Nuclei in the Cosmos
School
2025

BEAMS, TARGETS & DETECTORS
Part II

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Layout of the lectures

Lecture I

I. **Brief Introduction**

II. Beams for Nuclear astrophysics

1. Requirements
2. How to accelerate an ion
   - Accelerator types & purpose of each type
3. Radioactive beams
   - production methods
   - examples

III. Targets for nuclear astrophysics

1. Requirements
2. Solid targets
   - Production
   - Characterization
3. Gas targets

Lecture II

IV. Detectors for nuclear astrophysics

1. Some general characteristics of detectors
2. Requirements
3. Detection systems for charged particles
   - i) Silicons detectors
   - ii) Magnetic spectrometers
   - iii) Gas detectors
   - iv) Active Gas targets

   -Functioning principle
   -What is measured
   -Examples
4. Detection systems for gamma-rays
5. Recoils Separators for heavy recoils detection

Gas targets

Gas targets are important in nuclear astrophysics, especially for reactions involving gaseous elements (like **He**, **Ne**) and when using **inverse kinematics**.

Windowed Gas Cells: Chambers filled with gas, separated from the vacuum using thin entrance and exit windows made of thin foils (e.g., Havar, Mylar, Kapton, or titanium), usually a few micrometers thick.
Typical pressures of a few mbar to several hundred mbar.

- ☺ Simple design.
- ☺ Easy to control gas pressure and target thickness.
- ☹ Window degradation under heavy beam irradiation.
- ☹ Energy loss and straggling in window foils
- ☹ Background reactions from the windows

Windowless Gas Targets: Use differential pumping systems to isolate a high-pressure gas region from the vacuum beamline
- gas is injected as a narrow jet into the beamline.
- Extended gas cells – longer regions with gas

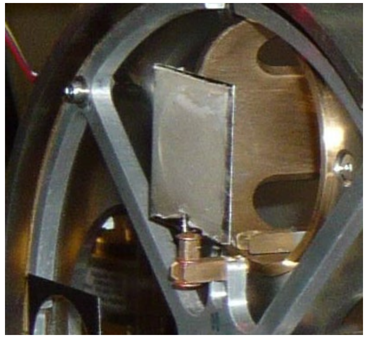
- ☺ No energy loss from window foils.
- ☹ Require complex differential pumping.
- ☹ Beam energy loss and spread in gas must be carefully characterized.
- ☹ Target thickness may vary along the beam path.

Recirculating Gas Systems: used especially for expensive isotopically enriched gases like ^{15}N,^{22}Ne,^{3}He, etc.
The Gas is continuously recirculated through the target and purification system. Used with windowless or closed gas cells.

- ☺ Saves rare/expensive gas.
- ☺ Maintains constant pressure
- ☹ Adds complexity (seals, valves, purifiers).

Targets for measurements in inverse kinematics when using radioactive beams

H targets for (p,γ) & (p,α) studies or D for (d,p), (d,n) transfer reactions



Solid CH_2 or CD_2 target: - easy to handle
- dx ~ 50 – 1000 μg/cm^2

But: non uniformity, carbon and deuterium contaminations

Cryogenic solid targets : - no carbon contamination
- more at/cm^2 for similar energy loss

But: not easy to handle,

^{4}He targets for (α,γ) studies & ^{3}He targets for (^{3}He,d) transfer reactions:

Window-confined gas target:

- high concentration (depending on pressure) **But:** Background induced by reactions on entrance and exit windows

Solid implanted target:

- easy to handle **But:** - low concentration (10^{15} -10^{17} at/cm^2) & Sputtering (He loss under irradiation)

Cryogenic solid or liquid targets - more at/cm^2 for similar energy loss than in gas

But: sophisticated **cryogenics** system (liquid helium supply, temperature control…), background from the windows

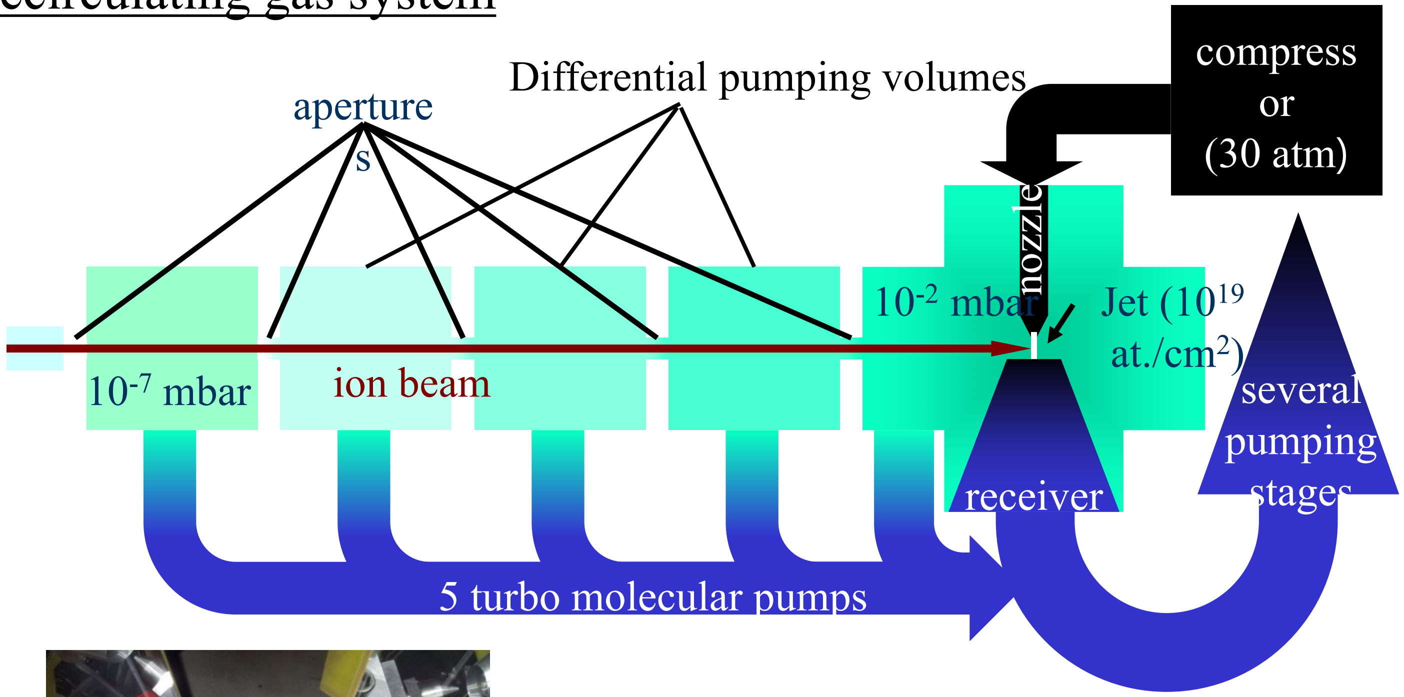
Windowless ultra jet gas target:

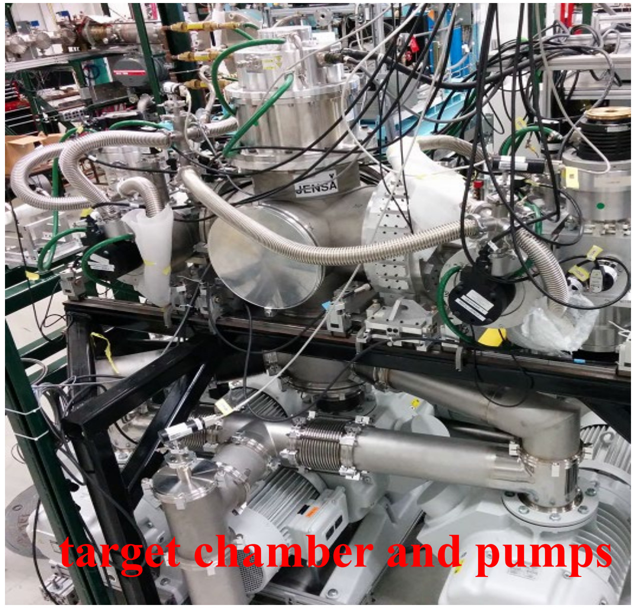
-high concentration 10^{19} at/cm^2 (e.g **JENSA**) **But:** need of differential-pumping system with high pumping speed

- no contamination, no degradation

Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target

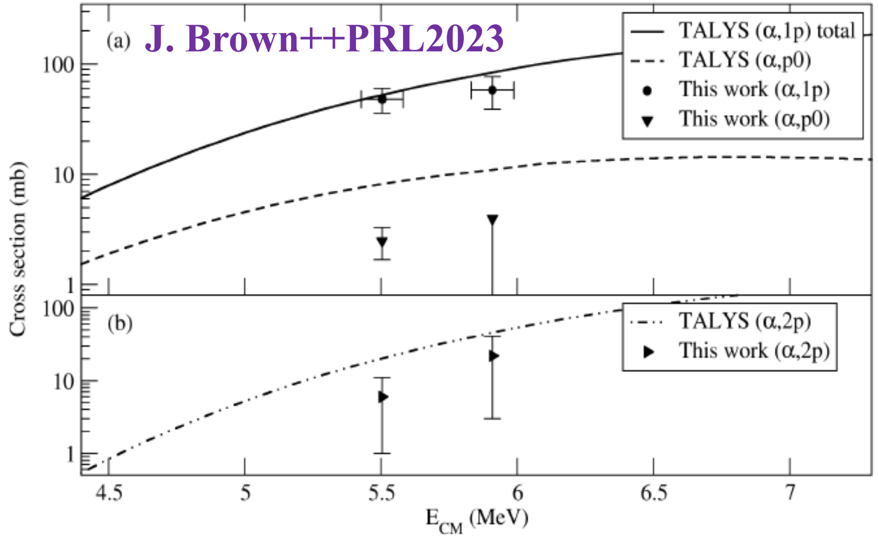
Recirculating gas system



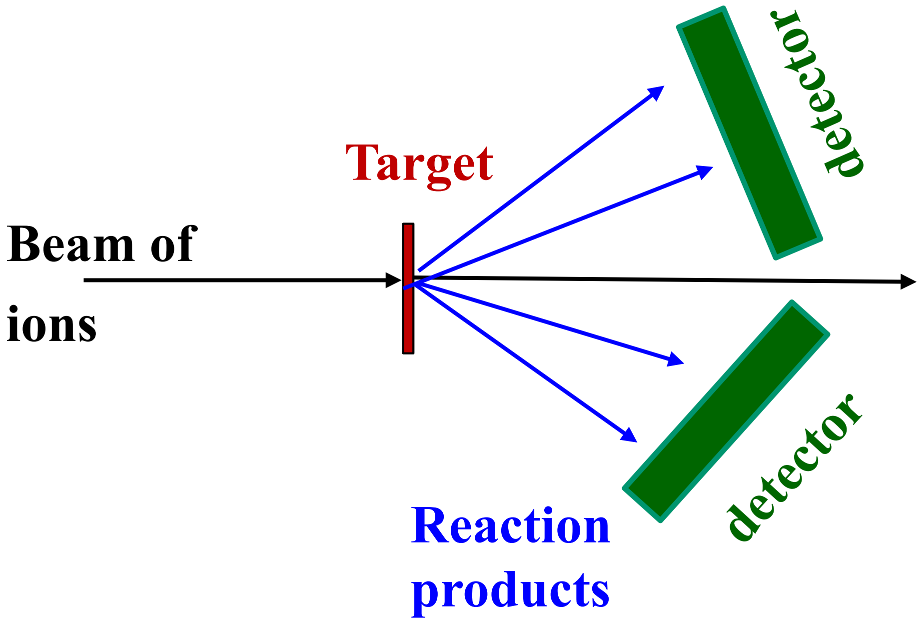


- First direct measurement of cross-section using **JENSA** target, ORRUBA Si detectors & low energy & reaccelerated radioactive beam @ NSCL: $^{34}Ar(\alpha,p)^{37}K$ for X-ray burst studies

Beam intensity~(2-8)×10^3 pps

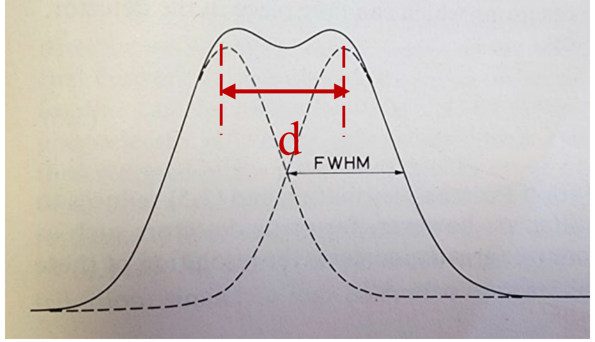


Detectors for Nuclear Astrophysics



Some general characteristics of detectors

- **Energy resolution FWHM**



R = FWHM (Full With Half Maximum)/E= $2.35\sigma/E = \Delta E/E$

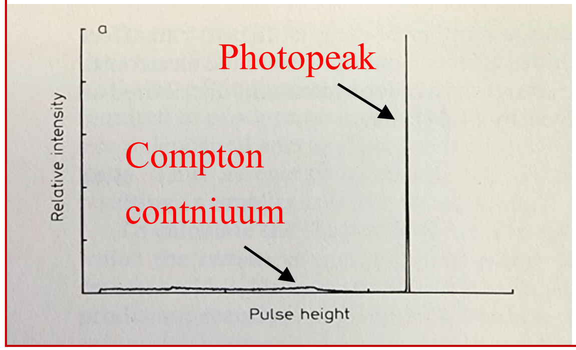
→ Two peaks are considered as resolved when **d > FWHM**

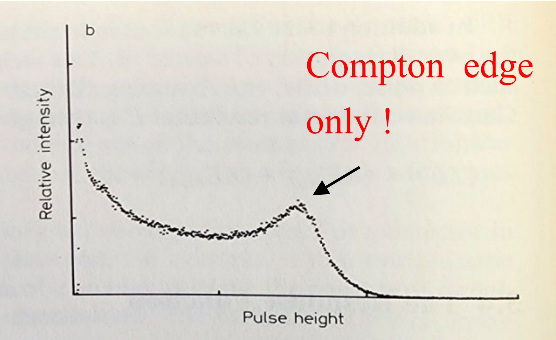
→ Example: For a γ-ray with E=1 MeV NaI detector : R= 8-9%
HpGe detector: R=0.1%

- **Response Function :** Pulse height and shape observed from the detector when it is bombarded by a given radiation at a given energy

Response function for a 661 keV γ-ray in:

HpGe detector	NaI scintillator





- **Time Response:** Time between the arrival of the radiation and the formation of an output signal

