# Direct and indirect low-energy reaction studies with light nuclei at CNA

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Junta de Andalucía

CNA Centro Nacional de Aceleradores — ICTS Infraestructuras Científicas y Técnicas Singulares

CSIC Consejo Superior de Investigaciones Científicas

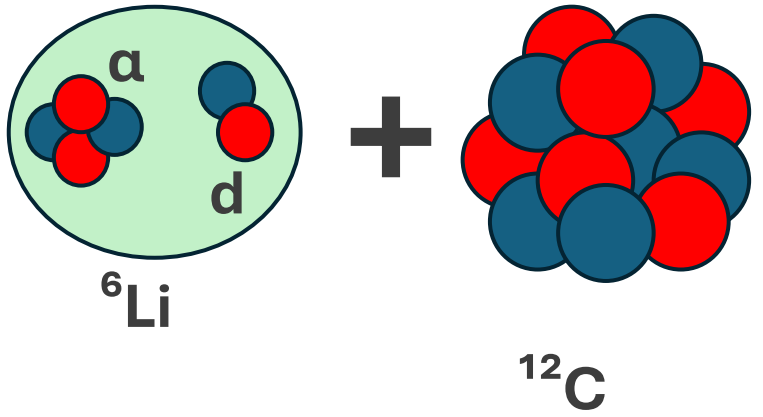
Universidad de Sevilla

# Outline

1. Basic Nuclear Physics (FNB) experimental line

2. New setup

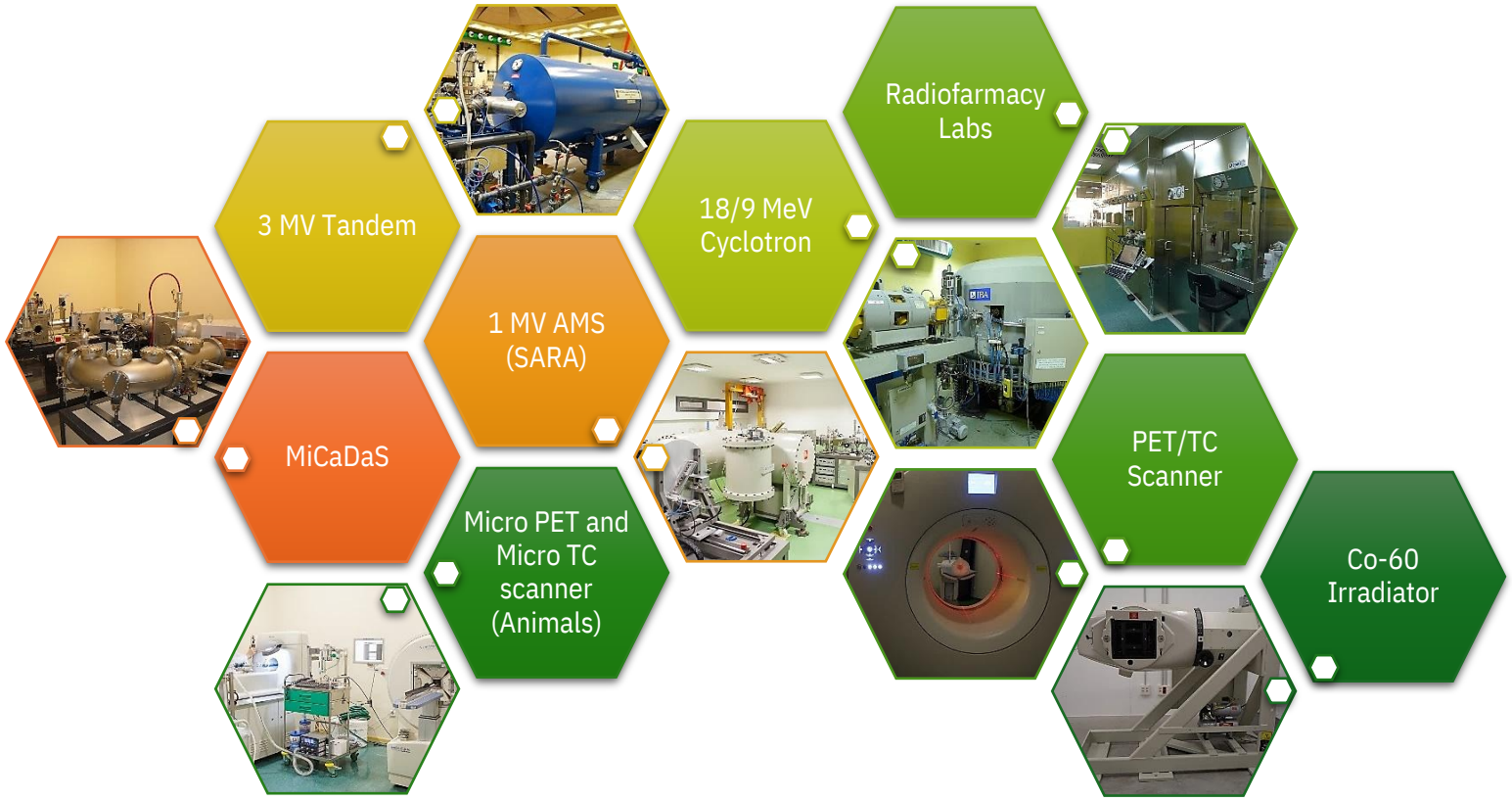
3. Setup validation via $^{6}Li+^{12}C$ reaction




4. Summary & Outlook

# Centro Nacional de Aceleradores (CNA)

## Interdisciplinary Research Centre





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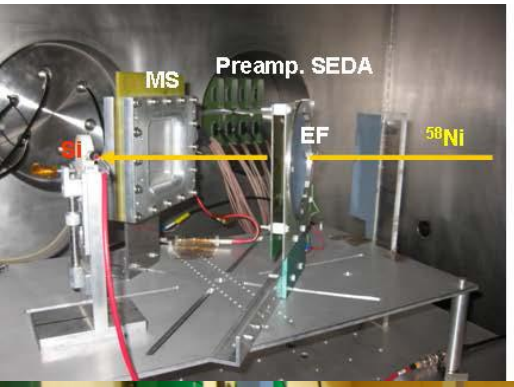
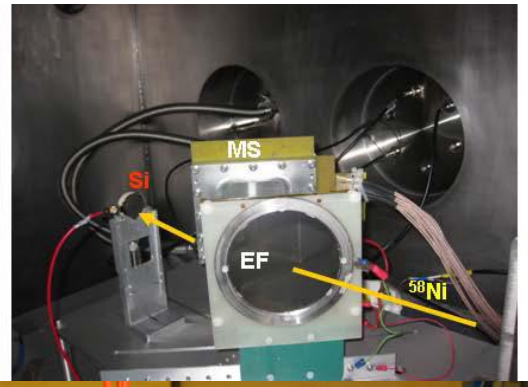
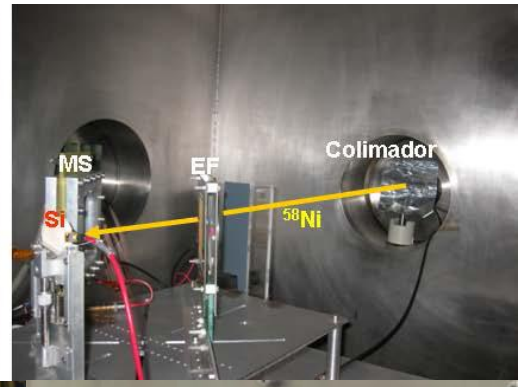
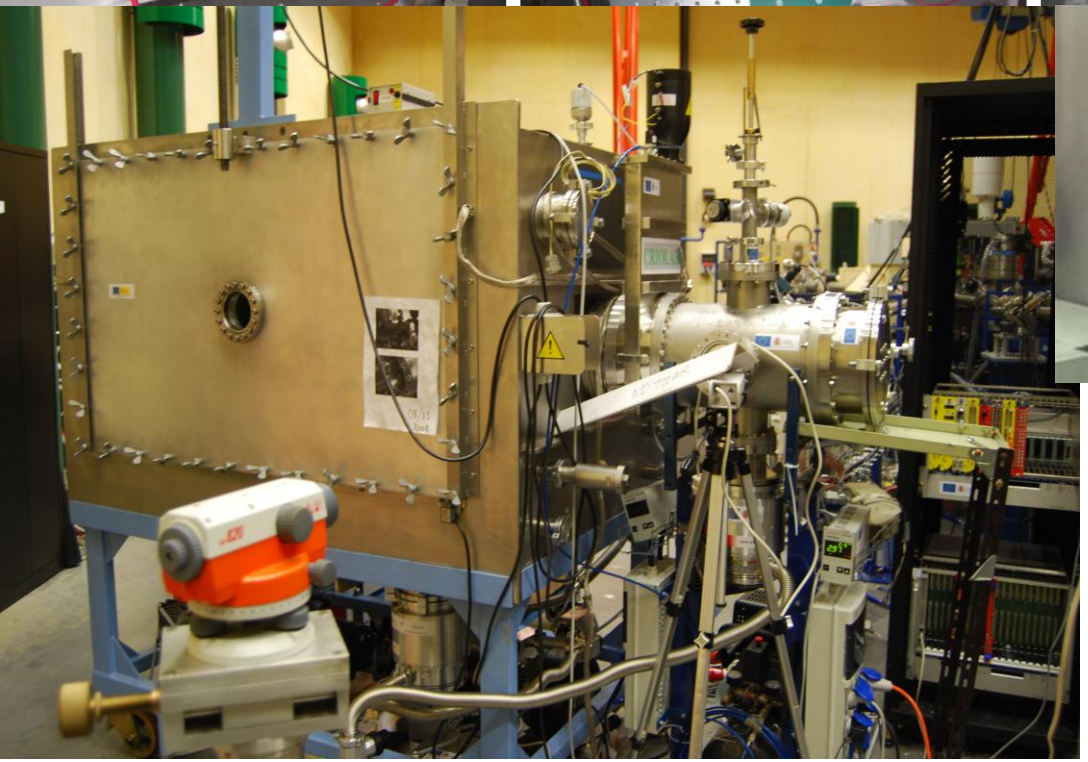
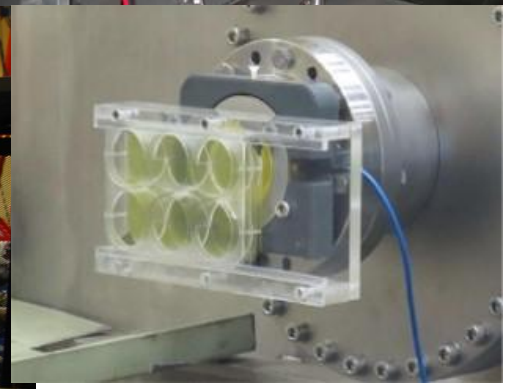
# Basic Nuclear Physics(FNB) experimental line



