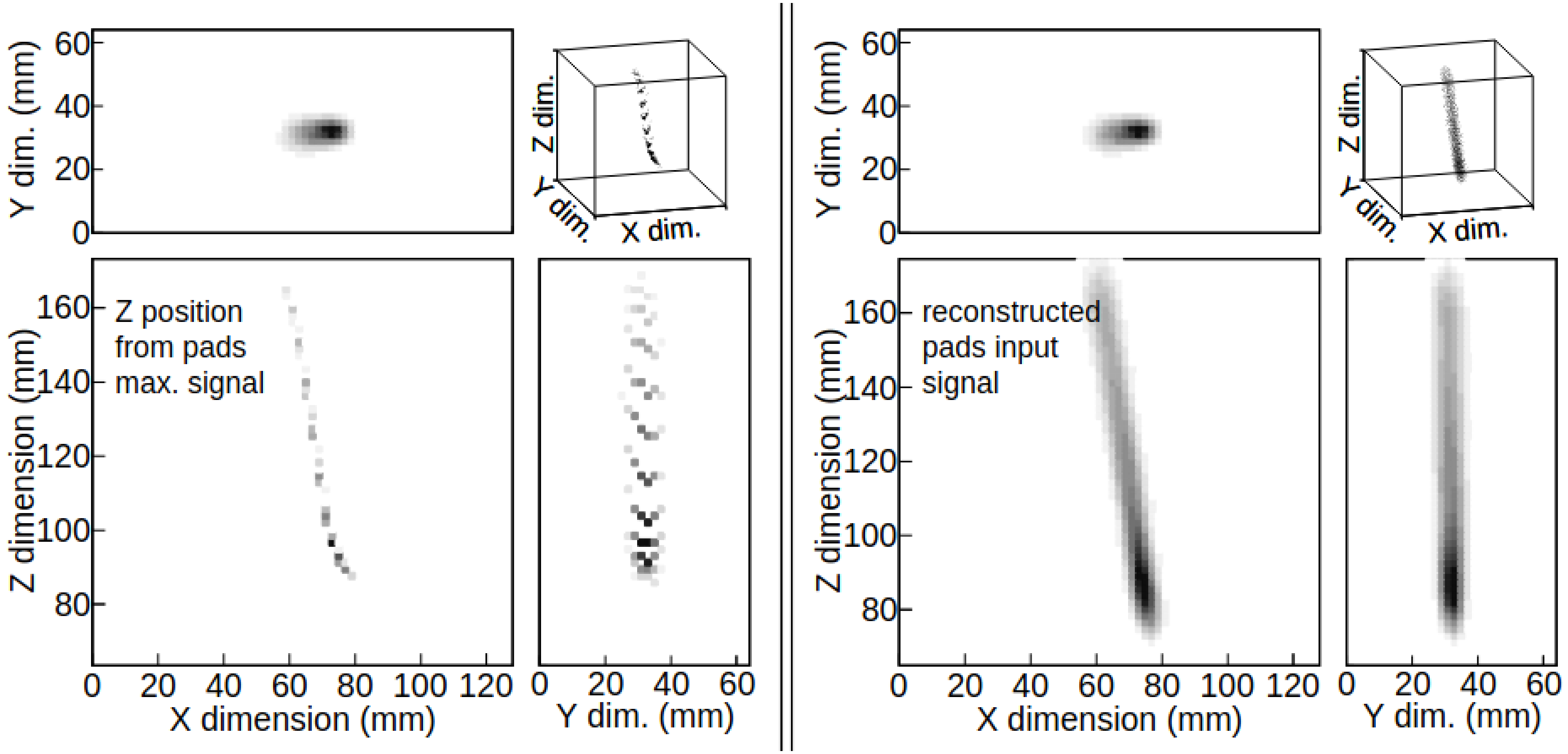


Deconvolution of physical signal

Data analysis : Signal processing & Tracking

Unlike other "classic" setups, getting particles angles with an active target requires some work!