GOOD timing: signal quickly formed in a sharp pulse almost vertical rising flank ⇒ a precise moment in time can be marked by the signal → important for Time-Of-Flight measurements

W. R Leo, Techniques for nuclear & particle physics

Some general characteristics of detectors

- **Efficiency:** $$\varepsilon_{Tot} = \frac{\text{Events registred}}{\text{Events emitted by the source}} = \varepsilon_{int} \times \varepsilon_{geom}$$

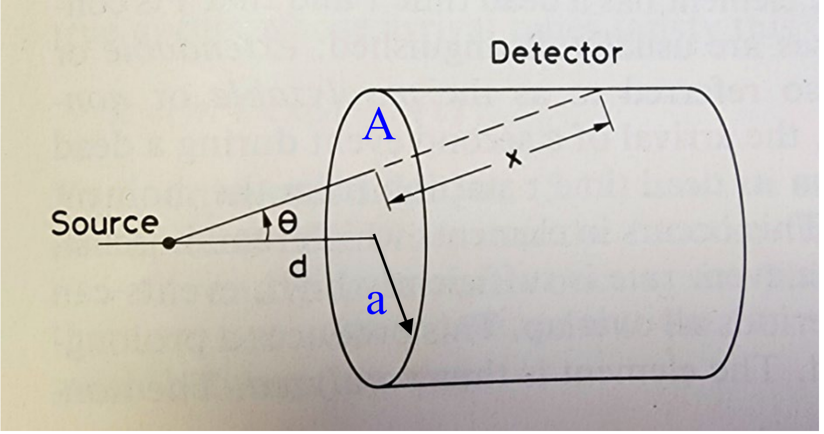
$$\varepsilon_{int} = \frac{\text{Events registred}}{\text{Events impinging on detector}}$$

depends on the radiation type, material,…

- ~100% for charged particles
- Low to moderate for γ-rays
- few -50 % for neutrons

$$\varepsilon_{geom} = \frac{d\Omega}{4\pi}$$

fraction of solid angle: pure geometry



$$d\Omega = \int \frac{\cos\theta}{r^2}\, dA = \frac{A}{d^2}$$

for d >> a (radius)

MonteCarlo simulations are needed for complex geometry …

Example of simulation package tool for nuclear physics:

nptool

A Matta et al 2016 J. Phys. G: Nucl. Part. Phys. 43 045113

Detection requirements for Nuclear Astrophysics

In case of direct measurements with stable beams: low cross sections → low yields → poor signal-to-noise ratio

⇒ **Requirements:** Improving the signal-to-noise ratio

⇒ High γ-ray, charged particle & neutron detection efficiency
⇒ Reducing background (noise) → perform **coincidence** measurements (LENA, STELLA,…) , **recoil mass separator** (ERNA, **DRAGON…**, and/or go **underground** (**LUNA**)

In case of indirect measurements (e.g. transfer reactions) with stable beams:

⇒ **Requirements:** Energy resolution to disentangle the various populated states of interest

⇒ **magnetic spectrometers**

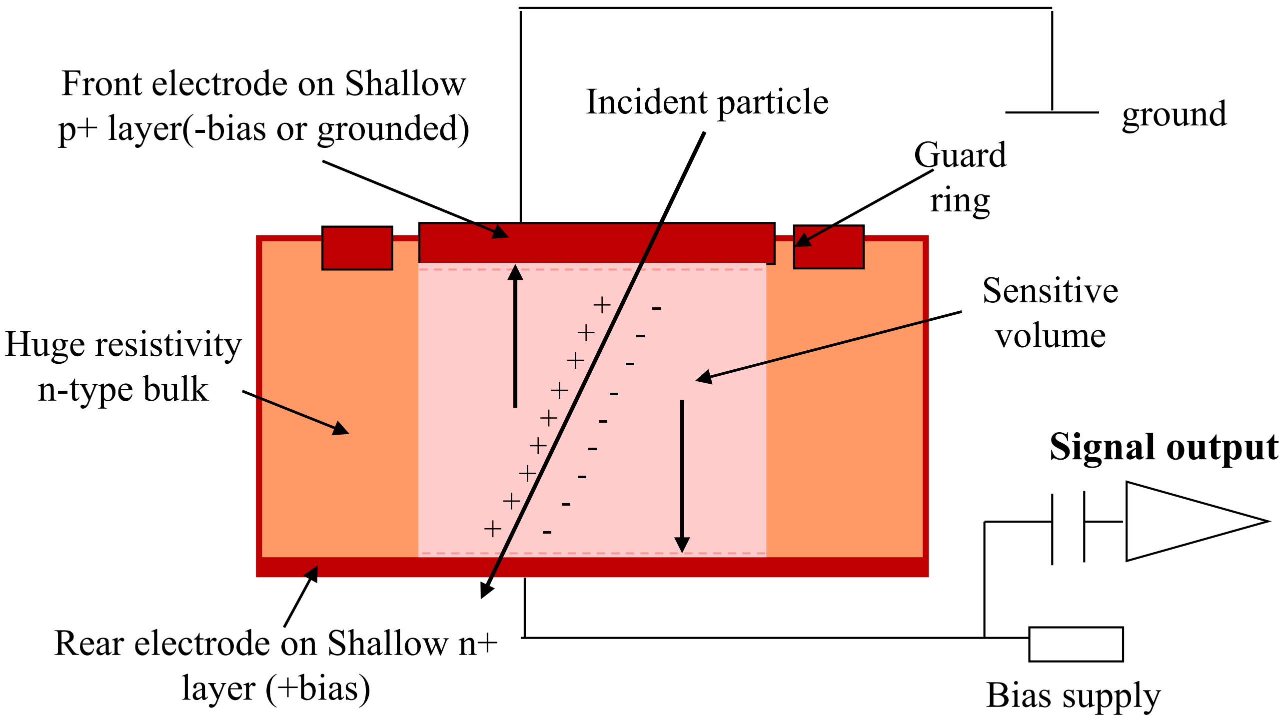
In case of direct or indirect measurements with radioactive beams: low beam intensities (≤ 10^6 pps)

⇒ **Requirements:** Increasing statistics while maintaining good energy resolution

⇒ large solid angle & efficient particle & γ-ray detection setups
→ for charged particles: - Large area, highly segmented silicon strip detector arrays: **MUST2,** ORRUBA, SHARC
- Solenoidal Spectrometers with ancilliaries (silicons) : **HELIOS** (ANL), ISS (Isolde)
- Active targets : **MUSIC**, **ACTAR-TPC**, ANASEN, AT-TPC
→ for γ-rays: Need 4π coverage: **GRETINA/GRETA, AGATA**
→ for heavy recoils : **recoil mass separators (DRAGON, SECAR,…)**

Charged particles detection: Silicon detectors

- Significant number of charge carriers are generated as a result of ionizing radiation. (3.6 eV/pair)
  => good energy resolution (< 1%)
- Widely used in nuclear physics for :
  - Particle identification
    → ΔE-E technique, E-ToF, Pulse Shape Analysis PSA
  - Energy measurement
  - Position measurement (e.g strip detectors)



- The energy loss of a charged particle through matter is given by the well-known Bethe-Bloch equation (for the stopping power):

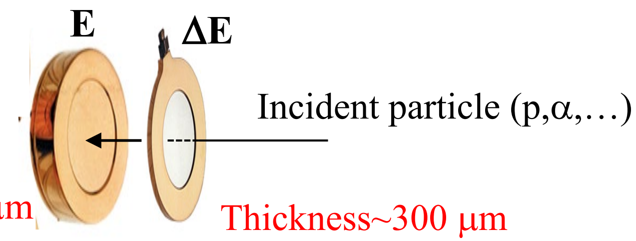
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Fon non relativistic cases: $\left\langle -\frac{dE}{dx} \right\rangle \sim \frac{mz^2}{E}$

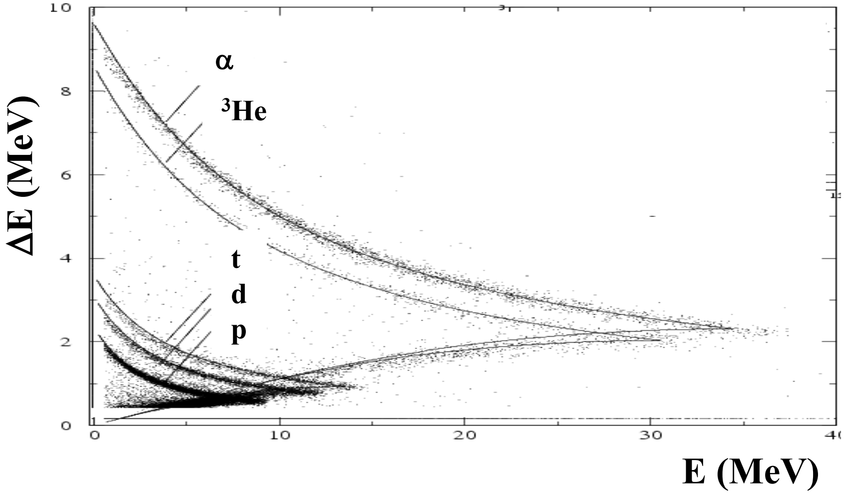
The most important ingredients are:
Z atomic number of absorber
A atomic mass of absorber
z charge number of incident particle
m atomic mass of incident particle
E ~ kinetic energy

ΔE-E particle identification technique

- Two detection layers are required; particles must pass through the first layer and be stopped in the second



- By plotting the energy loss (ΔE) measured in the first detection layer against the residual energy (E) measured in the second layer

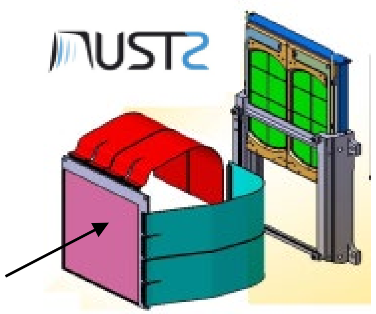


→ Identification in charge & mass of the detected particles

$$\left\langle -\frac{dE}{dx}\right\rangle \sim \frac{mz^2}{E}$$

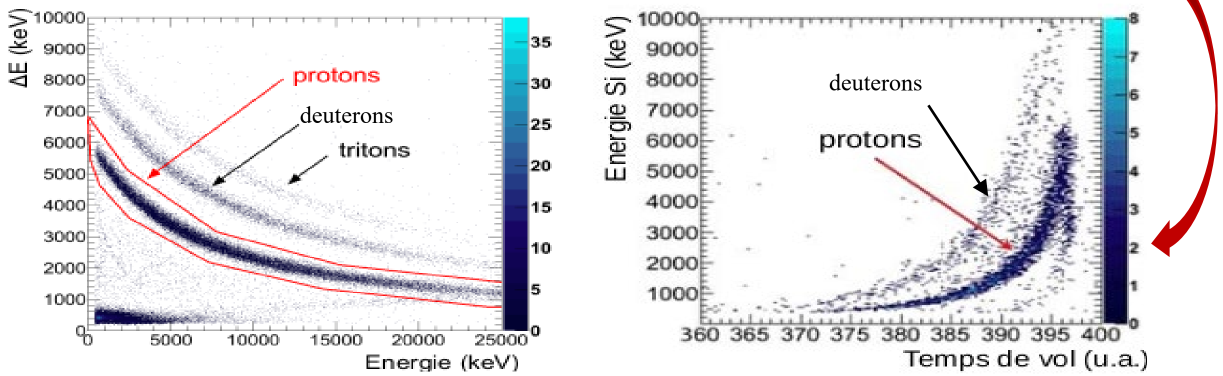
E-ToF (Time of Flight) id technique

- Can be performed with a single detection layer
- For particles that stop within the detector, the measured energy $E = mv^2/2$ => E-ToF correlation is sensitive to the particle's mass.
- Achieving precise ToF measurement requires a long flight path



First layer: **DSSD** (double sided strip detector) (300 μm, 128 strips in X & Y)
Second layer : **SiLi** (4.5 mm)

$E_{protons}$ < 6 MeV stop in DSSD ⇒ identification via E-ToF



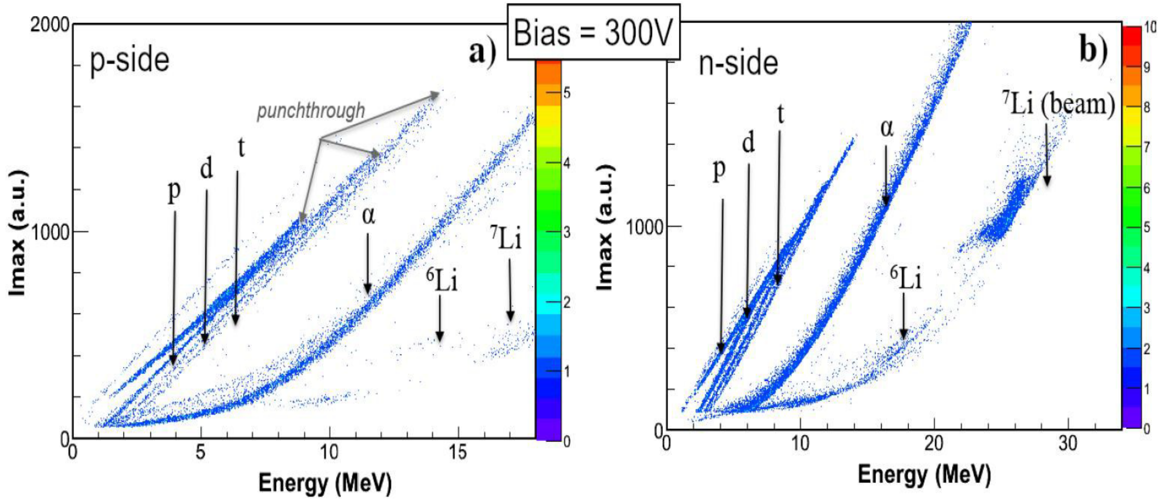
→ Study of ^{60}Fe(n,γ) ^{61}Fe reaction via d(^{60}Fe,p)^{61}Fe transfer reaction