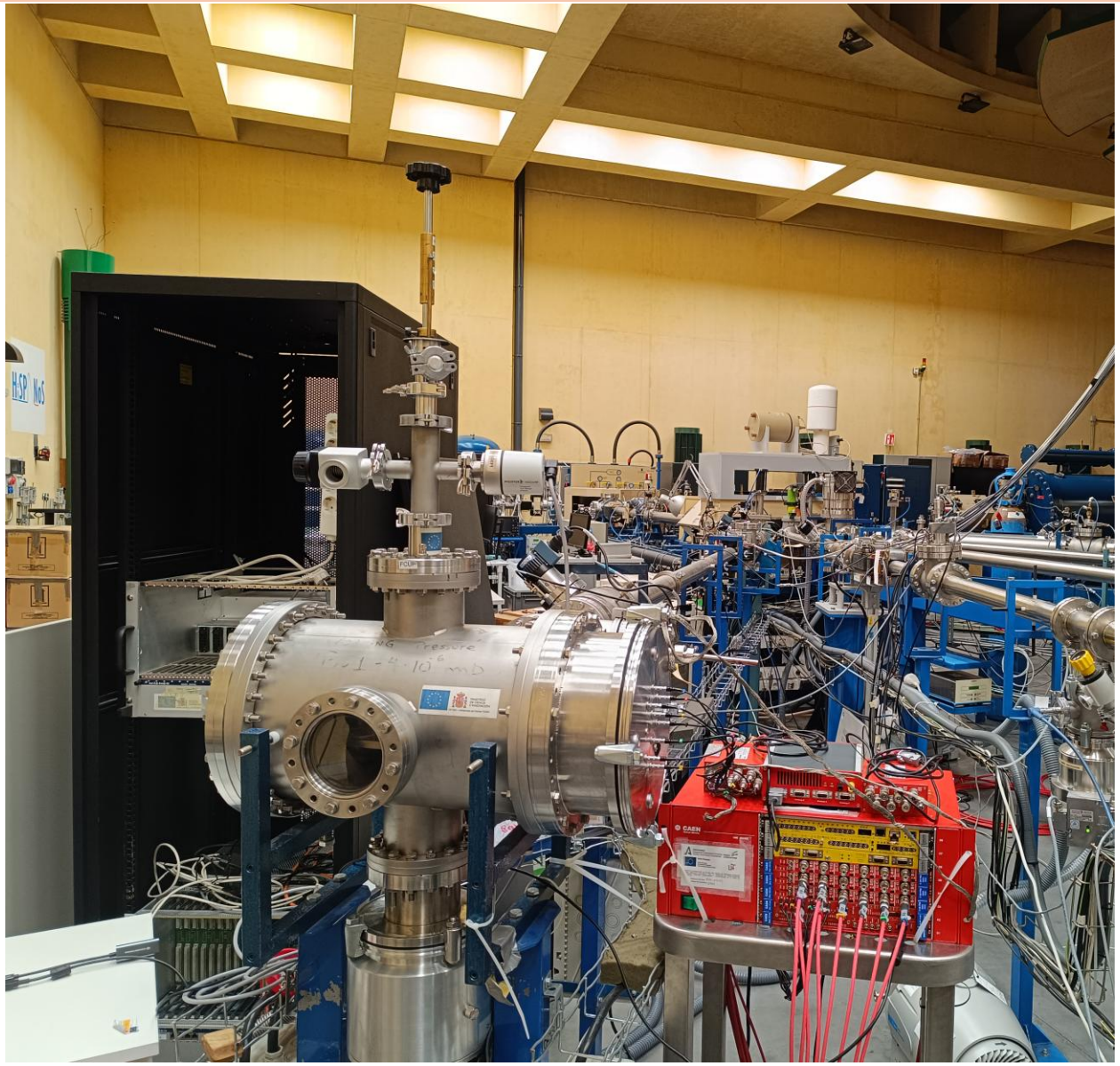





- Medical physics experiments
- Gaseous detectors development
- Test and characterization of nuclear instrumentation for experiments at other facilities

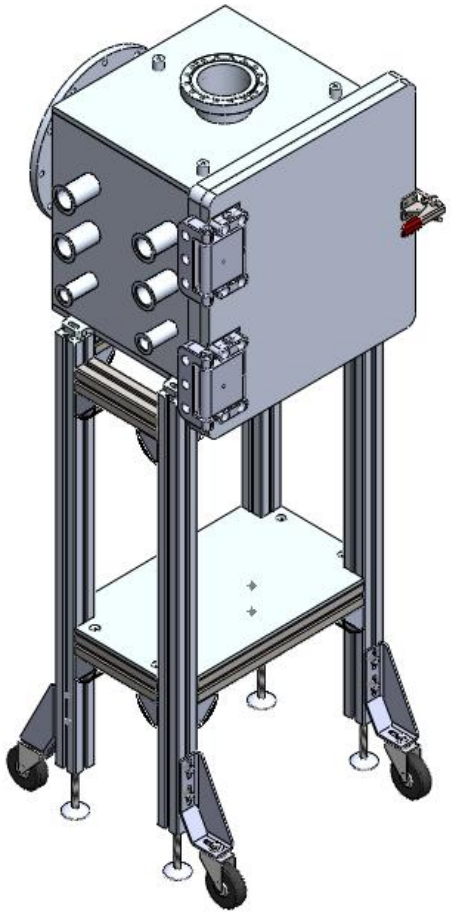
# Basic Nuclear Physics(FNB) experimental line



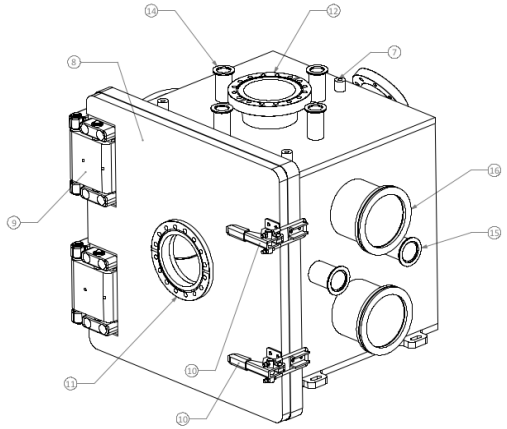
- Medical physics experiments
- Gaseous detectors development
- Test and characterization of nuclear instrumentation for experiments at other facilities

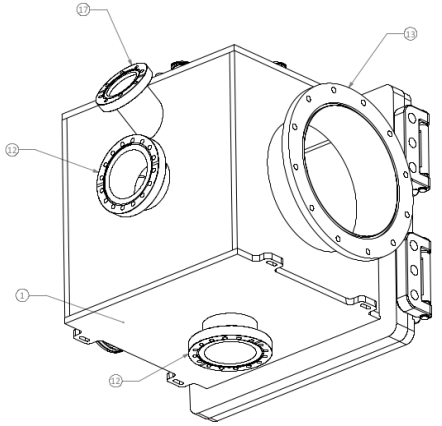
**Nuclear reaction studies with light ions ($^{6}$Li,$^{7}$Li,$^{9}$Be,$^{10}$B...) at low energies at FNB**