→ Counting & fitting tracks

Novel particle tracking algorithm based on the Random Sample Consensus Model for the Active Target Time Projection Chamber (AT-TPC)

Yassid Ayyad [a b], Wolfgang Mittig [a], Daniel Bazin [a], Saul Beceiro-Novo [a], Marco Cortesi [a]

NIM A880, 166 (2018)

Automatic trajectory recognition in Active Target Time Projection Chambers data by means of hierarchical clustering

Christoph Dalitz [a], Yassid Ayyad [b 1], Jens Wilberg [a], Lukas Aymans [a], Daniel Bazin [c], Wolfgang Mittig [c]

Computer Phys. Comm. 235, 159 (2019)

Tracking algorithms for TPCs using consensus-based robust estimators

J.C. Zamora, G.F. Fortino

NIM A988, 164899 (2021)

Machine learning methods for track classification in the AT-TPC

M.P. Kuchera [a], R. Ramanujan [b], J.Z. Taylor [a], R.R. Strauss [b], D. Bazin [c], J. Bradt [c], Ruiming Chen [a]

NIM A940, 156 (2019)

Tracking algorithms for the active target MAYA

T. Roger [a b], M. Caamaño [c], C.E. Demonchy [d], W. Mittig [e], H. Savajols [a], I. Tanihata [f]

NIM A638, 134 (2011)

Proton 3D tracking and emission time from a short-lived isomer with ACTARTPC

J. Giovinazzo [a], T. Roger [b], B. Blank [a], D. Rudolph [c], H. Alvarez-Pol [d], A. Arokiaraj [e], P. Ascher [a], M. Camaaño-Fresco [d], L. Caceres [b], D.M. Cox [c], B. Fernández-Domínguez [d], J. Lois-Fuentes [d], M. Gerbaux [a], S. Grévy [a], G.F. Grinyer [f], O. Kamalou [b], B. Mauss [g 1], A. Mentana [e 2], A. Ortega Moral [a], J. Pancin [b]...M. Versteegen [a]

NIM A1042, 167477 (2022)

Partial conclusion

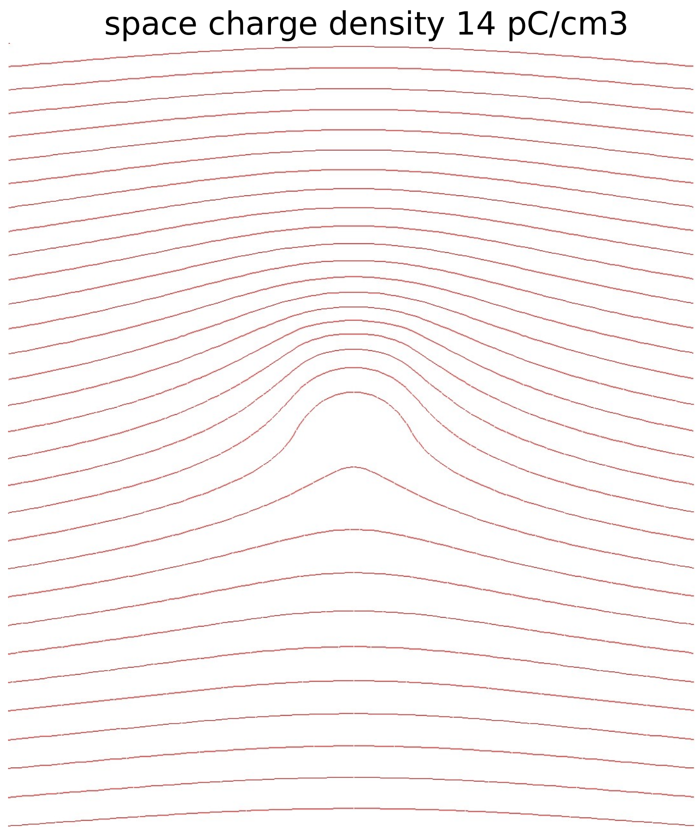
- ✓ Resonant scattering : Full reaction channel identification is possible
- ✓ Inelastic scattering : Access to (very) forward cm angles, with detection of very low energy products
- ✓ Implantation / decay : No detection dynamics problem, no beta background
- ✓ Transfer reactions : very efficient for low intensity beams
  → target thickness up to x100 compared to solid target experiments, with very limited loss of resolution