Giron et al, PRC2017

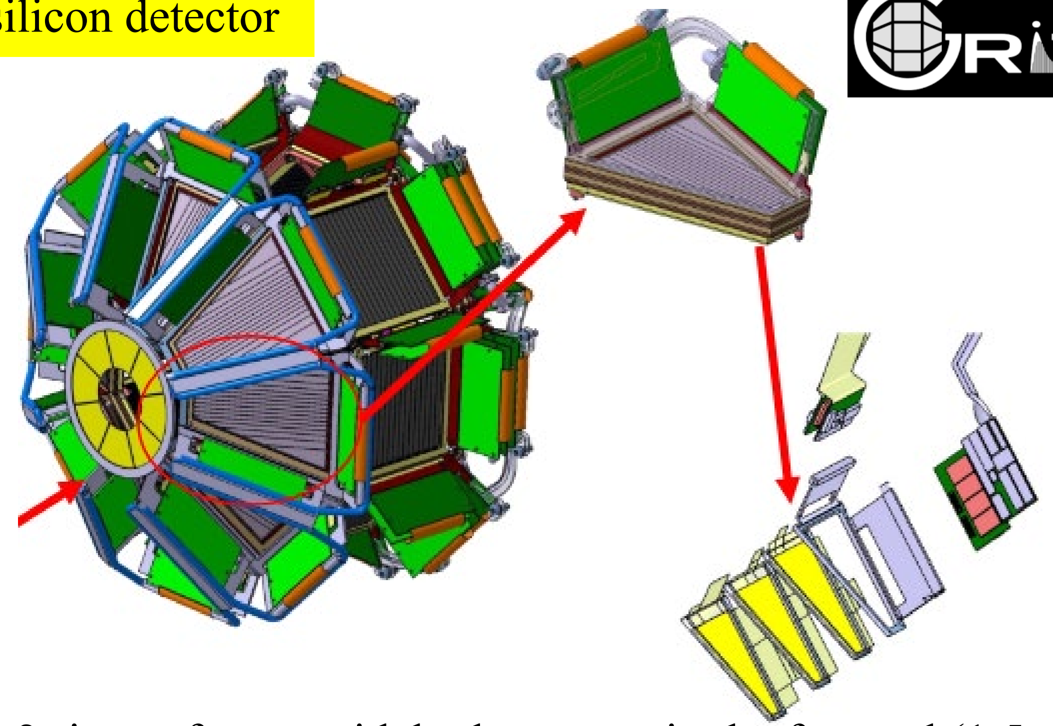
Silicon detectors: Pulse Shape Analysis technique

- Particles with different Z & A induce different signal shapes in the detector ⇒ particle identification is obtained by correlating the deposited energy with one of the pulse shape parameter- such as the signal rise time, decay time or the amplitude of the current signal Imax)

- Will be used in the **next generation** silicon detector array **GRIT** (Granularity, Resolution, Identification, Transparency) for particle identification



4 π silicon detector



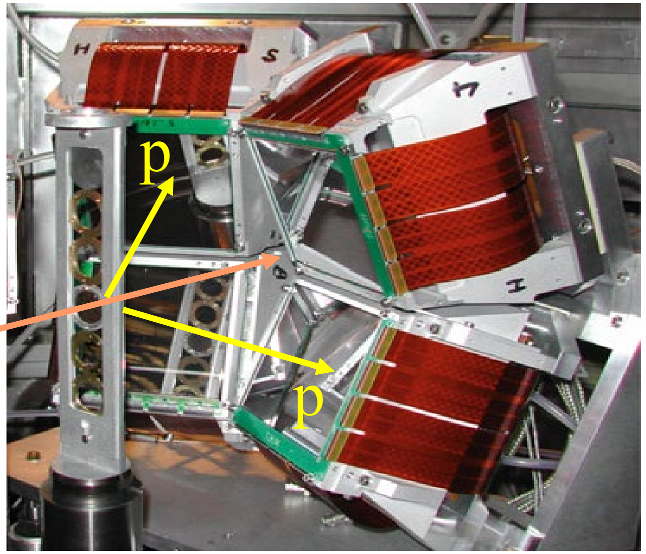
- 2 rings of trapezoidal telescopess in the forward (1.5 mm thick DSSSD, 128 strips in X & Y) and backward direction (500 um thick, 32 strips in X & Y)
- 1 ring of square telescopes at 90 degrees

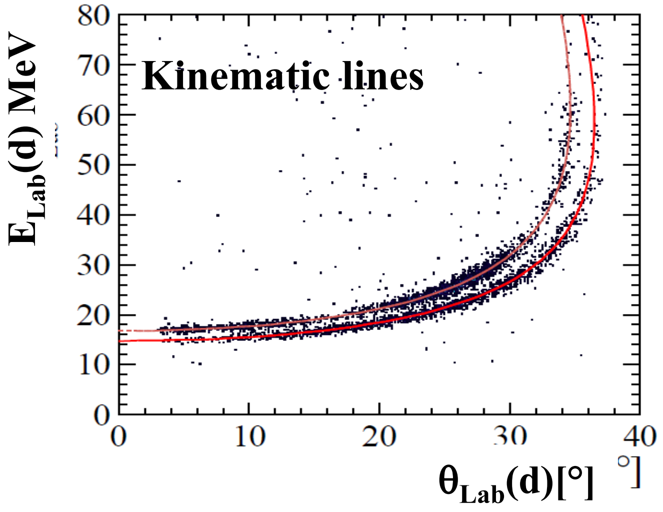
Highly Segmented Silicon detectors

- Useful for reaction studies with radioactive beams (low beam intensities)
- Measurement of **energy** & **ANGLE** of the emitted particles in one experimental setting

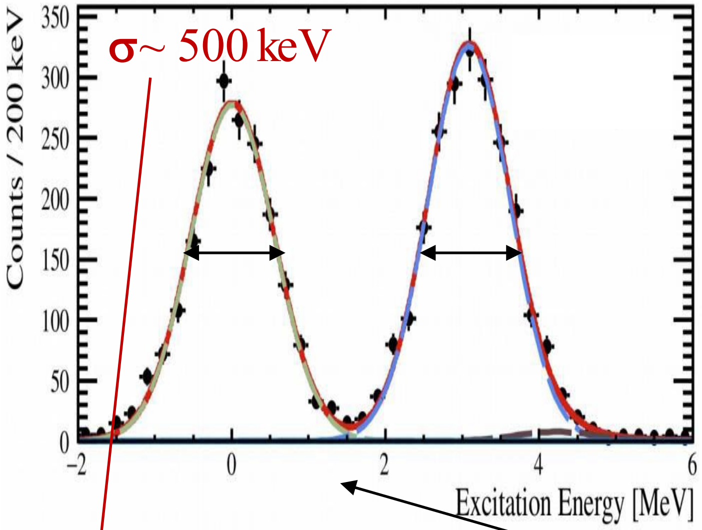
Eg: transfer reaction **^{37}Ca + p⟶ d+^{36}Ca** ; the detected particle is the deuteron

DSSD (300 µm, 128 strips in X & Y)

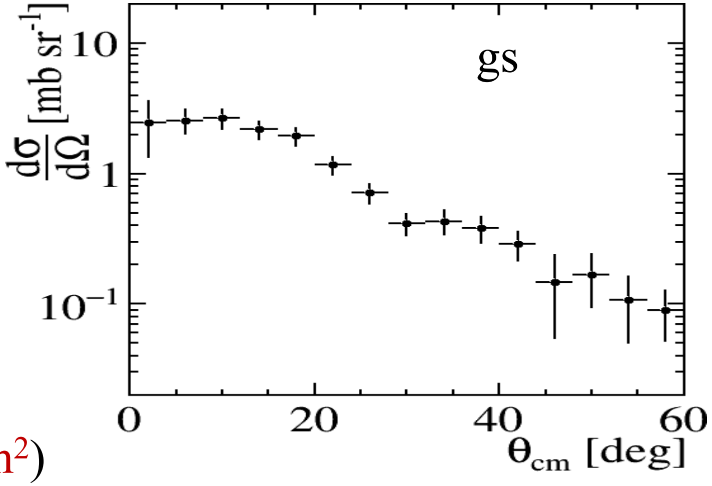




From (**E_{Lab}(d), θ_{Lab}(d)**→Reconstruction of the excitation energy spectrum of the nuclei ^{36}Ca by the missing mass method **A. Michalowicz, Kinematics of nuclear reactions**



→ By fitting by slice of θ_{cm} ⇒ dσ/dΩ for each state)



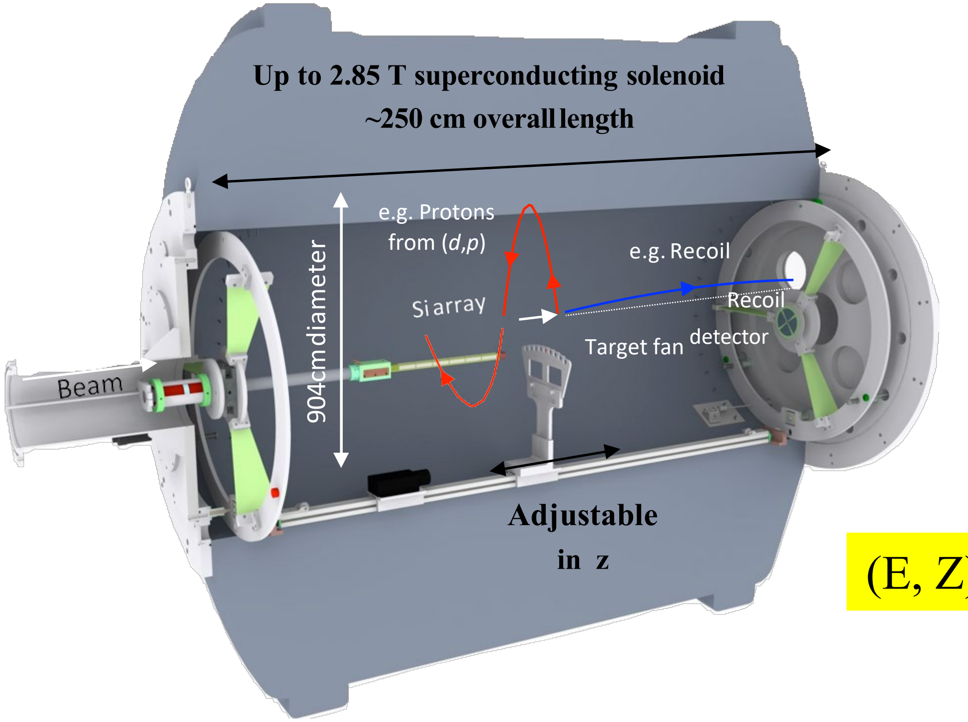
L. Lalanne et al PRC2022

σ(DSSD/MUST2) ~15 keV
for an alpha of 5 MeV

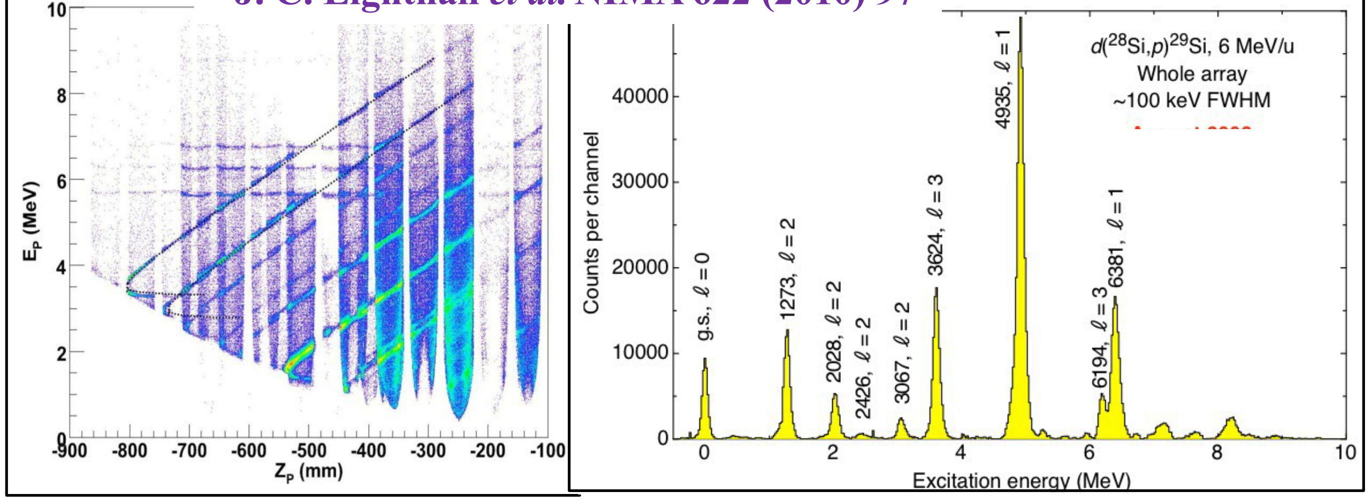
Excitation energy resolution depends strongly on target thickness (used CH_2= 9 mg/cm^2)

Silicon detectors in Solenoidal spectrometers: HELIOS @ANL

Helical Orbit Spectrometer



J. C. Lighthall *et al.* NIMA 622 (2010) 97



(E, Z) measuremnt → θ → Ex

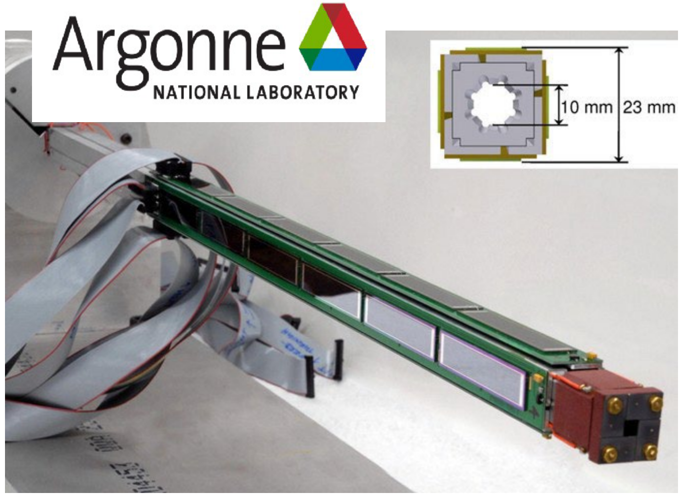
Acceptance depends on:

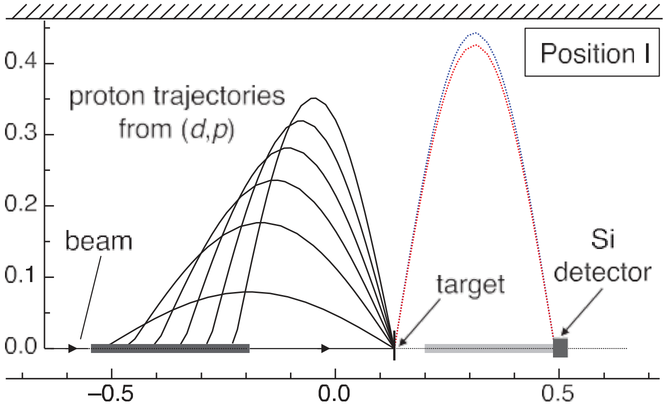
array length, target-array distance and field.

e.g. d(^{28}Si,p) @ 6 MeV/u, B=2.0 T,

each detector 21 msr, total 0.50 sr

- Square barrel of 6 Position Sensitive Detector per side 700µm
- resistive division active area 9mm × 51mm
- Total Silicon length ~300 mm
- 42% solid angle coverage

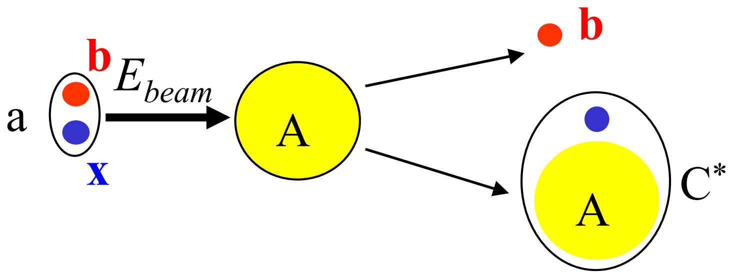




Charged particles detection: Magnetic spectrometers for indirect studies (e.g transfer reactions)

- From the transfer reaction **a(=x+b)+A** $\longrightarrow$ **C*(x+A)+b**, we can have access to important spectroscopic parameters (Ex, $\Gamma_{c,\gamma}$, …) to calculate the reaction of interest **x+A** $\longrightarrow$ **C*** $\rightarrow$ **C+γ** / **B+c (c=p,n,α,...)**

(See Richard's lecture)



What do we measure by detecting b?