# Basic Nuclear Physics (FNB) experimental line

**40x40x40 cm$^3$ aluminium chamber**

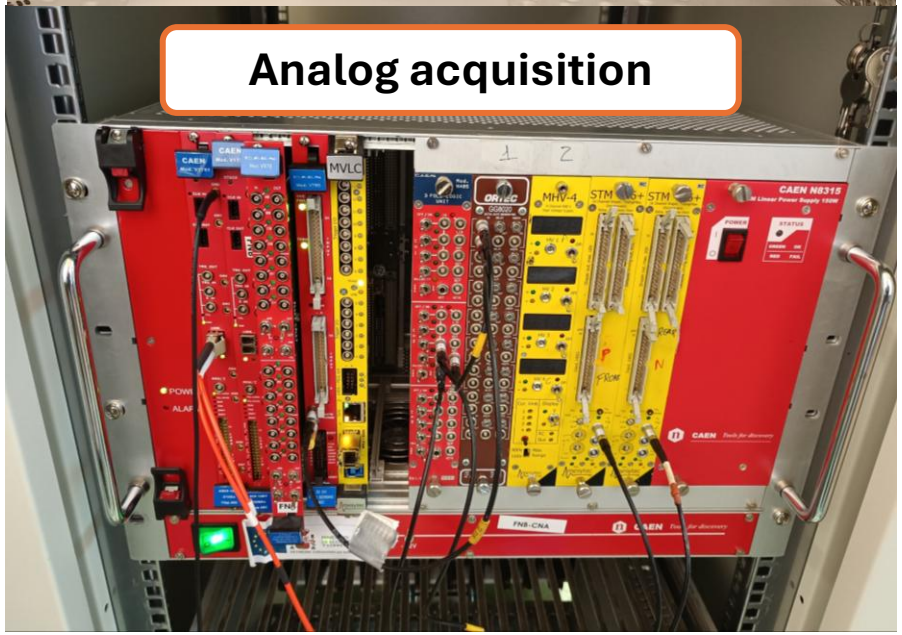


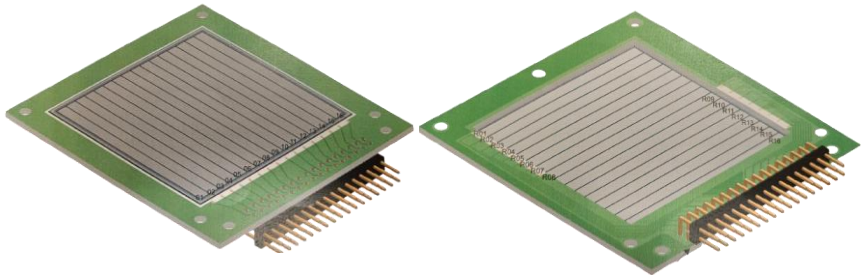


# Acquisition system

**S/DSSS detectors**

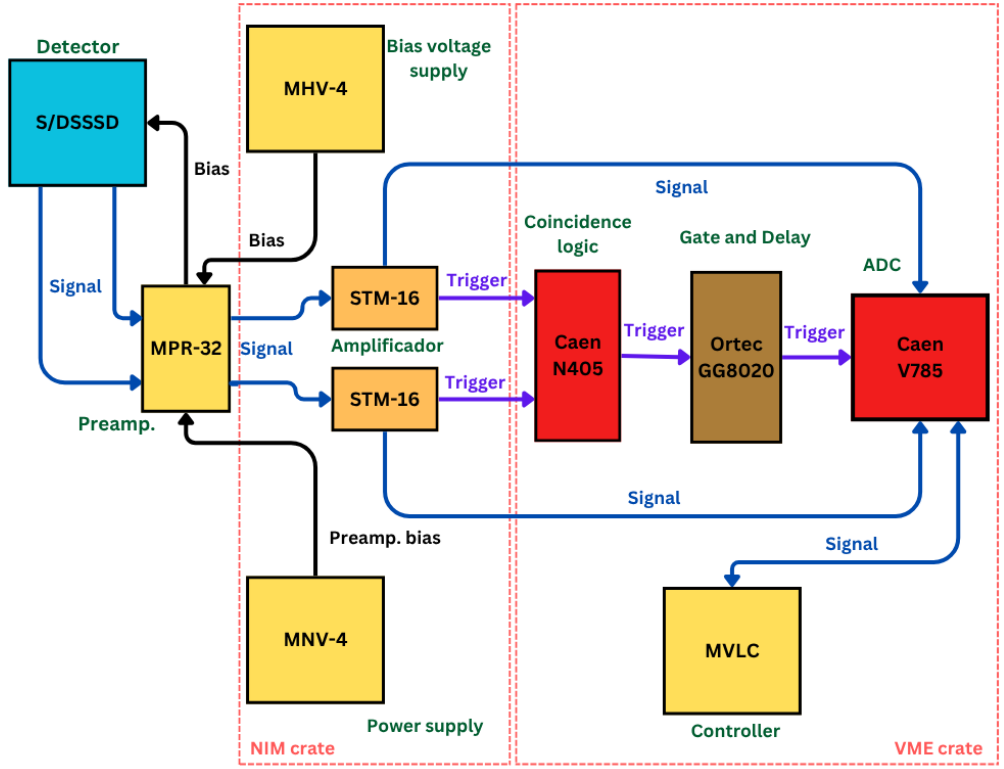
**Analog acquisition**





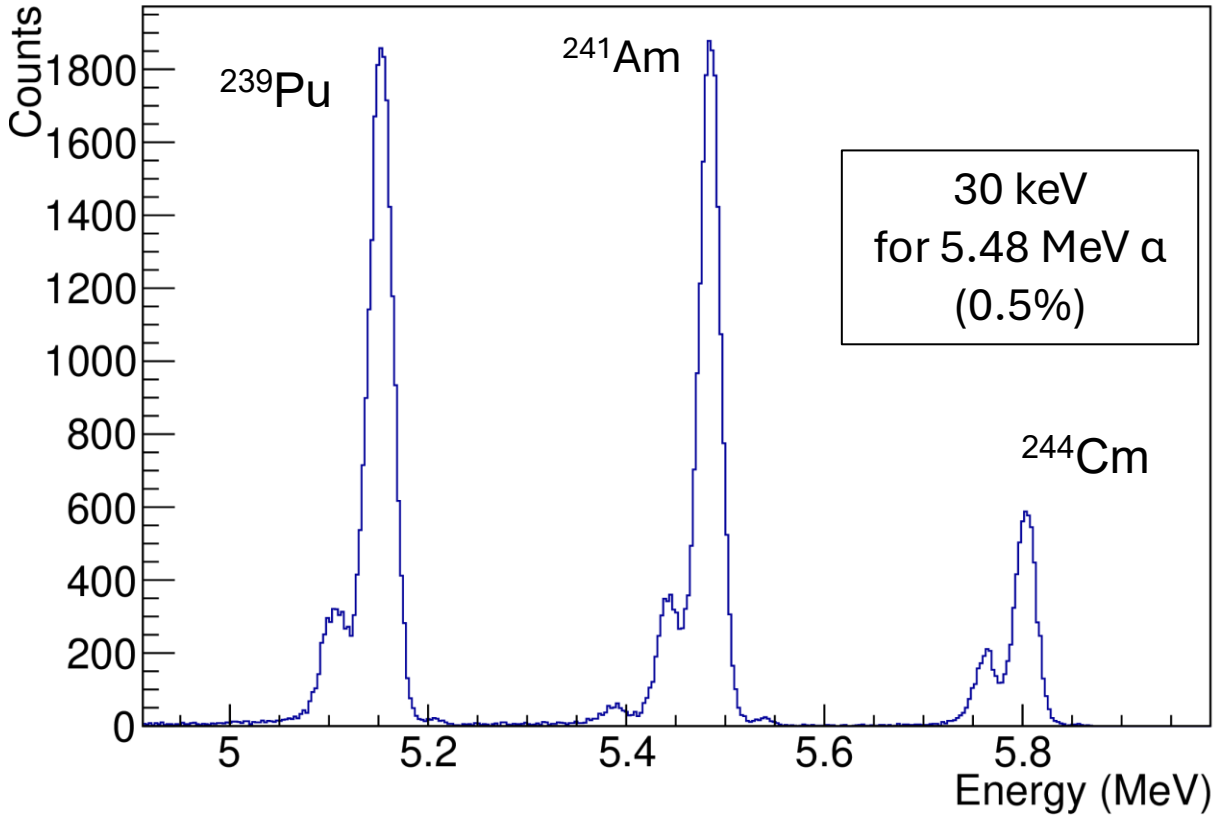
**Thickness S/DSSSD**

- 40 um
- 20 um
- 500 um
- 300 um (PAD)

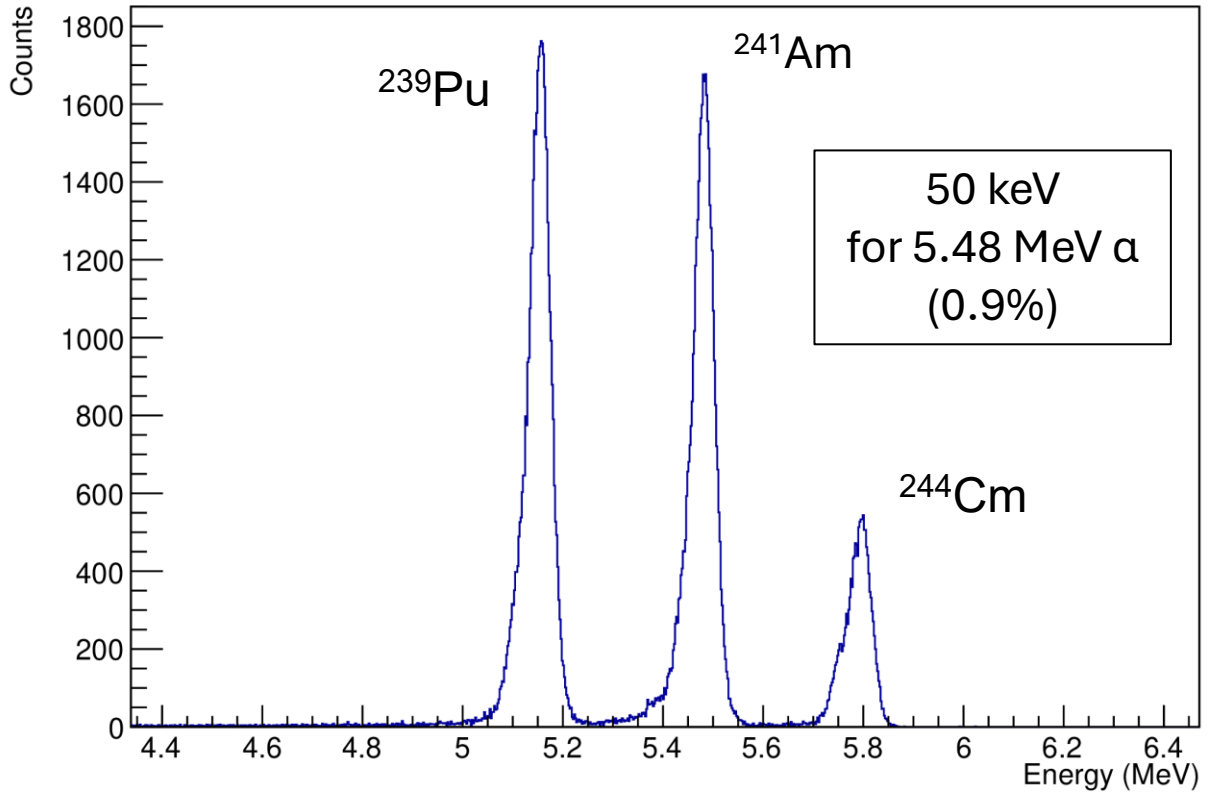


# Energy resolution

DSSSD 500 um




DSSSD 40 um



# Study of $^{6}Li+^{12}C$ reaction

Cluster structure (α+d)