- ✗ Limited in beam intensity / beam energy deposit: the target is also the detector (gaseous = slow!)

Reactions with high intensity / heavy beams (astrophysics, fission, ...)

✓ Beam intensity (energy deposit) limit: the target is also the detector (and the detector is gaseous!)

→ Space charge due to primary ions distorting the E field

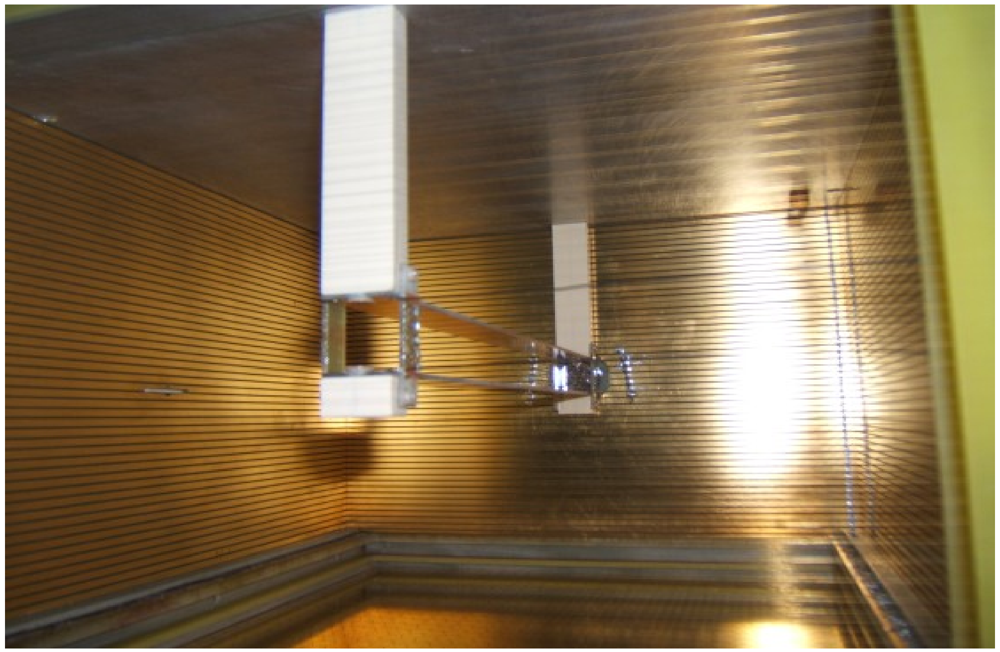


Drift E filed lines with an equivalent of 10^5 Hz of ^{136}Xe @ 7A MeV in 100 mbar iC_4H_{10}

→ Projected tracks are deformed (resulting in systematic errors in the angles)

Reactions with high intensity / heavy beams (astrophysics, fission, ...)