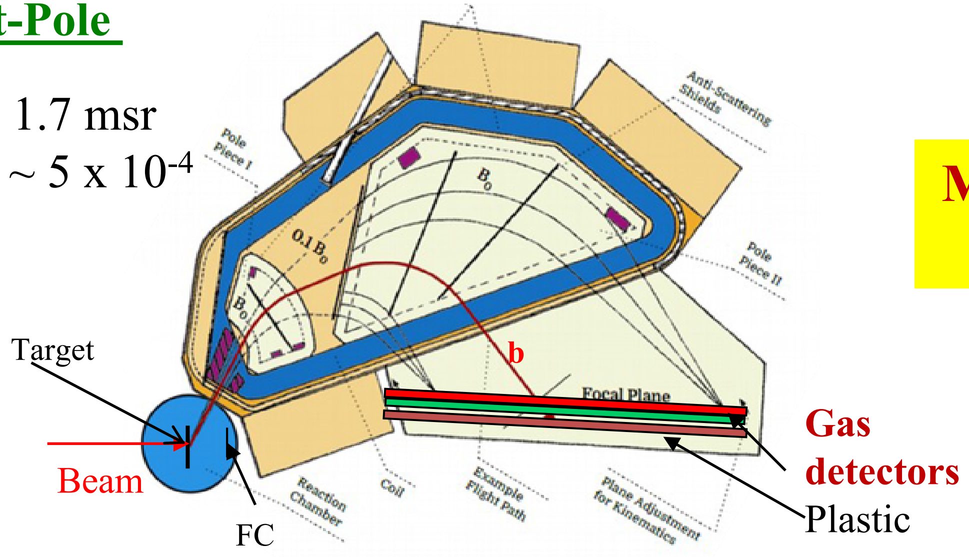
E_b, $\theta_b \rightarrow$ Excitation Level energies of C*: $\mathbf{E_x}$ (kinematics)

$\text{Yield}_b(\theta) \rightarrow$ Differential cross-sections of each state: $\mathbf{d\sigma/d\Omega}$

- Particle **b** can be detected in **silicon detectors or** in a focal plane of a **magnetic spectrometer**.
- **BUT**: **Better energy resolution (< 0.1%)** with **magnetic spectrometers**

Split-Pole

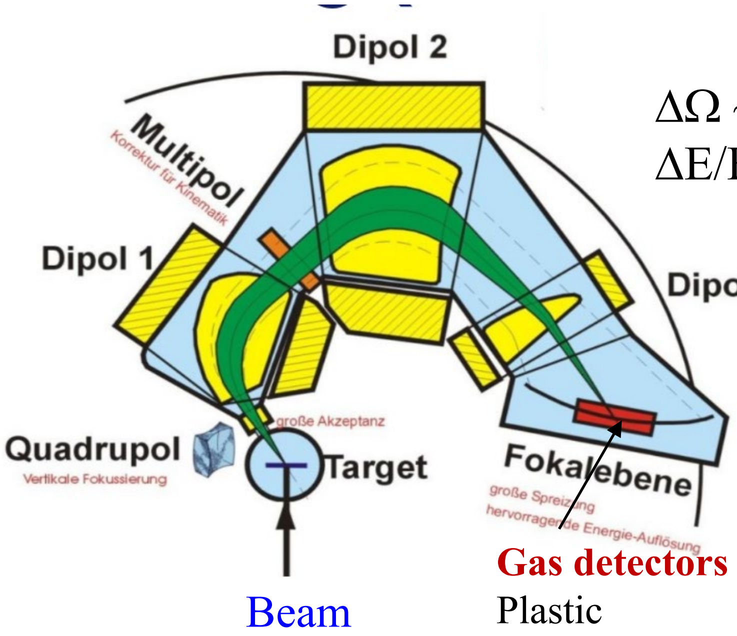
$\Delta\Omega \sim 1.7$ msr
$\Delta E/E \sim 5 \times 10^{-4}$



Magnetic rigidity
$B\rho = mv/q$

Q3D

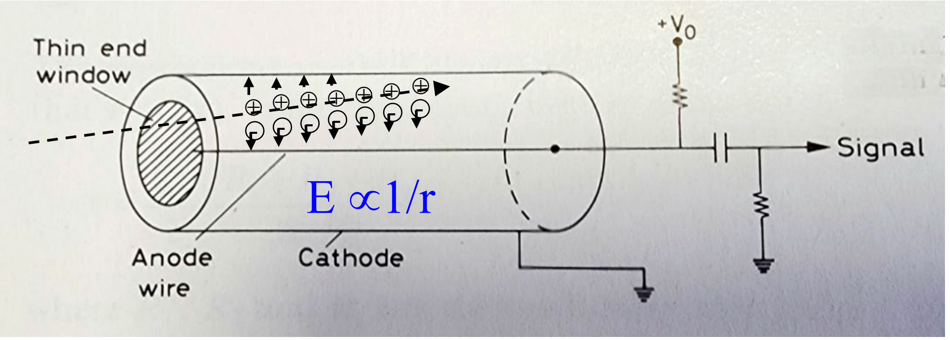
$\Delta\Omega \sim 6\text{-}12$ msr
$\Delta E/E \sim 2 \times 10^{-4}$

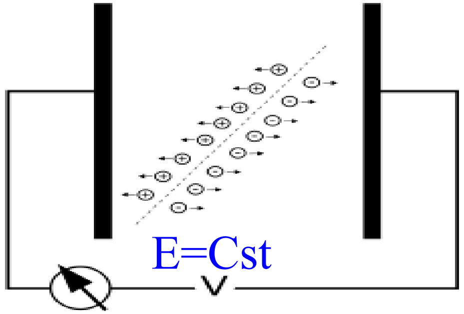


W. R Leo, Techniques for nuclear & particle physics

- **Basic principle**: - gas ionization from radiation interaction;
  - electric signal originated by ion-electron pairs collected through an electric field
- **Working regimes**: Ionisation chambers, Proportional counters, Geiger-Müller

- **Ionization chambers**: the simplest gas detector





General constituents

- Container filled with gas
- Two isolated electrodes with opposite charge
- High Voltage

Choice of gas: Propane (C_3H_8) or **Ar** (more dense) to increase ionzation probability

Detection efficiency: ~ 100% for charged particles

Signal outputs : small, need amplification

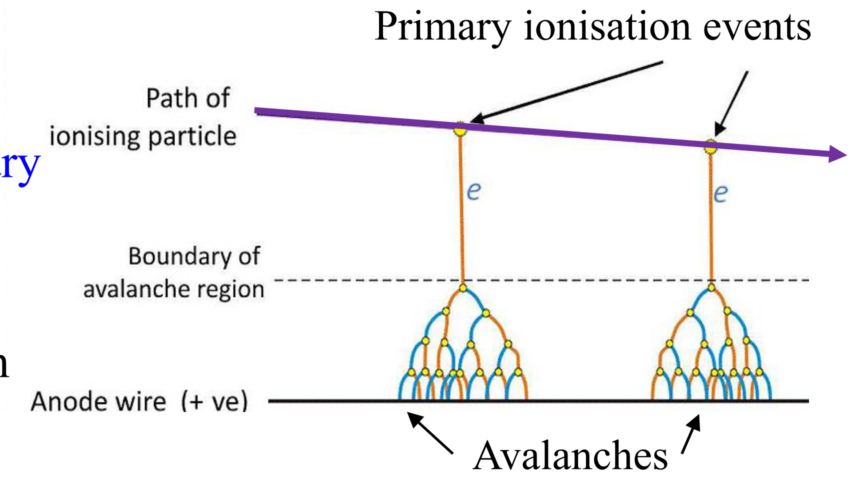
- **Proportional Counters**:

→ When the e^- get closer to the thin anode wire, the electric field strength increases

→ In a high-field region near the wire, electrons gain enough energy to cause secondary ionizations ⇒ **Avalanche Formation**

⇒ **signal output:** High - Pulse height ∝ energy of the original ionization

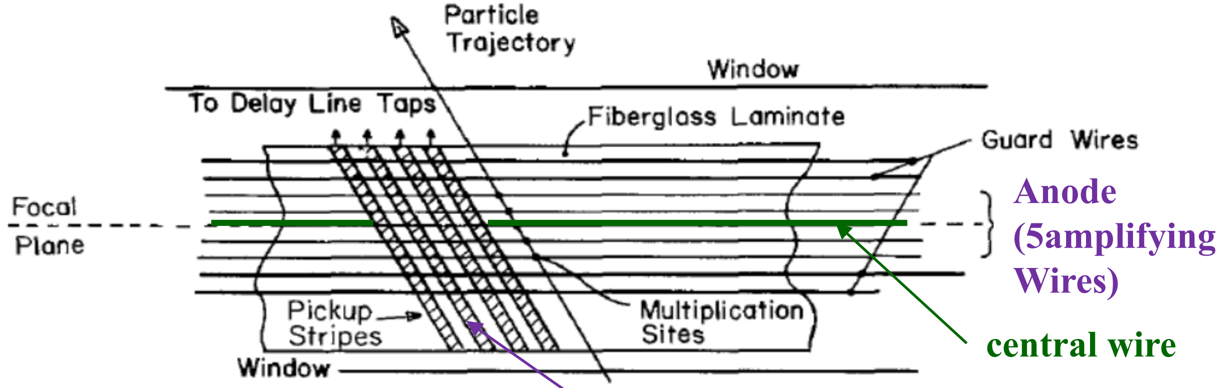
→ The applied V is high enough to create amplification via avalanches, but not so high as to cause continuous discharge (which would enter the Geiger-Müller region).



Gas detectors : Position sensitive proportional gas counter @ Split-Pole (Orsay)

- **Position measurement**
  - The charge avalanche near the anode wires induces a signal on a single cathode strip.
  - Cathode strips are connected to a delay line
  - ΔT between signal arrivals at both ends of the delay line is measured using a TAC (Time-to-Amplitude Converter)

  → Position of the particle on the focal plane ⇒ magnetic rigidity $B\rho$

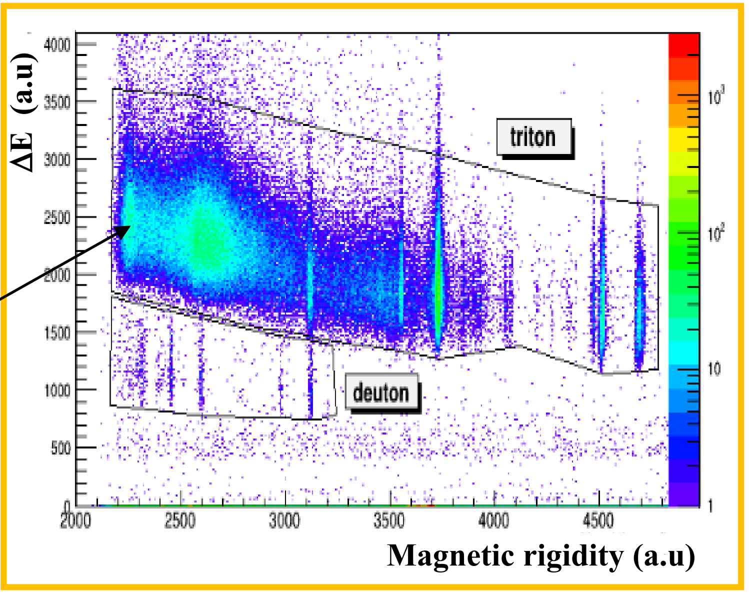


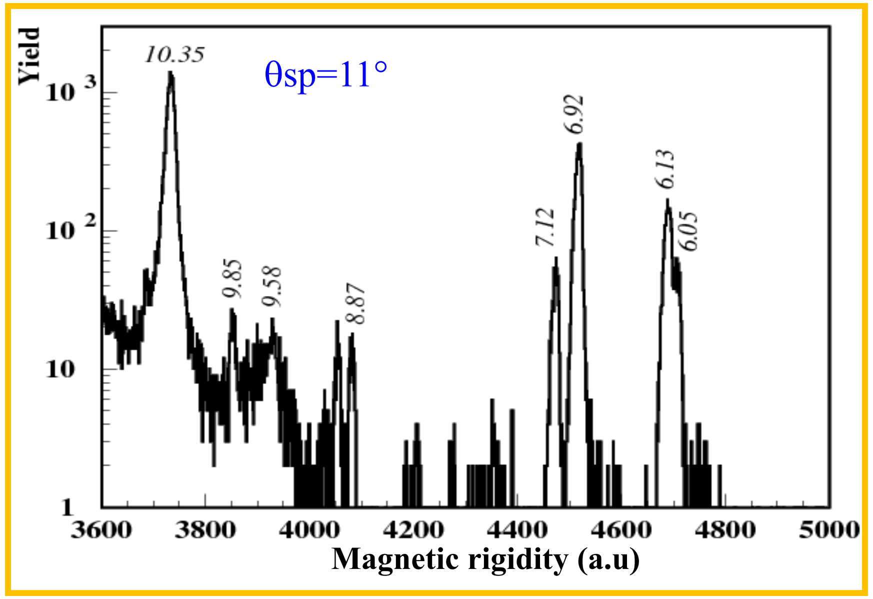
- **Energy loss measurement**
  - The central anode wire works as a conventional proportional counter.
  - Provides a measure of energy loss ΔE