Weakly bound nuclei
**$Q_\alpha$ = - 1.474 MeV**

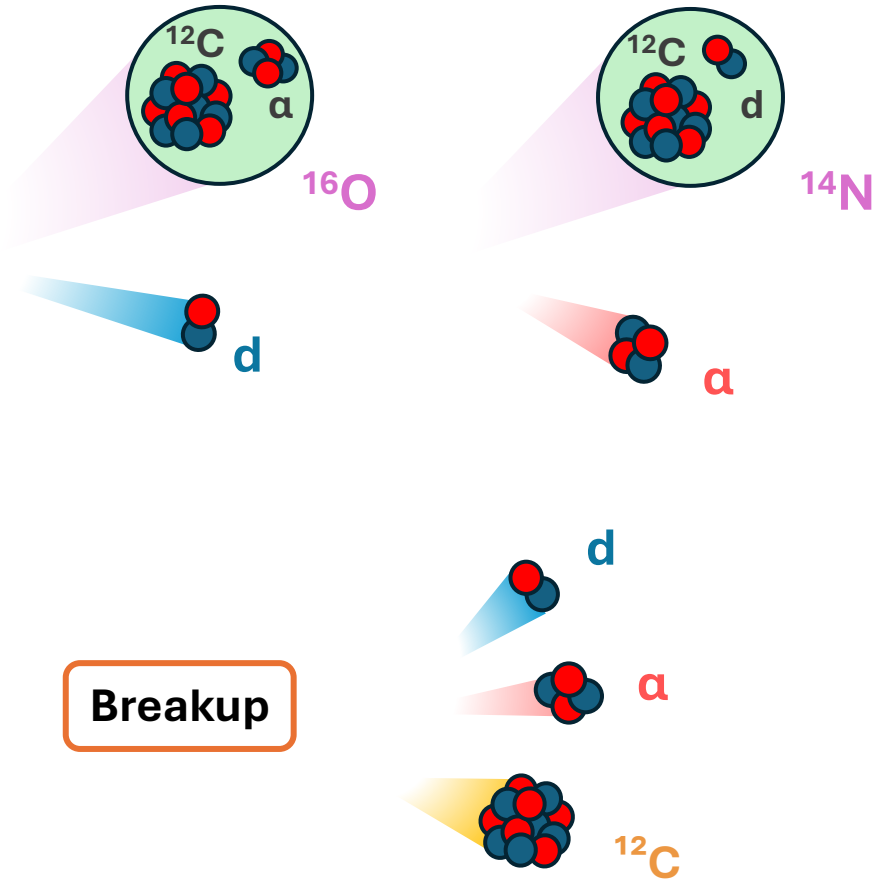
Tightly bound nuclei
**$Q_\alpha$ = - 7.367 MeV**


Coulomb barrier **$V_b$~ 4.5 MeV**

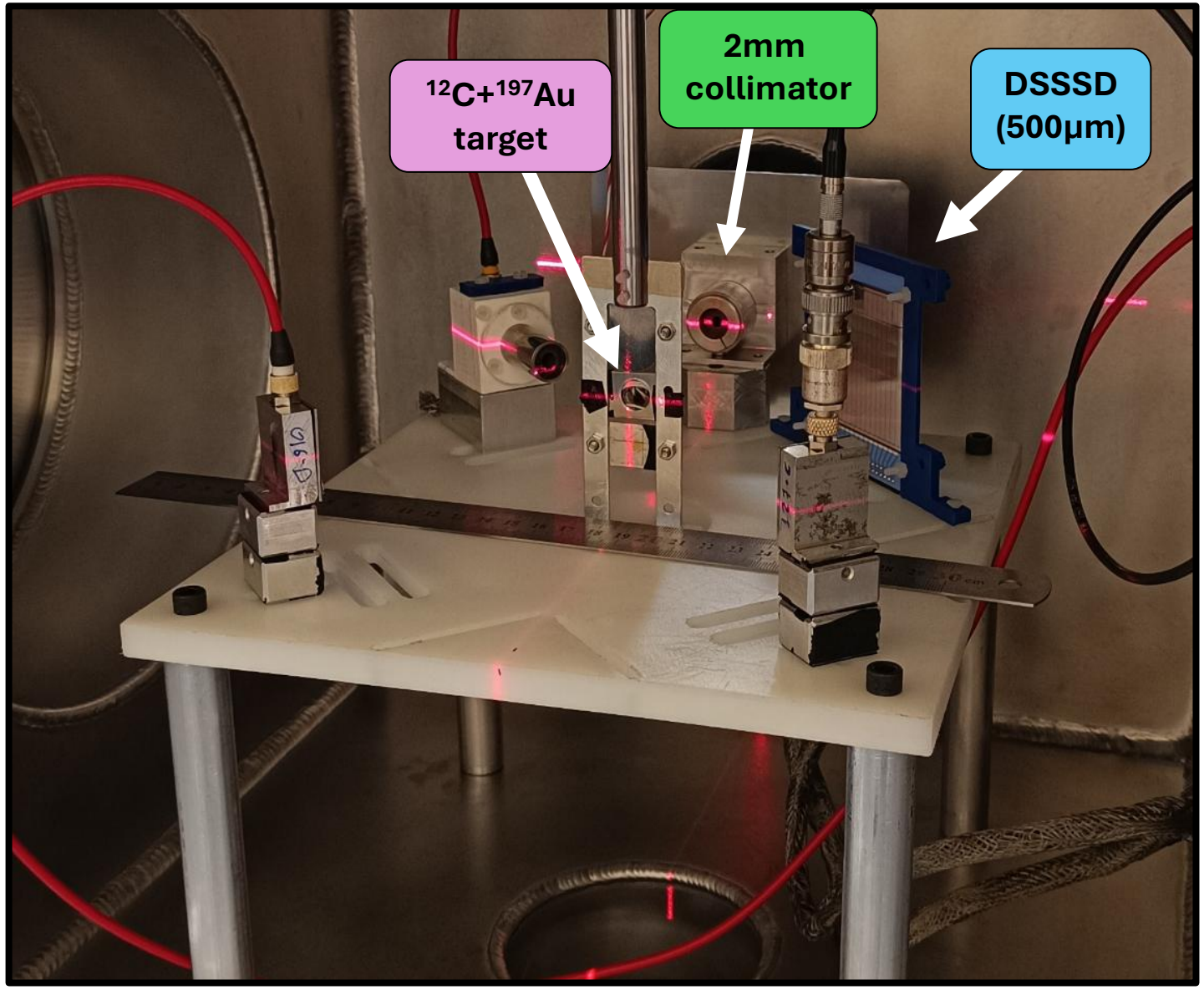
Measurement with **beam energies** of 5.5, 6, 6.5, 7, 7.5 and 8 MeV

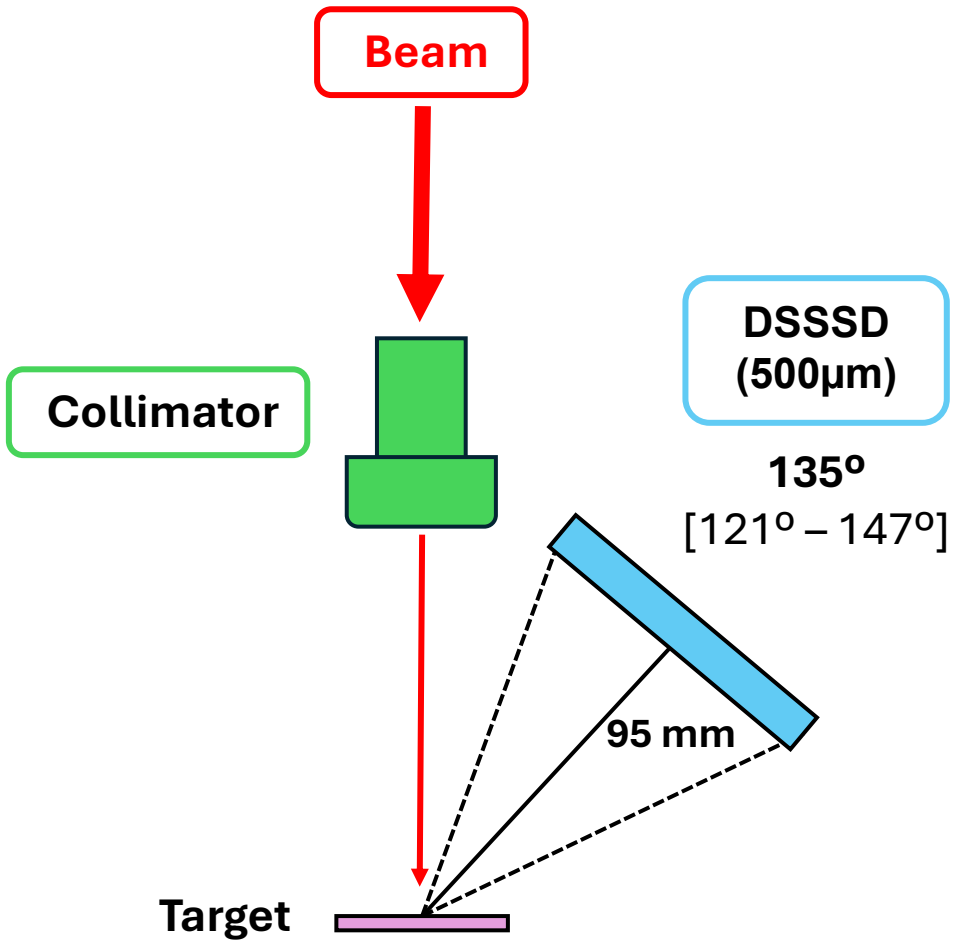
**Alpha transfer**
$^{12}C(^{6}Li,d)^{16}O$