✓ Beam region screening with double wire field cage (MAYA / ACTAR TPC)



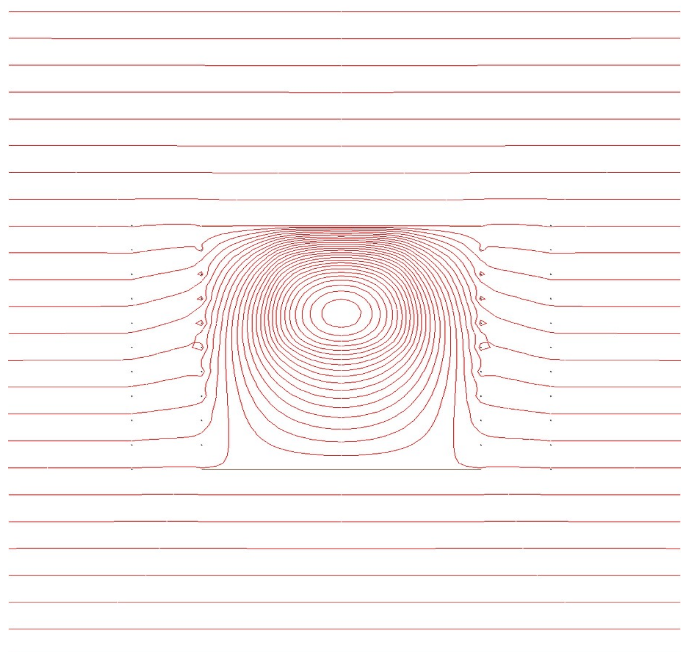
*C. Rodriguez et al., NIM A**768**, 179 (2014)*

mask with double wire planes

space charge density 140 pC/cm3

→ Equivalent: 10^6 Hz of ^{136}Xe @ 7A MeV in 100 mbar iC_4H_{10}

Simulations: R. Revenko (GANIL)



→ Successfully used to study fission of actinides created by the fusion/transfer of ^{238}U with/on ^{12}C with MAYA

C. Rodríguez-Tajes et al., Nucl. Phys. A **958**, 246 (2017)

Reactions with high intensity / heavy beams (astrophysics, fission, ...)

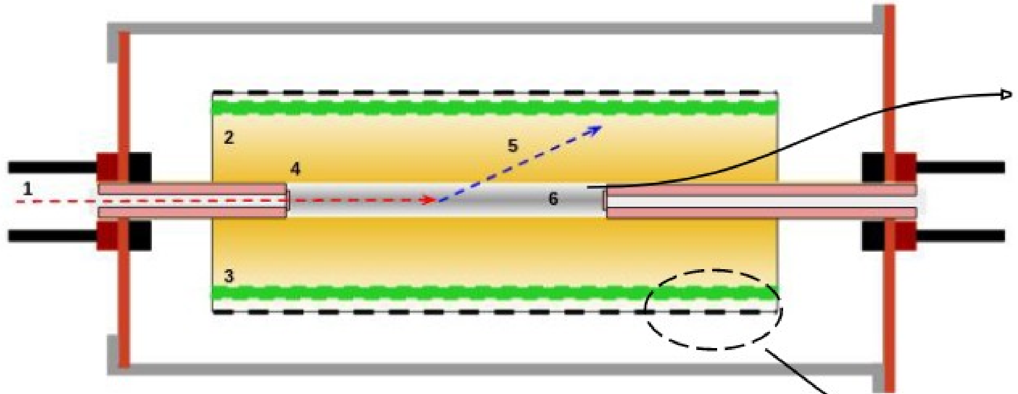
✓TACTIC (U. York - TRIUMF)