- **$^{12}C(^{7}Li,t)^{16}O$ case:**

  → Indirect study of $^{12}C(\alpha,\gamma)^{16}O$

Identification spectrum





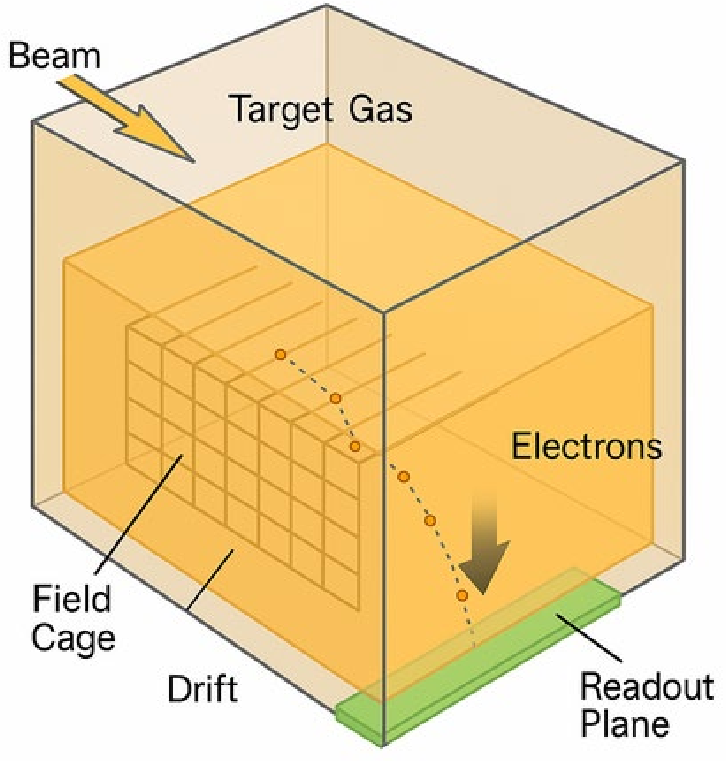
N. Oulebsir+PRC2012

Triton magnetic rigidity $B\rho$ spectrum ⇒ E_{triton}

$(E_{triton}, \theta_{triton}) \Rightarrow Ex$ (kinematics)

Charged particles detection: Active Gas targets

- The gas acts as both the target material and the detection medium.
- The key to their operation lies in tracking charged particles as they move through the gas via the ionization of the latter.
- Can reconstruct the entire reaction kinematics inside the gas volume (Time Projection Chamber (TPC)).
- Great for low-yield or exotic beam reactions
- Adjustable pressure for tuning thickness
- Often used for inverse kinematics with radioactive beams. Examples: MUSIC, ACTAR TPC@GANIL, AT-TPC at NSCL/FRIB.



Active gas target

Functioning principle: It is all about ionization & drift

When a charged particle (from the beam or a reaction product) moves through the gas, it ionizes gas atoms along its path

→ The particle creates free electrons and positive ions along its trajectory.

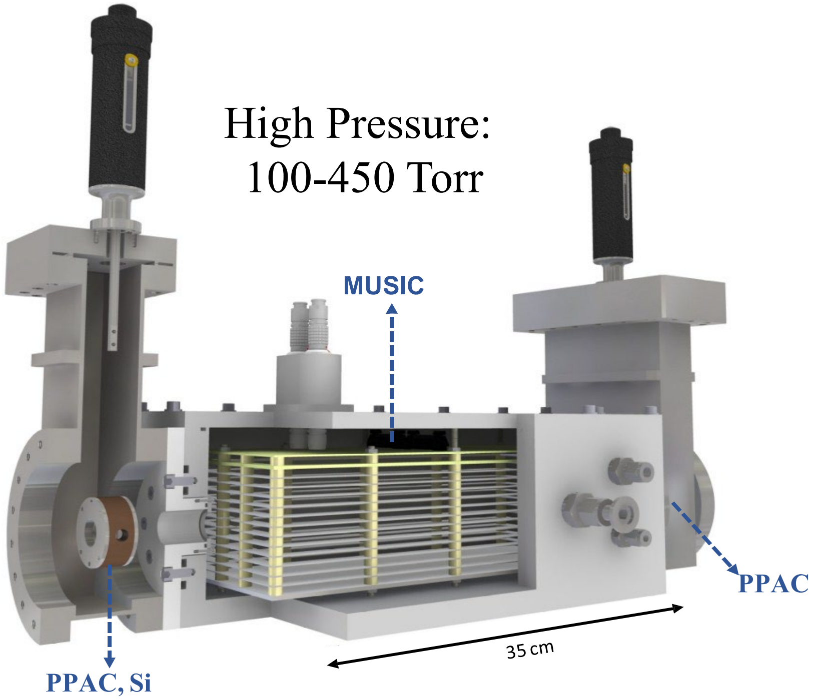
→ An applied electric field causes the free electrons to drift toward a readout plane (e.g., a pad array or wires) over microseconds.

→The drifting electrons are amplified (using e.g., Gas Electron Multipliers [GEMs], Micromegas, or multi-wire proportional chambers) and then recorded, providing a 3D reconstruction of the particle track (TPC).

Challenges: Complex data analysis and reconstruction (TPC) & limited rate capabilities (10^3-10^4 pps).

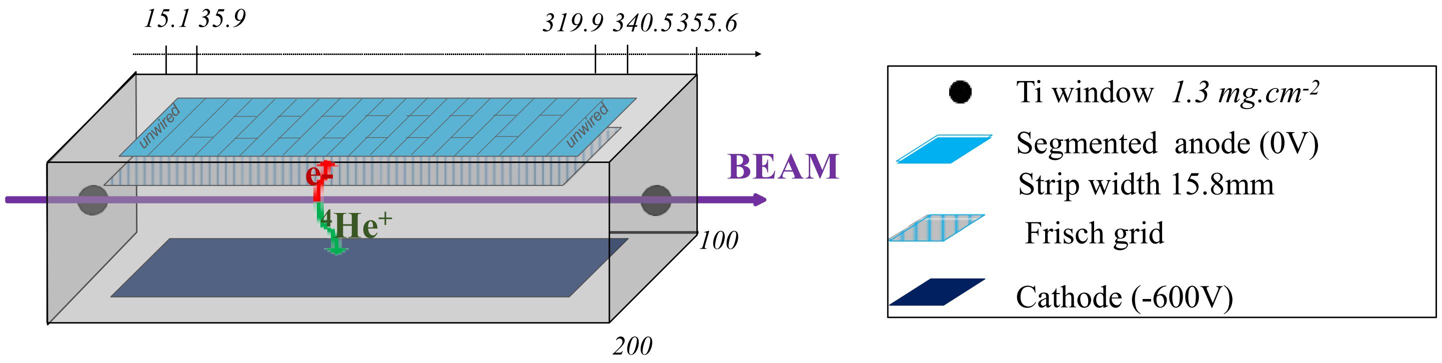
Active targets example: Multi-Sampling Ionization Chamber (MUSIC) @ ANL

- For charged particle-induced reactions studies with radioactive ion beams & stable beams at low to intermediate energies.
- A large ionization chamber filled with a low-Z gas like helium or hydrogen.
- Unlike TPCs (which track full 3D particle paths), MUSIC detector is better at measuring energy loss (dE/dx) across multiple regions (sampling layers) as the beam or recoil moves through the gas.



Parallel Plate Avalanche Counter (PPAC)
→ Beam trackers (timing, filled C_4H_{10})
Si detector
→ Calibration of the beam energy loss
→ Coincidence recoil – light particle

Anode segmentation → can measure reaction cross-sections across a wide range energies with a mono-energetic beam

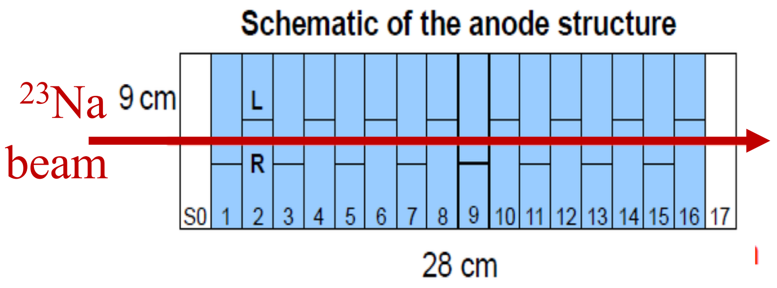


- Reaction vertex position and particle identification
- Used extensively at ATLAS and CARIBU facilities.
- Often used for (α, n), (α,p), (α, γ) key astrophysics reactions & elastic scattering studies.
- Efficient for low-intensity beams (~10^3 pps) → ideal for rare isotopes.

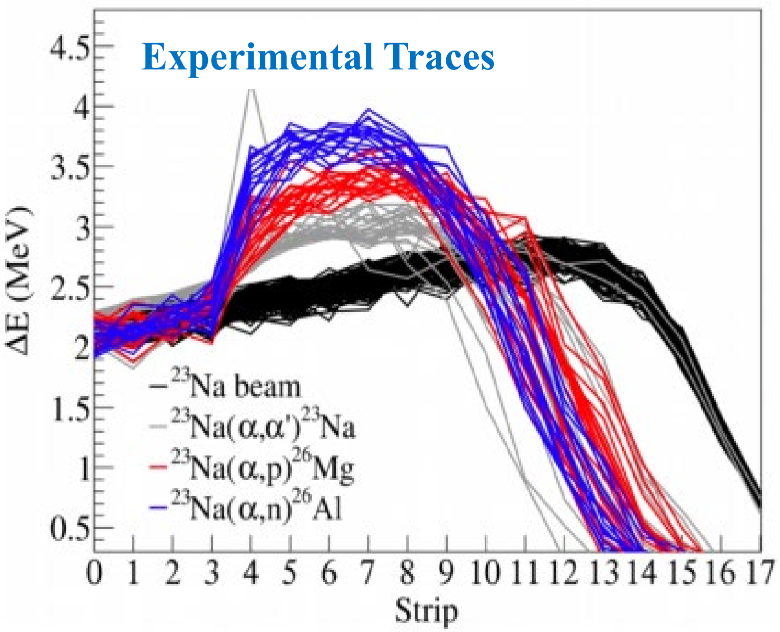
MUSIC: ^{23}Na(α,n)^{26}Al & ^{23}Na(α,p)^{26}Mg test cases

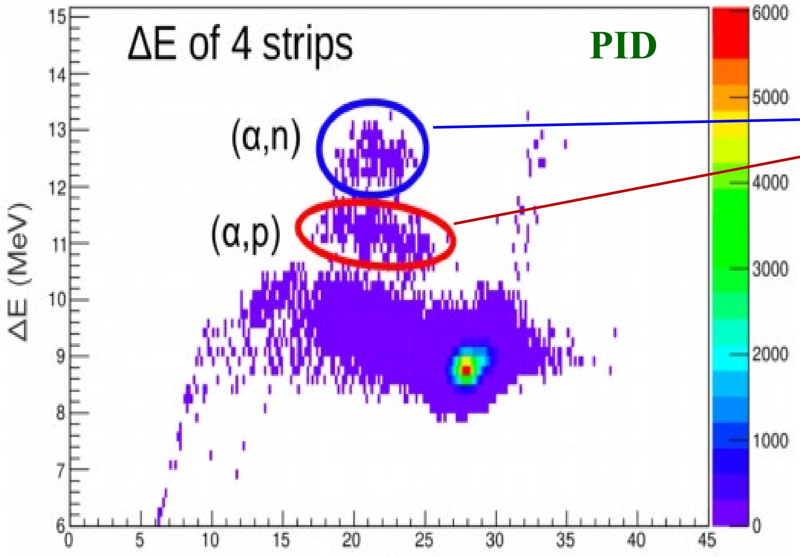
→ Have impact on ^{26}Al nucleosynthesis in massive stars

- Direct measurement of ^{23}Na+α reactions in MUSIC @ two ^{23}Na beam incident energies: 51.5 & 57.4 MeV , Pressure= 403, 395 Torr
- Detection of the heavy recoils
- Two methods to identify & quantify ^{23}Na+α reactions: with **Traces** & **PID**

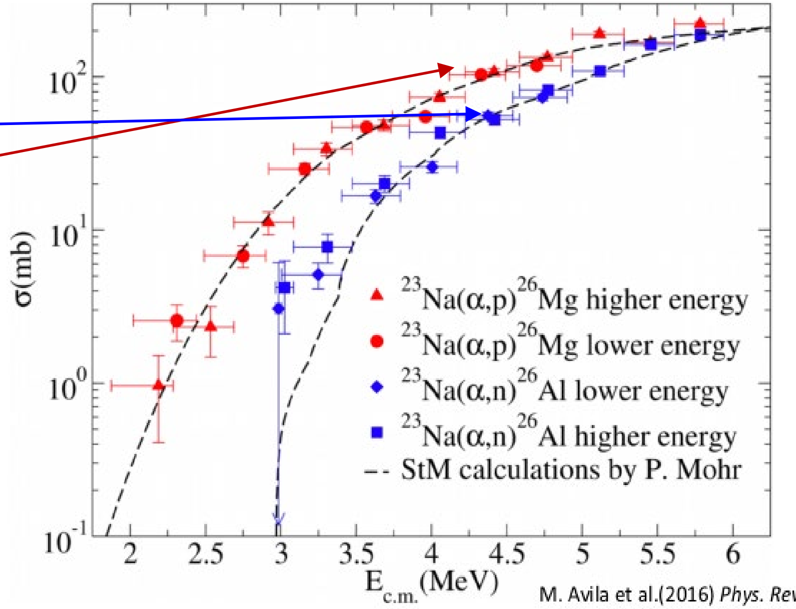


Example: Identification of events from reactions occuring in strip 4





$$E = \sum_4^{18} \Delta E_i \text{ MeV}$$



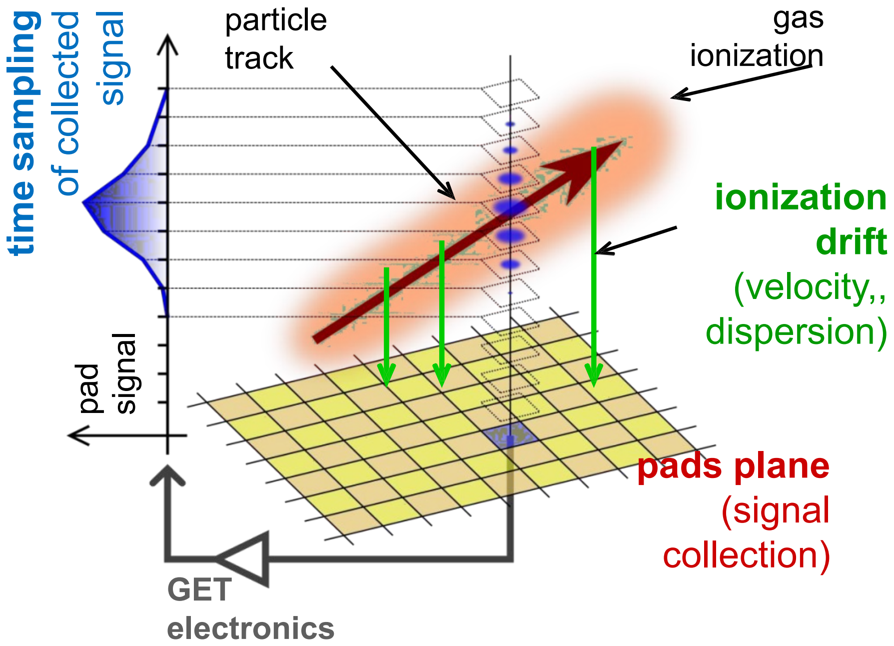
M. Avila et al.(2016) *Phys. Rev.*

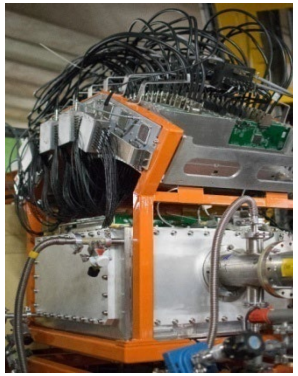
→ Better separation of the three reactions is obtained by averaging the ΔE values over the 4 strips after the interaction in strip 4