**Deuteron transfer**
$^{12}C(^{6}Li, \alpha)^{14}N$



# Single configuration setup

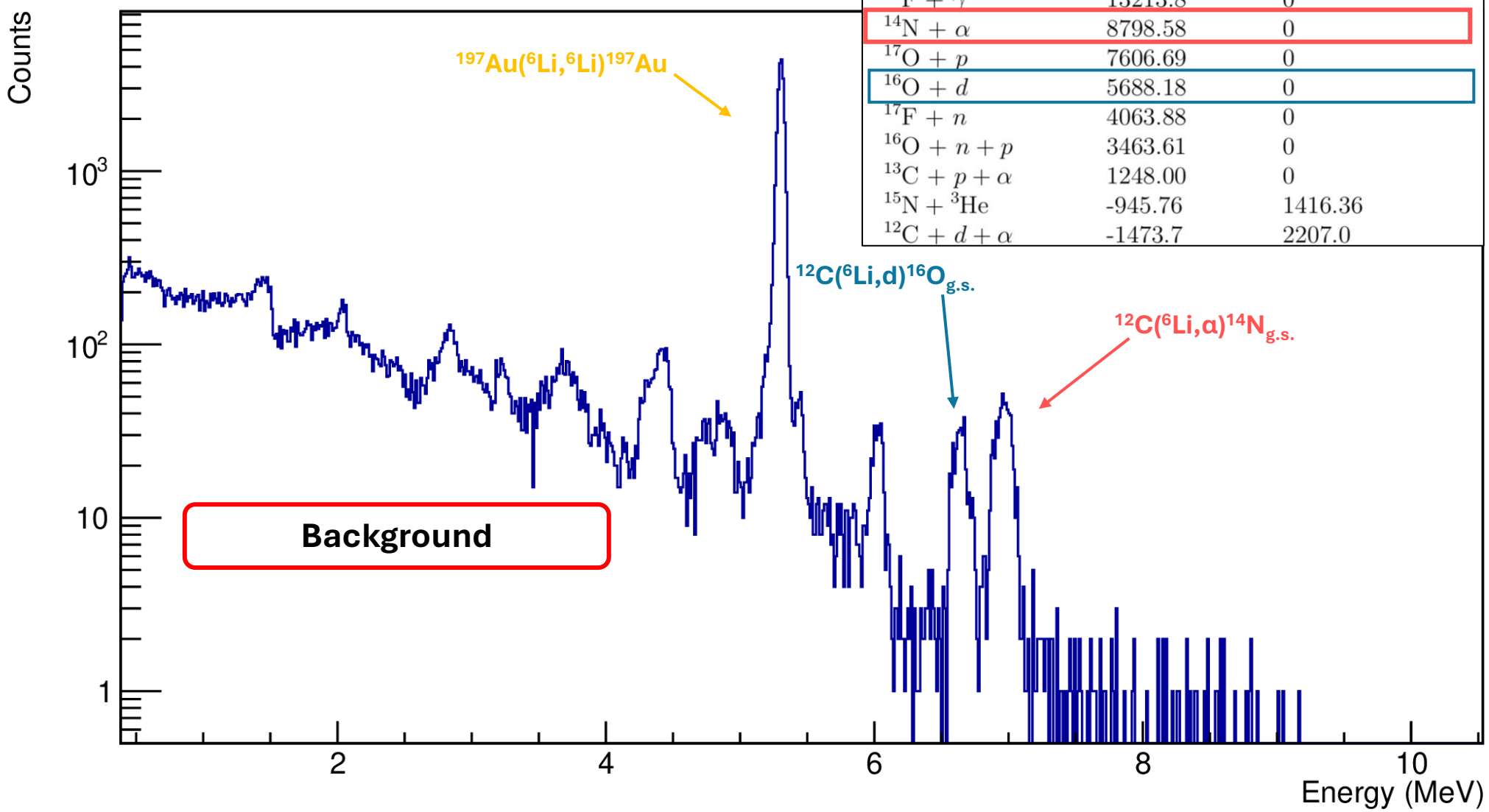


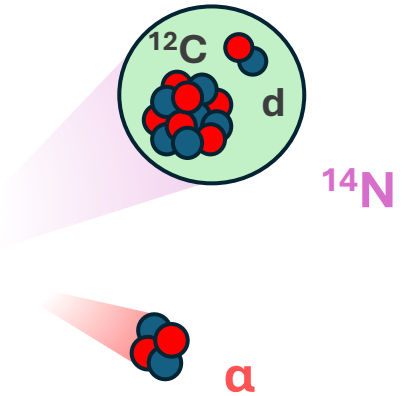
# Channels identification

6Li + 12C @ **6MeV** ( $\theta_{lab.} \sim 130^{o}$)

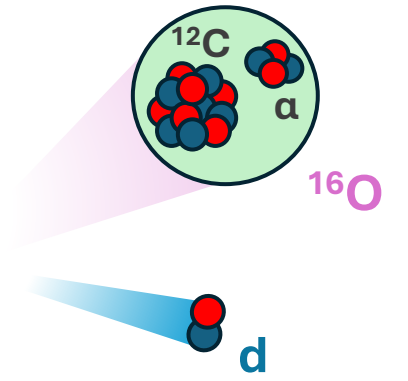
| Reaction Products | Q-value (keV) | Threshold (keV) |
|---|---|---|
| $^{18}F + \gamma$ | 13213.8 | 0 |
| $^{14}N + \alpha$ | 8798.58 | 0 |
| $^{17}O + p$ | 7606.69 | 0 |
| $^{16}O + d$ | 5688.18 | 0 |
| $^{17}F + n$ | 4063.88 | 0 |
| $^{16}O + n + p$ | 3463.61 | 0 |
| $^{13}C + p + \alpha$ | 1248.00 | 0 |
| $^{15}N + ^{3}He$ | -945.76 | 1416.36 |
| $^{12}C + d + \alpha$ | -1473.7 | 2207.0 |