TACTIC

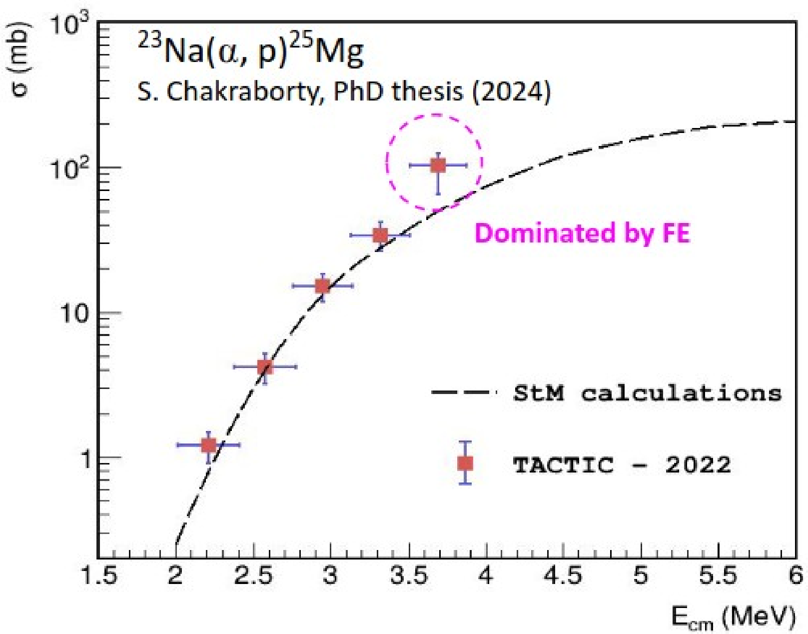
(**TRIUMF** **A**nnular **Ch**amber for **T**racking & **I**dentification of **C**harged particles)

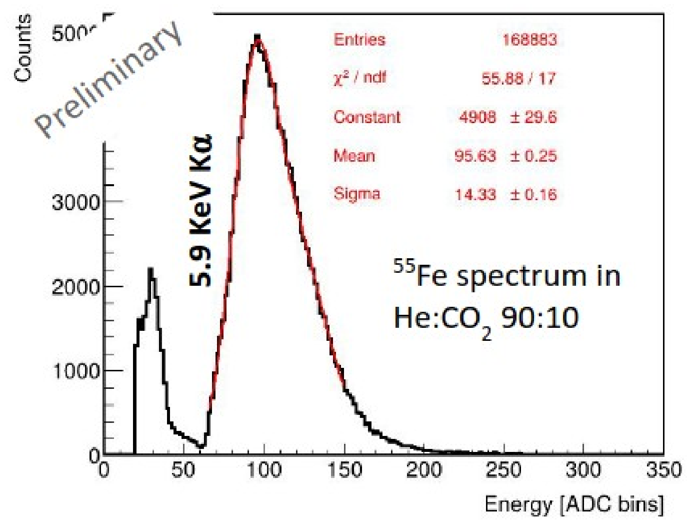
TRIUMF UNIVERSITY of York

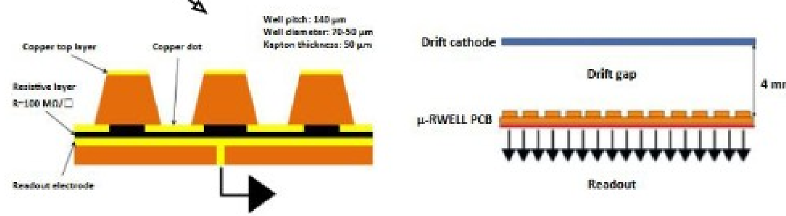
- Cylindrical Active Target TPC
- Direct measurements of nuclear reactions at astrophysically relevant energies
- **First successful CS measurement in 2022**



Cathode cage: Allows high intensity (~ 10^7 pps) RIB measurements







G. Bencivenni et al., JINST (2015)

µRWELL: Novel gas multiplication stage the "**beating heart**" of TACTIC

TRIUMF Science week 2025; S.Chakraborty

Conclusion

Wide physics program covered by Active targets & TPCs

→ Resonant scattering
→ Inelastic scattering and giant resonances
→ Transfer reactions
→ Reactions of astrophysical interest
→ Rare and exotic decays (2p, β2p, …)
→ Transfer-induced fission
→ … !

Physics program continuously extended thanks to continuous technical developments

→ ^{3}He targets soon available (AT-TPC, ACTAR TPC, …?)
→ Other isotopic gases

Price to pay: quite complex data analysis

→ Machine learning seems promising
→ Generic & "user friendly" codes available
→ However, no generic algorithm, need case by case optimization

ACTAR TPC Collaboration