M.L. Avila et al., NIM A 85, 63 (2017)

Active target example: ACtive TARget and Time Projection Chamber (ACTAR TPC)

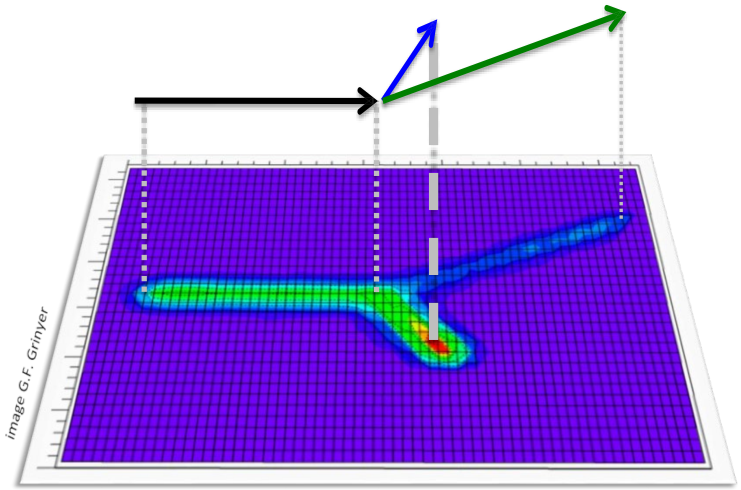
- **Key feature:** High granularity & 3D tracking capability
  → **128×128 pads** collection plane





Measures :

- Particle tracks in 3D → position, direction ⇒ emission angle
- Energy loss (dE/dx) → useful for particle identification
- Interaction vertex → can determine where the reaction occurred



pads plane (signal collection)	**TPC principle**	**time sampling of signal**
2D digitization	$z \Leftrightarrow t$	3D digitization

$$\Delta E(x,y,z) \iff \Delta E[x_i,y_j](z) \iff \Delta E[x_i,y_j](t) \iff \Delta E[x_i,y_j,t_k]$$

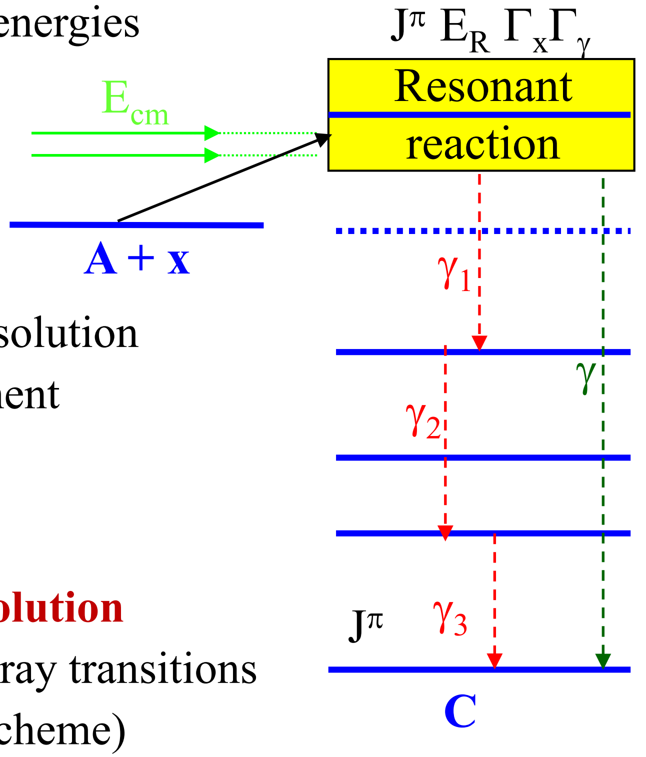
- Excitation function measurement
- Angular distribution of reaction products

γ-rays detection

A(x,γ)C resonant reaction case: States of interest are above the particle threshold and often at high energies

⇒ High γ-ray energy when decaying directly to the ground state

⇒ Low γ-ray energy when decaying via successive cascades



NO detector offers simultaneous measurement of both high-energy and low-energy γ-rays with optimal conditions

High γ-ray energy: Scintillators (BGO, NaI, BaF_2, $LaBr_3$)

→ **High efficiency**, good timing, bad resolution

→ good for total cross-section measurement

Dedicated or coupled

Arrays

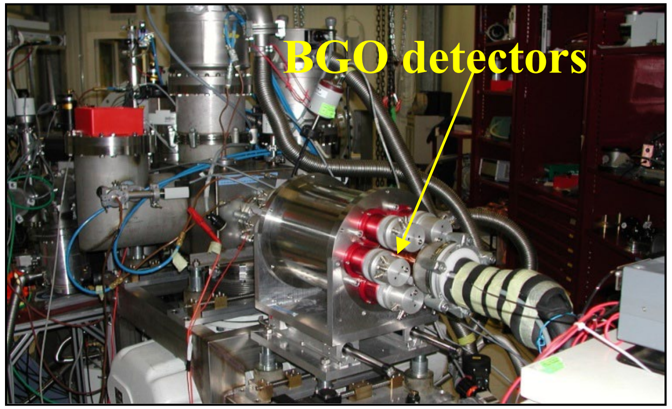
Low γ-ray energy: High purity Ge detectors → **Good energy resolution** to measure all γ-ray transitions (detailed decay scheme)

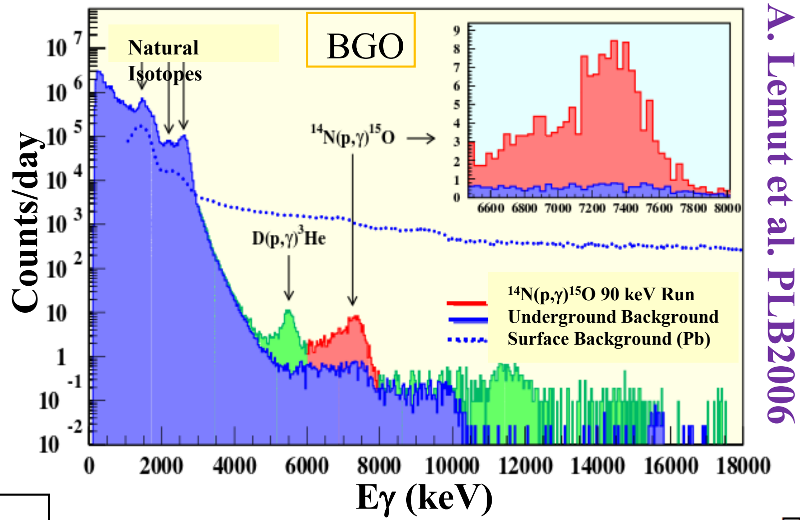
Detector	Density | Z	ΔT (FWHM)	ΔE/E @ 1.33 MeV	Volume Max	Relative full energy peak efficiency @ 1.33 MeV
BGO	7.13 | 83	~ 5.0 ns	~ 15%	> 4 dm^3	100% (ref)
NaI	3.67 | 53	~ 1.5 ns	~ 7%	> 4 dm^3	~ 75-80%
BaF_2	4.88 | 56	~0.4 ns	~11%	> 4 dm^3	~ 50-60%
$LaBr_3$	5.08| 47|	~0.3 ns	~3%	<2 dm^3	~ 85-90%
HpGe	5.32 | 32	~ 3.0 ns	~ 0.2 %	< 0.2 dm^3	~ 8-30 % (geom)

Used γ-rays detection setups: Direct measurements with stable beams

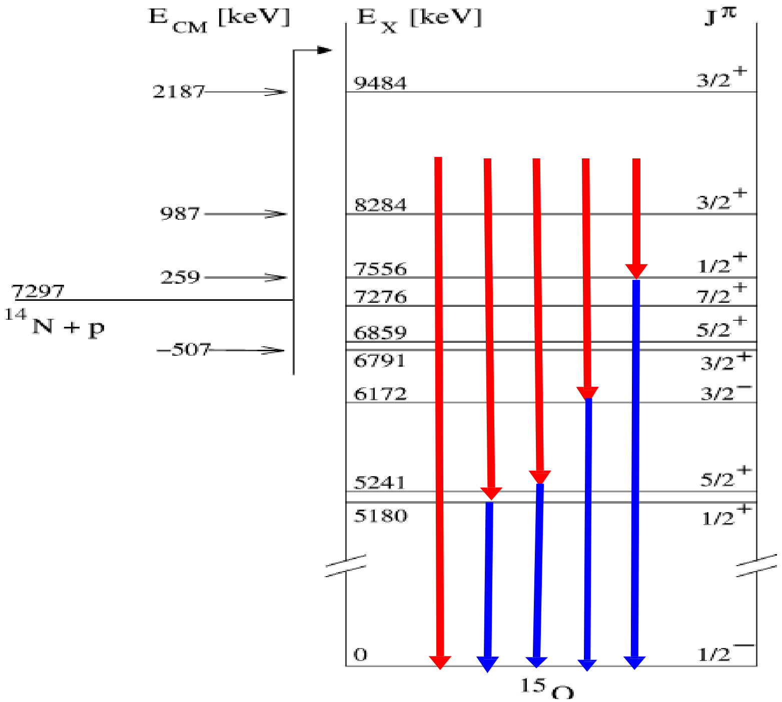
$^{14}N(p,\gamma)^{15}O$ experiment @ LUNA 400 KV: CNO solar neutrino/globular cluster age

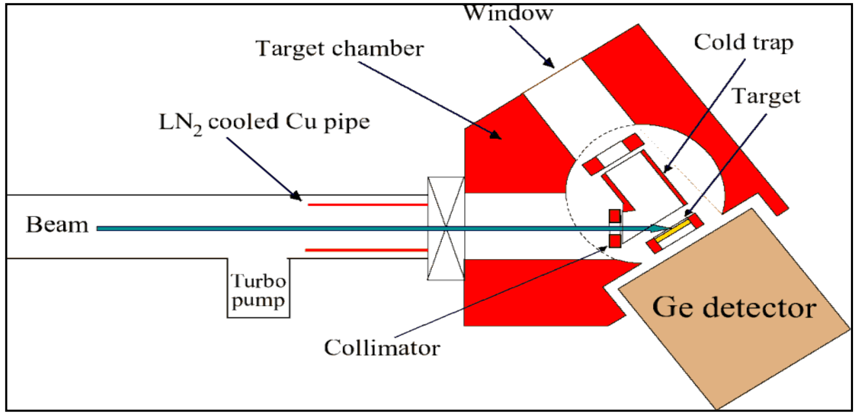
- **Low energy protons**: 70-230 keV → **4π BGO** detector+gas target:
  → Measurement of total cross section; high E_γ efficiency $\varepsilon \approx 70\ \%$ (for E_γ=7 MeV)
- **High energy protons:** 114 -367 keV → **HPGe** detectors+ solid target
  → Measurement of all γ-transitions & branching ratios , high resolution

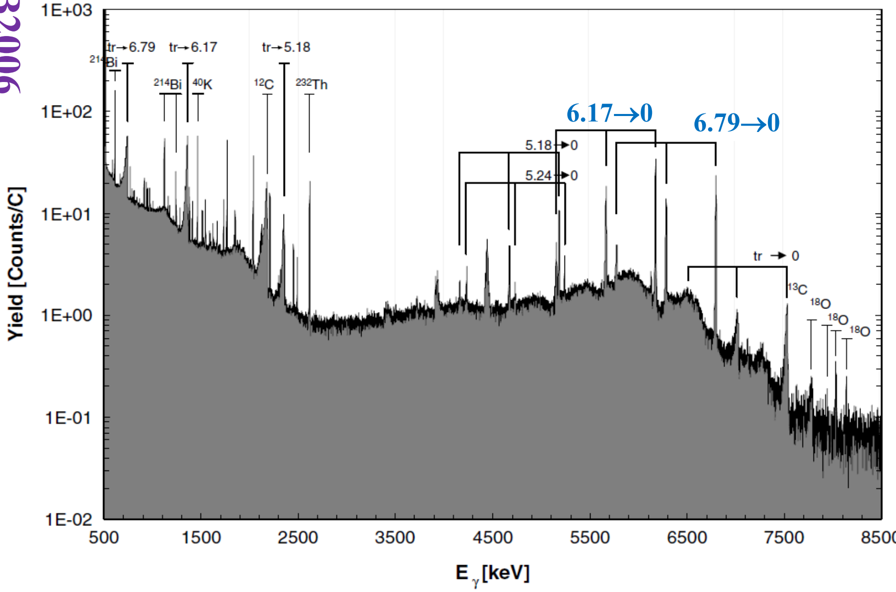




A. Lemut et al. PLB2006







G. Imbriani et al. EPJA2005

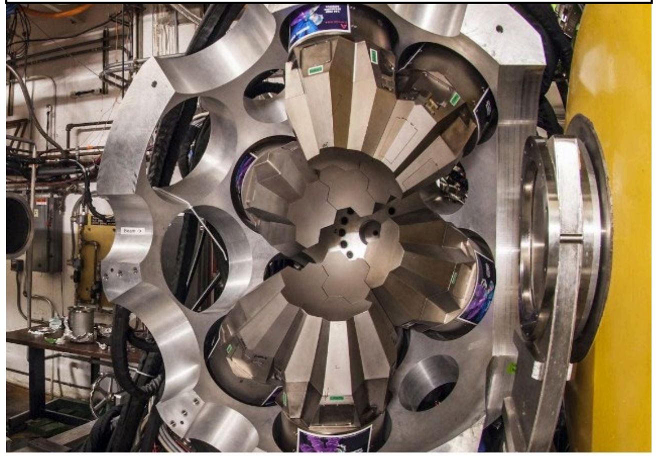
The new generation of γ-rays detection arrays