**Deuteron transfer**
$^{12}C(^{6}Li, \alpha)^{14}N$

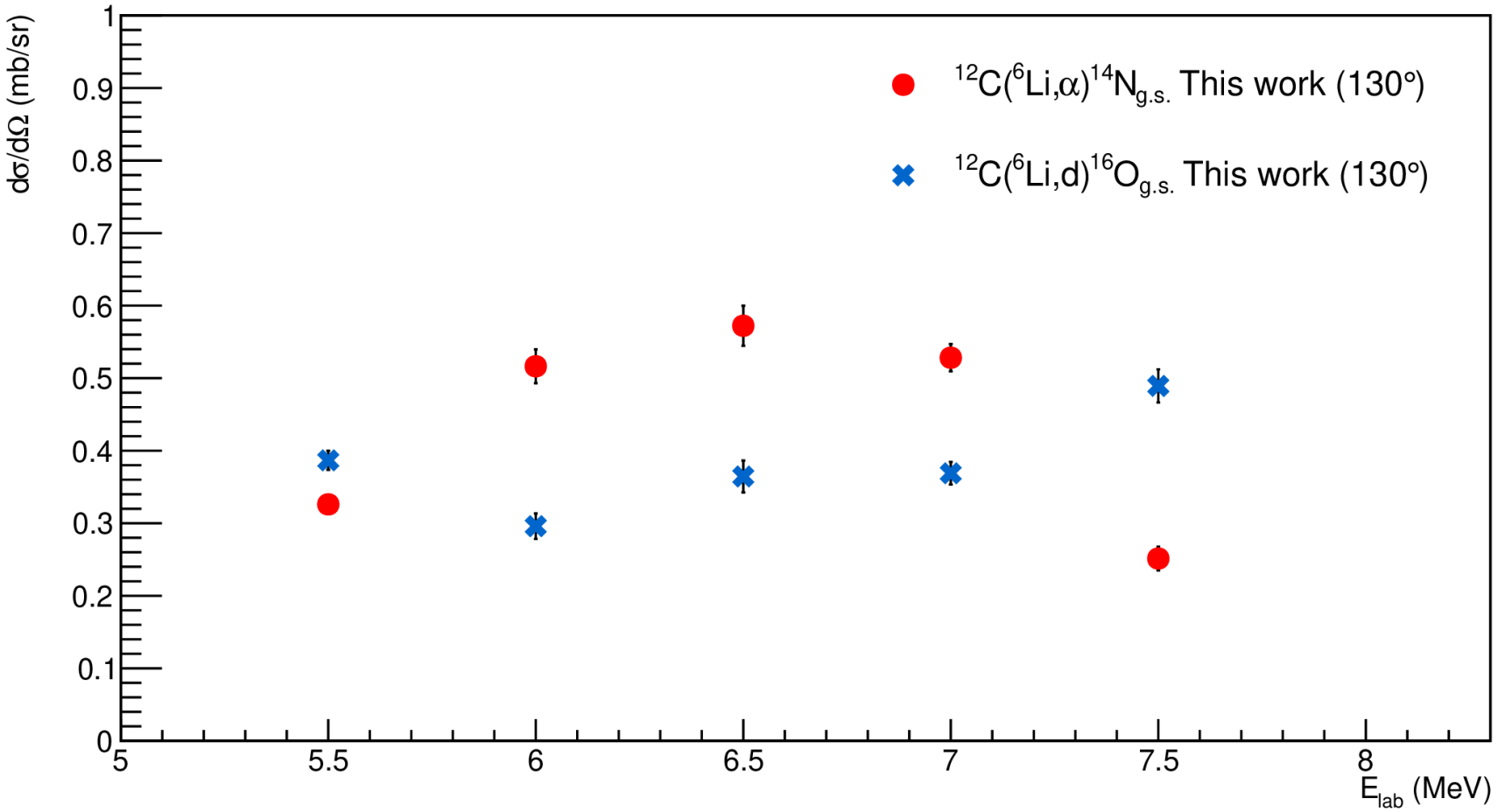



**Alpha transfer**
$^{12}C(^{6}Li,d)^{16}O$



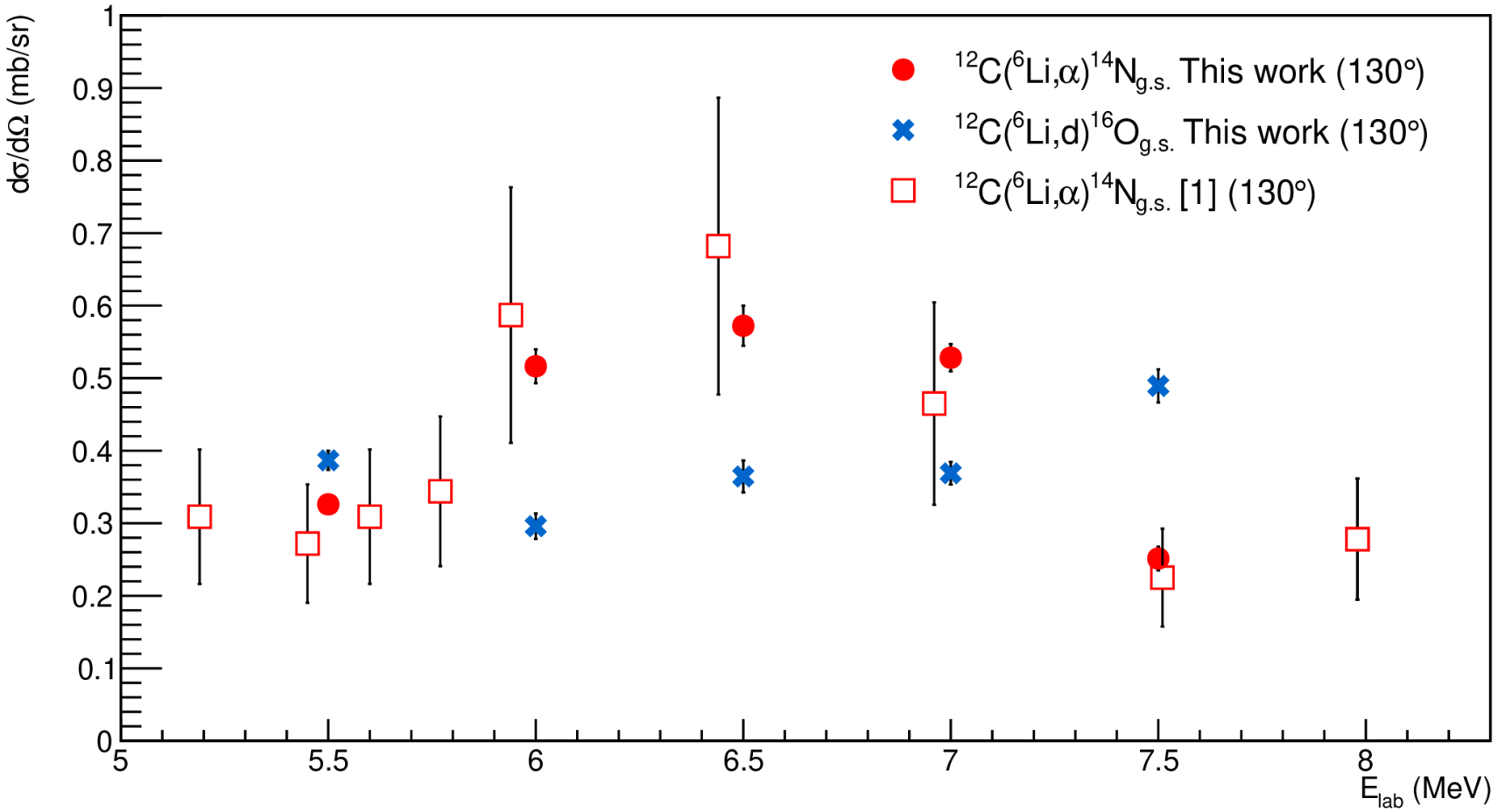
# Excitation functions

**$^{12}C(^{6}Li,\alpha)^{14}N_{g.s.}$ and $^{12}C(^{6}Li,d)^{16}O_{g.s.}$ excitation function** at 130º (lab.)



# Excitation functions

**$^{12}C(^{6}Li,\alpha)^{14}N_{g.s.}$ and $^{12}C(^{6}Li,d)^{16}O_{g.s.}$ excitation function** at 130º (lab.)

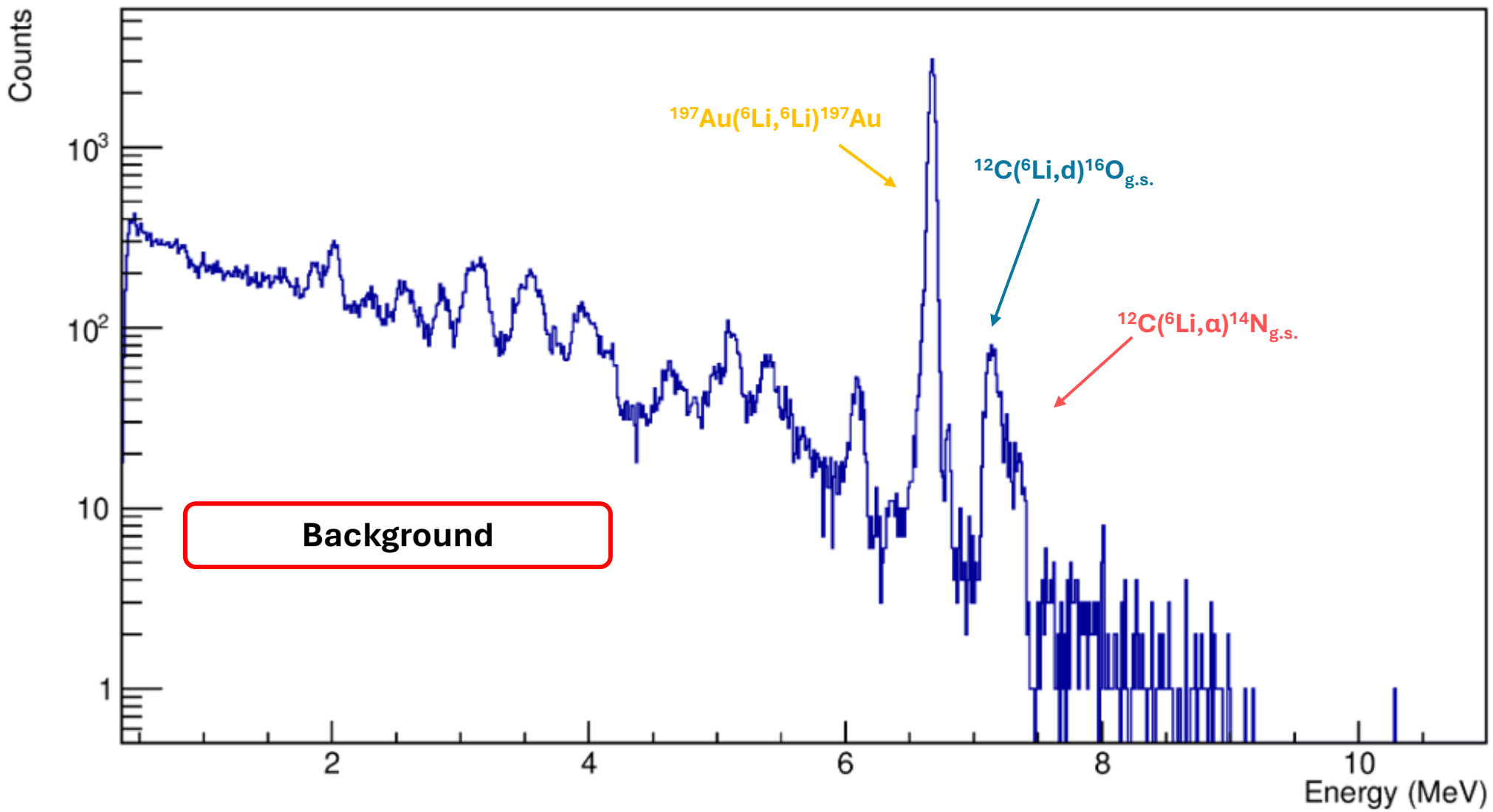




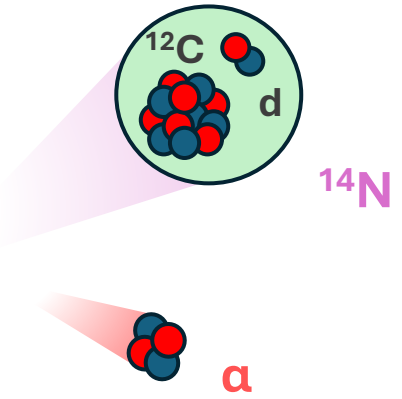
**[1]** J. Schwenzel et al.
*Nucl. Phys. A **367**, 145-156 (1981).*