- Developped for reaction measurements at the radioactive beam facilities (FRIB, SPIRAL, SPES, FAIR,…)

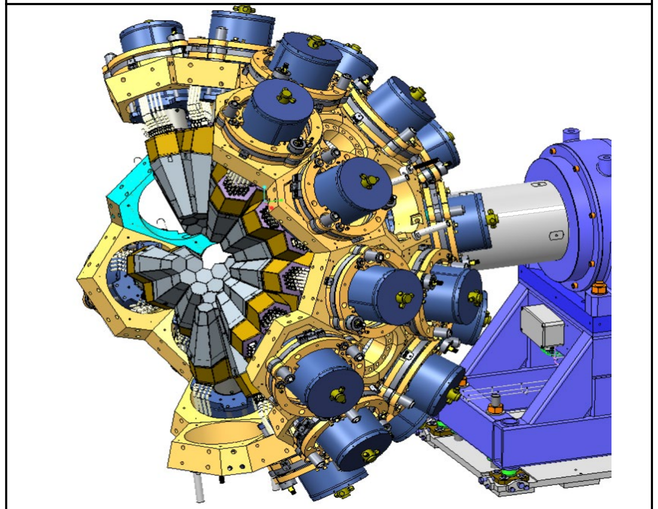
- Low beam intensity
- Large Doppler broadening
- High background (natural & beam induced)
- High counting rates
- High γ-ray multiplicities

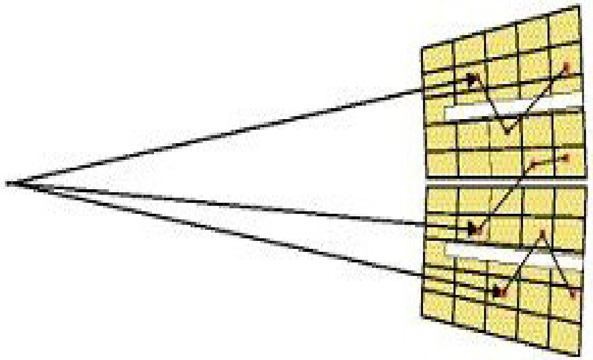
- The **new generation**: **4π array** of **segmented** large-volume HPGe crystals

GRETA/GRETINA in USA



AGATA in Europe



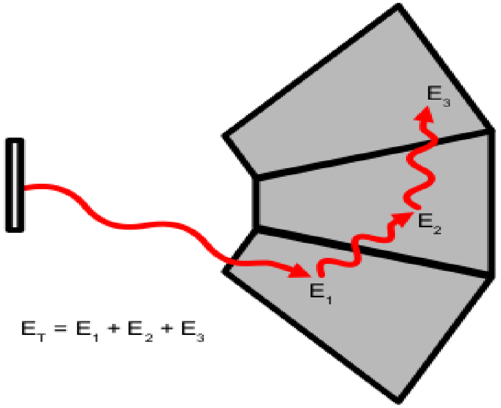


→ **Track** each gamma interaction through the crystal

→ **Reconstruct** the full energy by identifying and summing all the scattered interaction points
⇒ significantly improving the photopeak efficiency

→ **Reduce background** and **improve photopeak-to-total ratio**

→ Provide **3D localization** for **precise Doppler correction**

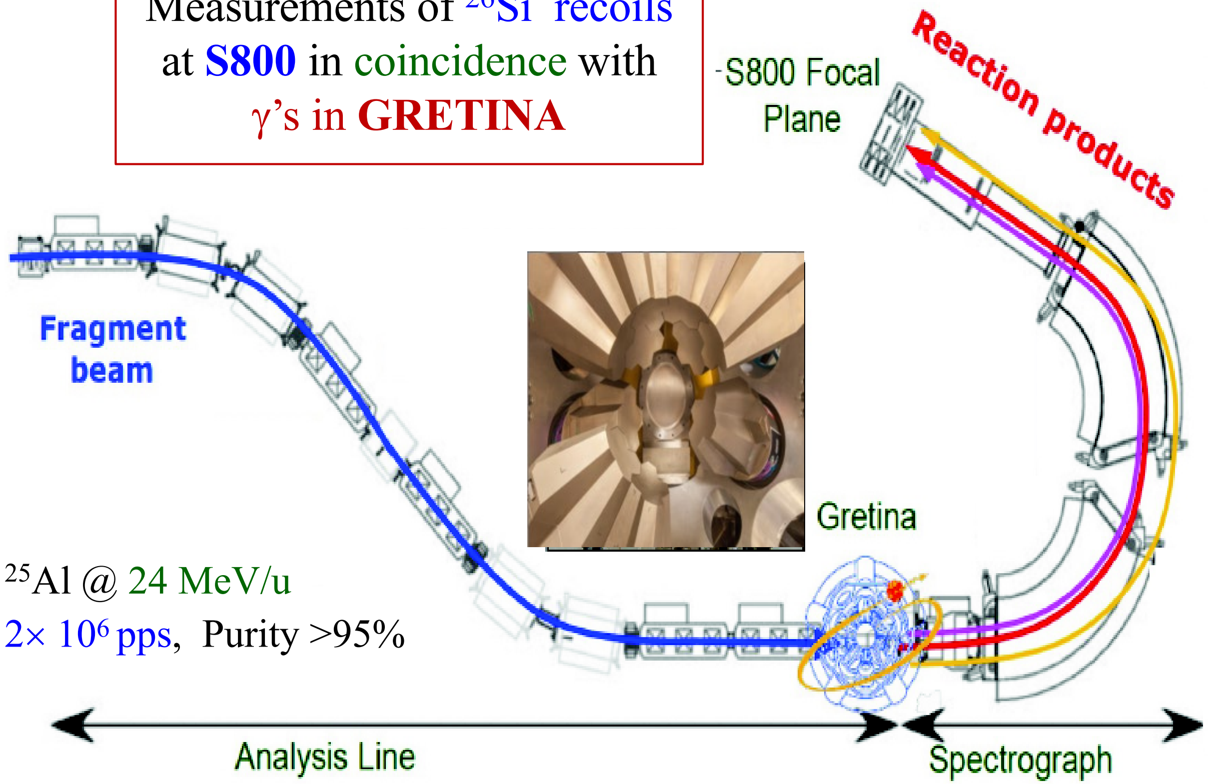


Experiment with GRETINA @ FRIB: The $^{25}Al(p,\gamma)^{26}Si$ case

→ Impact on 26Al nucleosynthesis in classical novae

→ Studied via $d(^{25}Al,n\gamma)^{26}Si$ transfer @ FRIB/S800 **C.Fougères+coll**

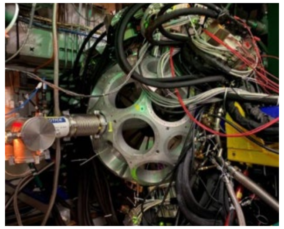
Measurements of ^{26}Si recoils at **S800** in coincidence with γ's in **GRETINA**

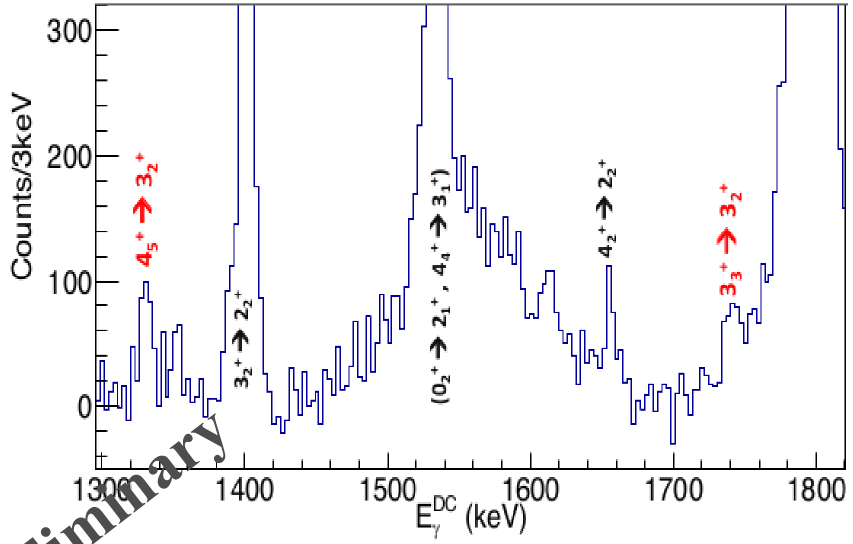


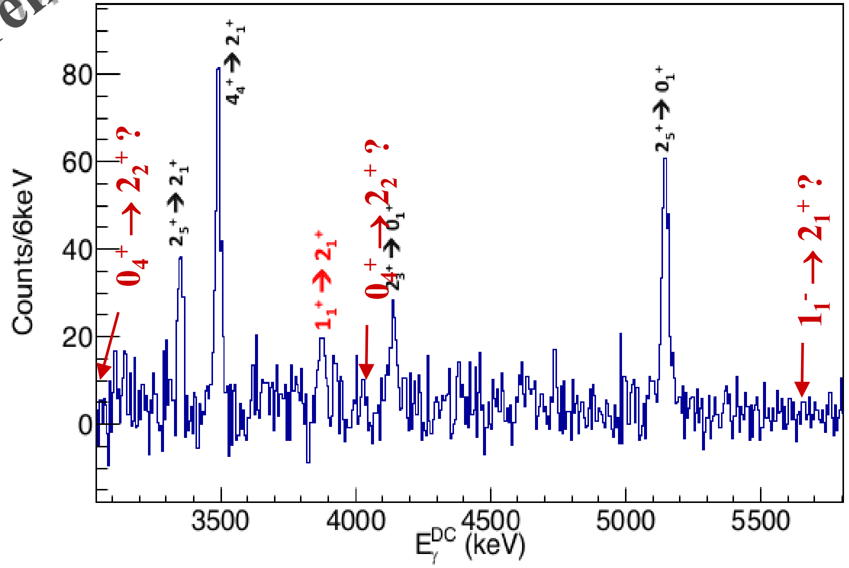
^{25}Al @ 24 MeV/u

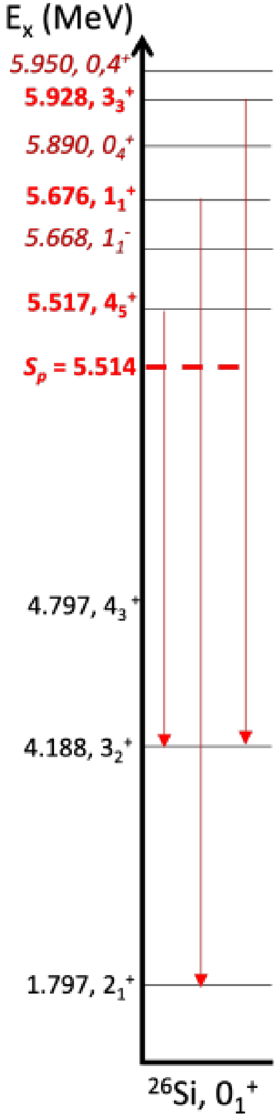
2× 10^6 pps, Purity >95%

CD$_2$ (**9.4 mg/cm²**)









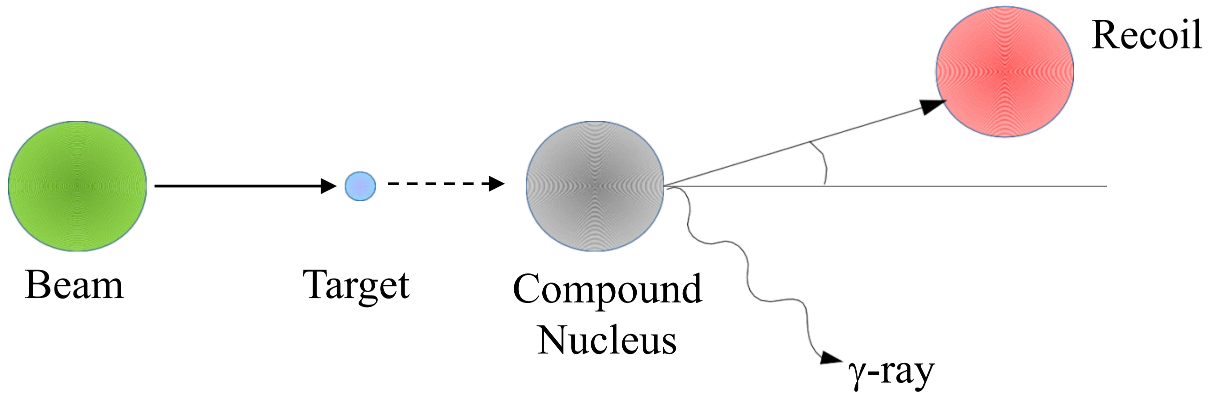
- Three resonant states among six of interest are identified in **^{26}Si**

Recoil separators

- γ-ray detection can be combined with **recoil separators** to detect in coincidence the ejected recoils
- Well suited to measure radiative (p,γ) & (α,γ) capture reactions in inverse kinematics **(see Longland lecture)**
- Recoil maximum angle:

$$\theta_{max} = \arctan\left[\frac{E_\gamma / c}{\sqrt{(2 m_b E_b)}}\right]$$

⇒ forward peaked emission **(θ ~ 1°)**



Most of the beam does not interact
→ recoil separator system needed to:

- Transport the recoil ions to a detection system (~100 % efficiency)
- Reject the incident beam

Requirements:

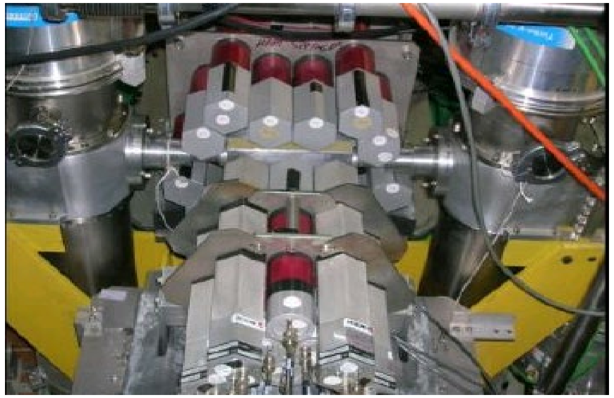
- high beam suppression factors (10^{10}-10^{15})

Few examples of recoil separators:

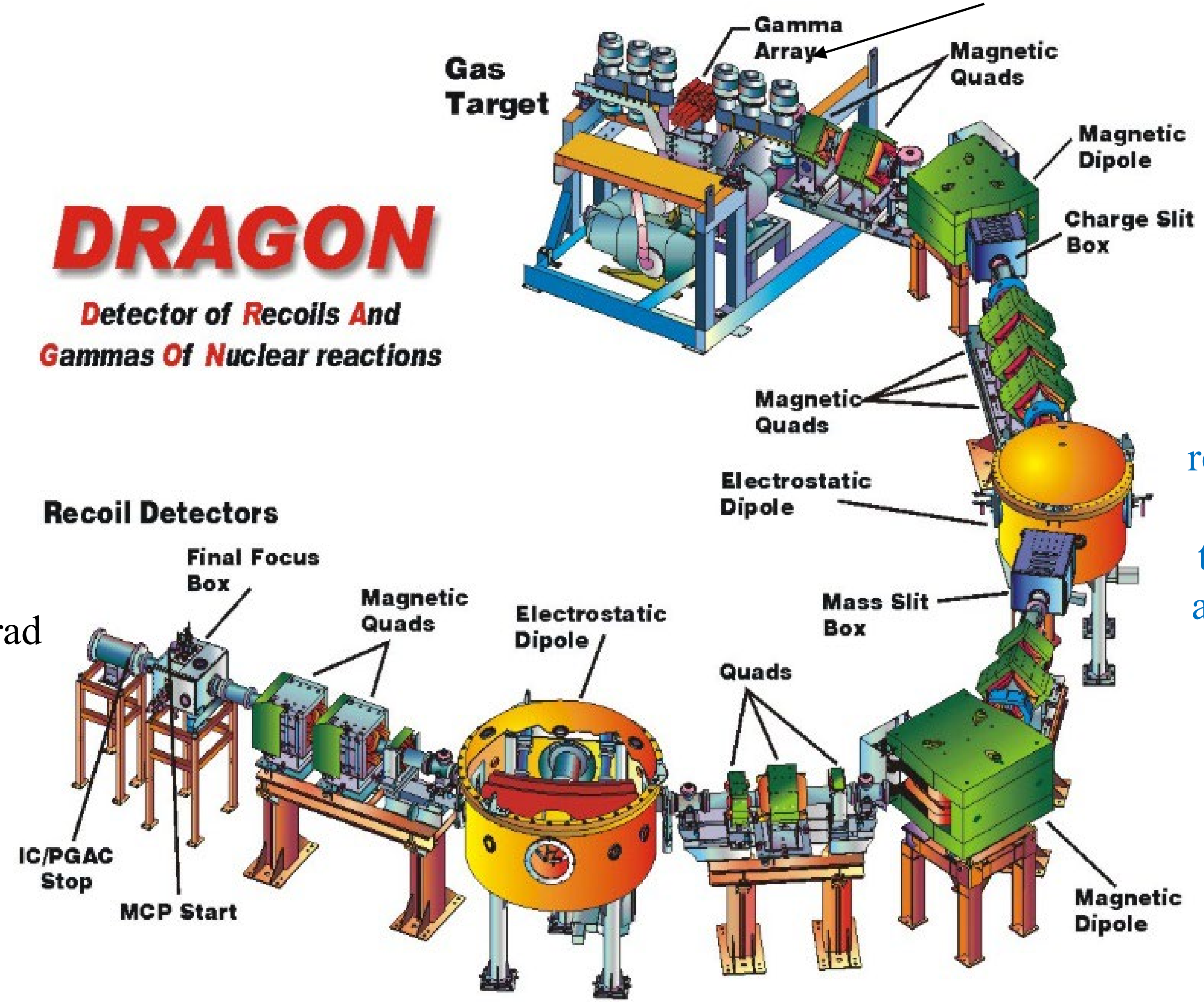
- ERNA
- FMA **(Fragment mass analyser)** @ Argonne Nat. Lab.
- DRAGON @ TRIUMF
- SECAR (FRIB)

DRAGON recoil spectrometer

BGO detectors



Target surrounded by array of BGO detectors



Primary beam rejected (E and B fields set to transport recoils and stop primary beam on slits)

ISAC 1: RIBs / stable (OLIS)

- 0° spectrometer
- Time of flight: 21 m
- Beam rejection: $10^{12} – 10^{15}$
- Angular acceptance: cone ±20 mrad

Target: windowless gas target

- Focal plane: MCP, DSSSD...
- BGO array: ε = 40-80%

J.M. D'Auria et al., NPA 701, 625 (2002)

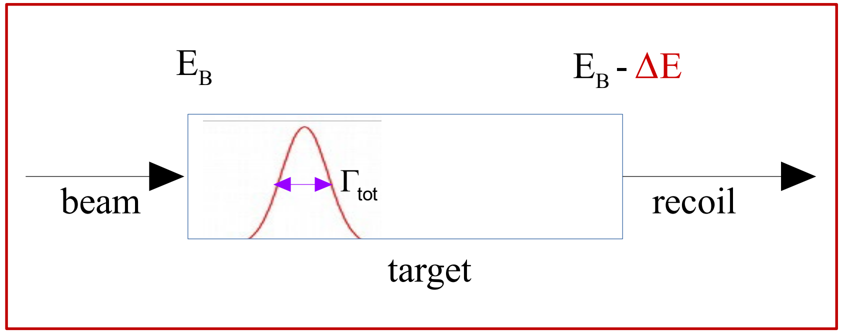
DRAGON: The $^{40}Ca(\alpha,\gamma)^{44}Ti$ case

- ^{44}Ti produced in massive stars has been observed in supernovae remnant (Cas A)

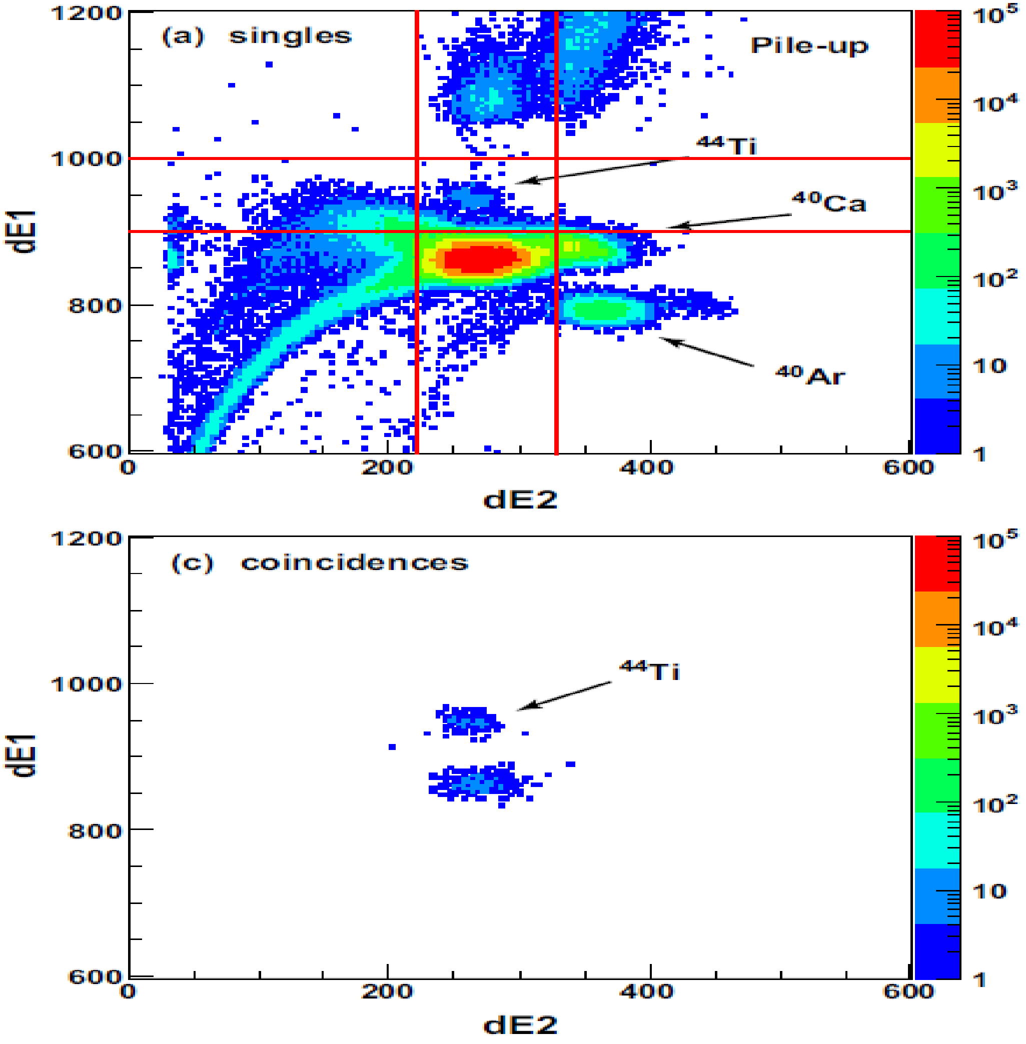
- Direct measurement of resonance strength using thick target yield formalism (Γ_{tot} < beam energy loss in the target) **(See Richard's lecture)**

$$\omega\gamma = \frac{2}{\lambda^2}\frac{m_t}{m_p+m_t}\left(\frac{dE}{dx}\right)Y$$

with *dE*/*dx* the stopping power of the projectile in the target



Selection of ^{44}Ti recoil events with the DRAGON



Vockenhuber et al PRC 2007

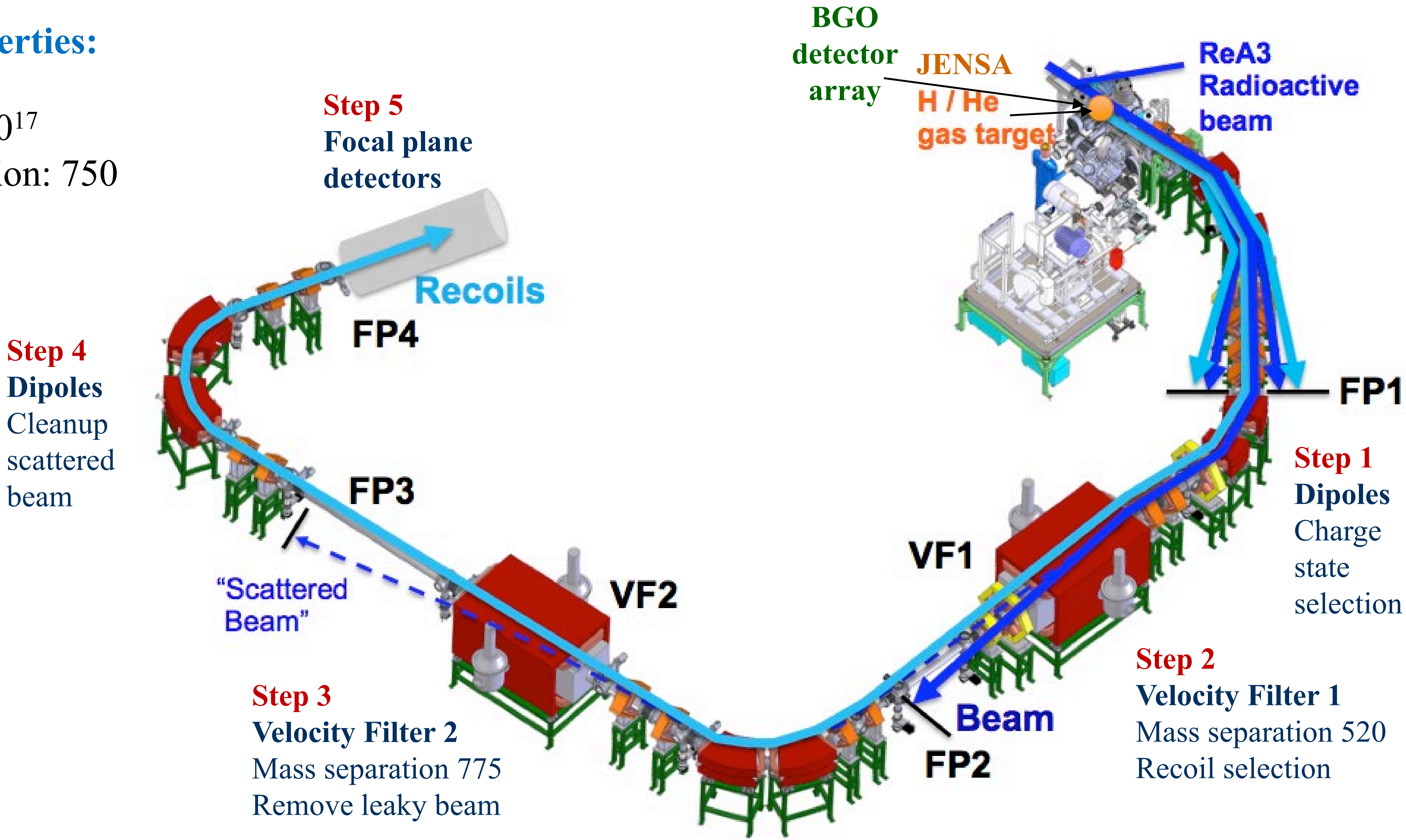
Strong resonance measurement @ Ex ~ 9.2 MeV

SECAR recoil Separator for Capture Reactions @ FRIB

- Dedicated for α and p capture reactions up to A=65 with proton rich nuclei (Classical Novae, X-ray bursts)

- **Separator properties:**

  → Rejection : 10^{17}
  → Mass resolution: 750



Unaddressed Topics

➢ Ions sources

- "The Physics and Technology of Ion Sources“ Ian G. Brown

➢ Neutrons beams

➢ Detection systems for neutrons

- " Radiation Detection and Measurement" Glenn F. Knoll
- "Techniques for Nuclear and Particle Physics Experiments" William R. Leo
- " Elements of Slow-Neutron Scattering: Basics, Techniques, and Applications ". Carpenter, J. M. & C. K. Loong.
- "Experimental Neutron Scattering “ B. T. M. Willis and C. J. Carlile

➢ Storage Rings

- “RIB physics with storage rings“ lecture of Yuri Litvinov
  https://ejc2015.sciencesconf.org/conference/ejc2015/pages/Skript_Litvinov.pdf

- " Low-energy nuclear reactions with stored ions: a new era of astrophysical experiments at heavy ion storage rings”, J. Glorius, C. Bruno EPJA59,81 (2023)

Thank You
for
Your Attention