# Channels identification

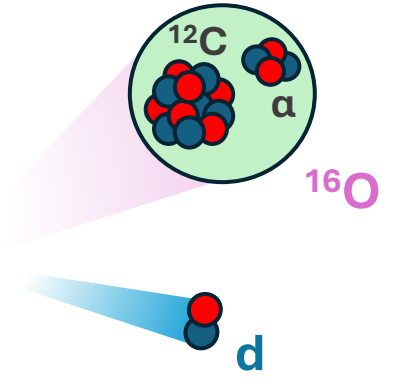
6Li + 12C @ **8MeV** ( $\theta_{lab.} \sim 130^{o}$)




**Deuteron transfer**
$^{12}C(^{6}Li, \alpha)^{14}N$

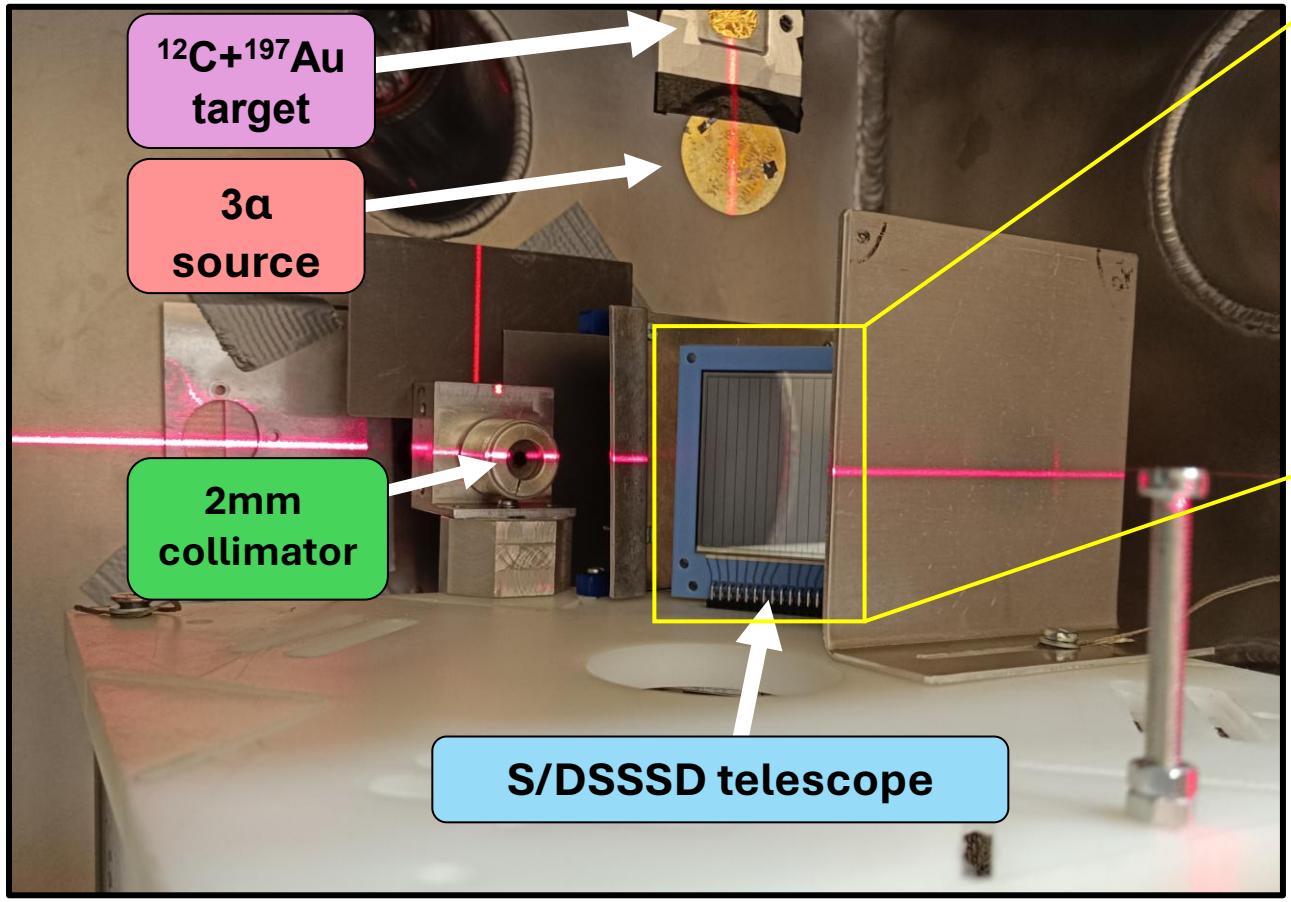


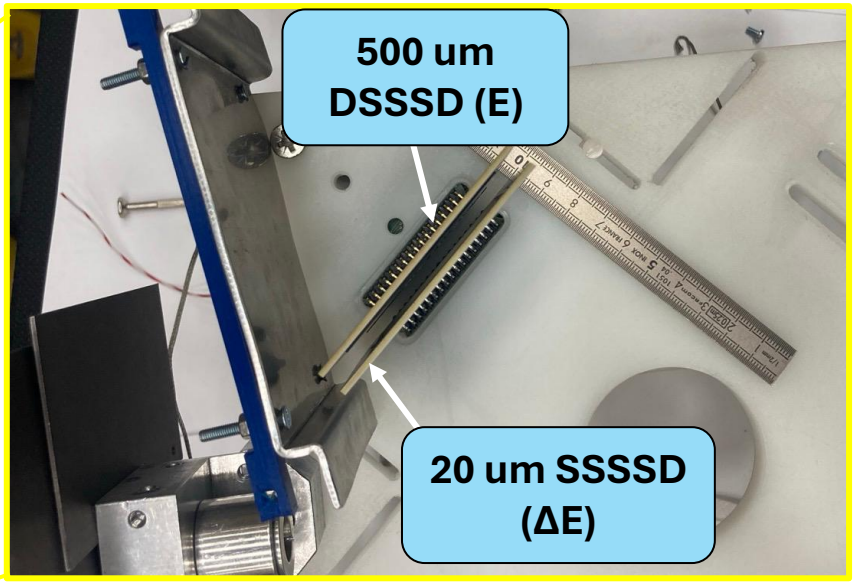

**Alpha transfer**
$^{12}C(^{6}Li,d)^{16}O$

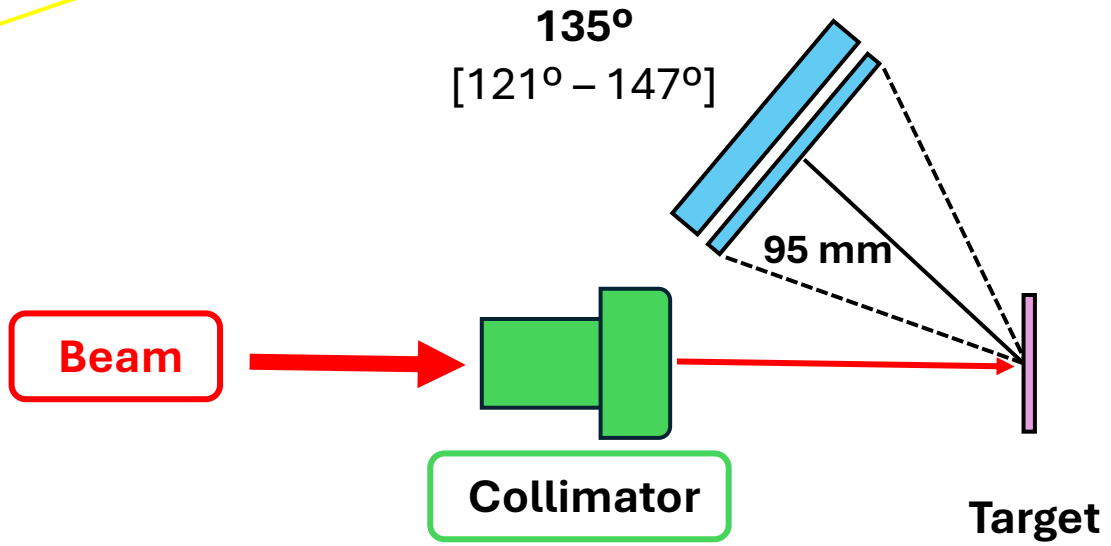


# Telescope configuration setup

6Li+12C @ 6MeV

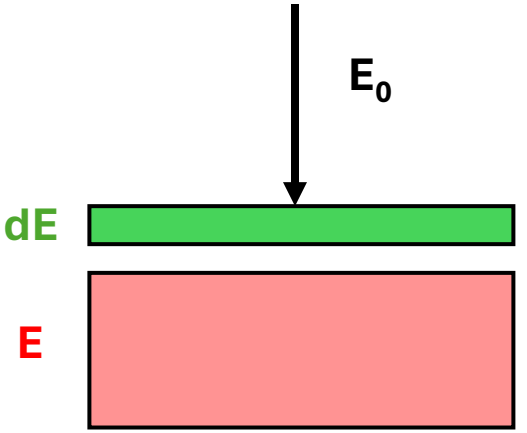


# Channels identification

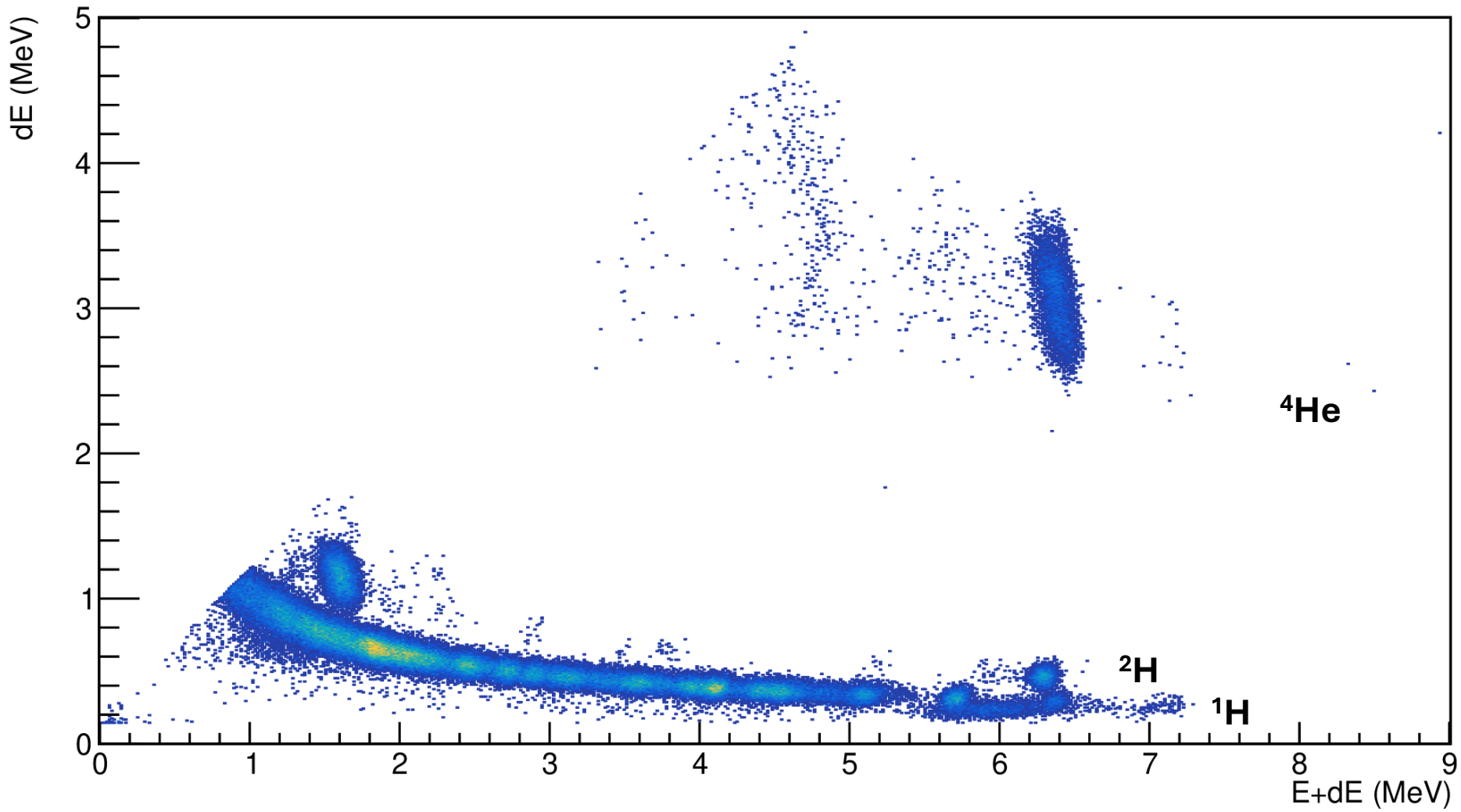
Particles identification



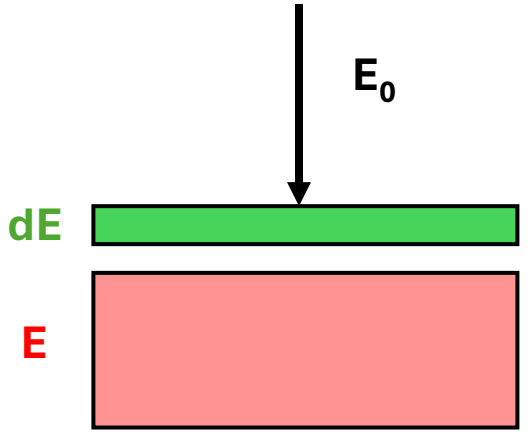

$$-\frac{dE}{dx} \propto \frac{Z^2 A}{E_0}$$

# Channels identification

$^{6}Li + {}^{12}C$ @ **6MeV** ( $\theta_{lab.}$~ 130º) telescope configuration




Particles identification




$$-\frac{dE}{dx} \propto \frac{Z^2 A}{E_0}$$

# Thickness characterization

Energy measured in thick detector

Thin detector thickness

Stopping power

$$E_0 - E = \int_0^{\Delta x} \frac{dE}{dx} dx'$$

Incident energy

# Thickness characterization

Energy measured in thick detector

Thin detector thickness

Stopping power

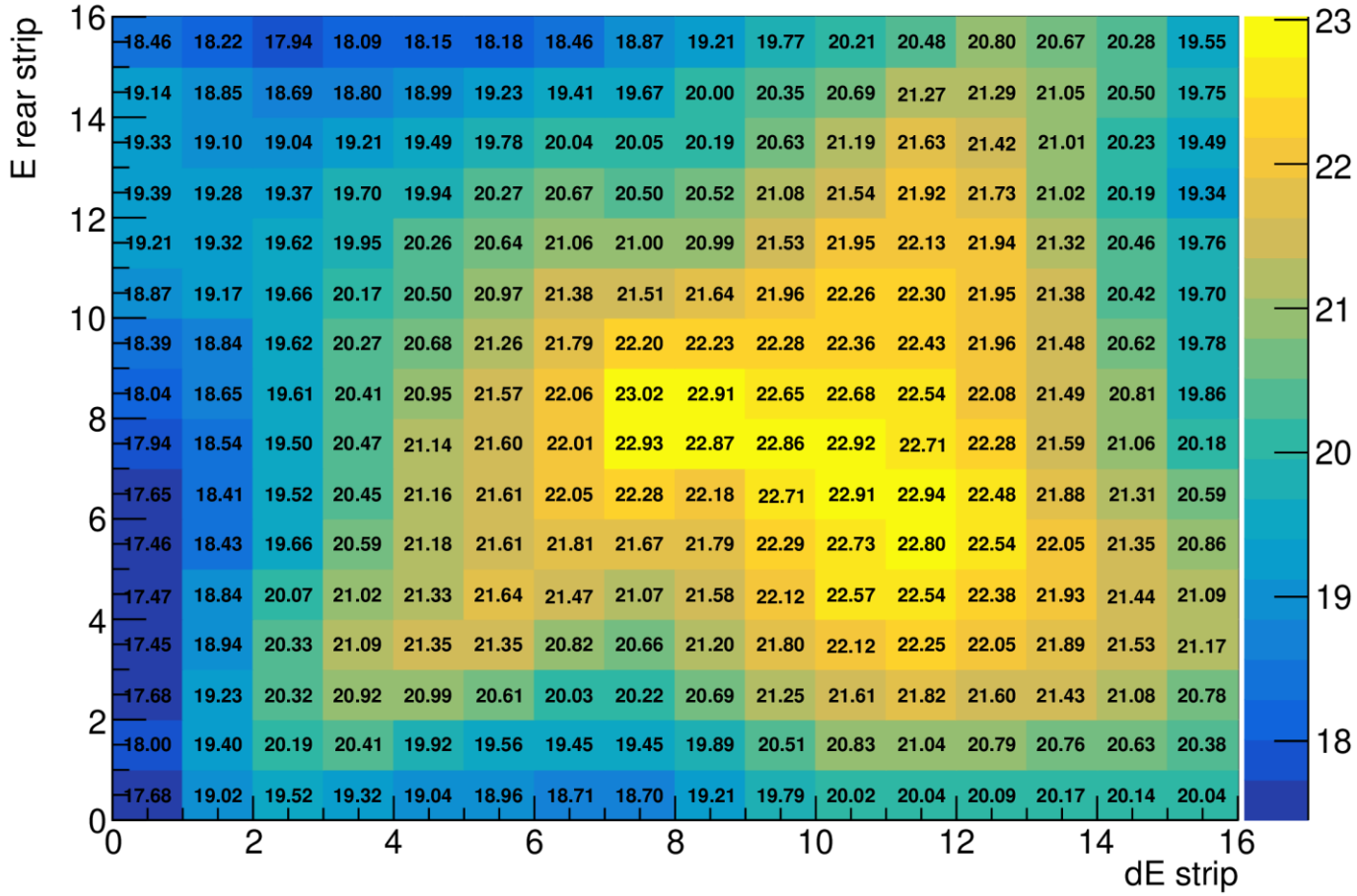
$$E_0 - E = \int_0^{\Delta x} \frac{dE}{dx} dx'$$

Incident energy

**Thickness from 17.5 μm to 23 μm**

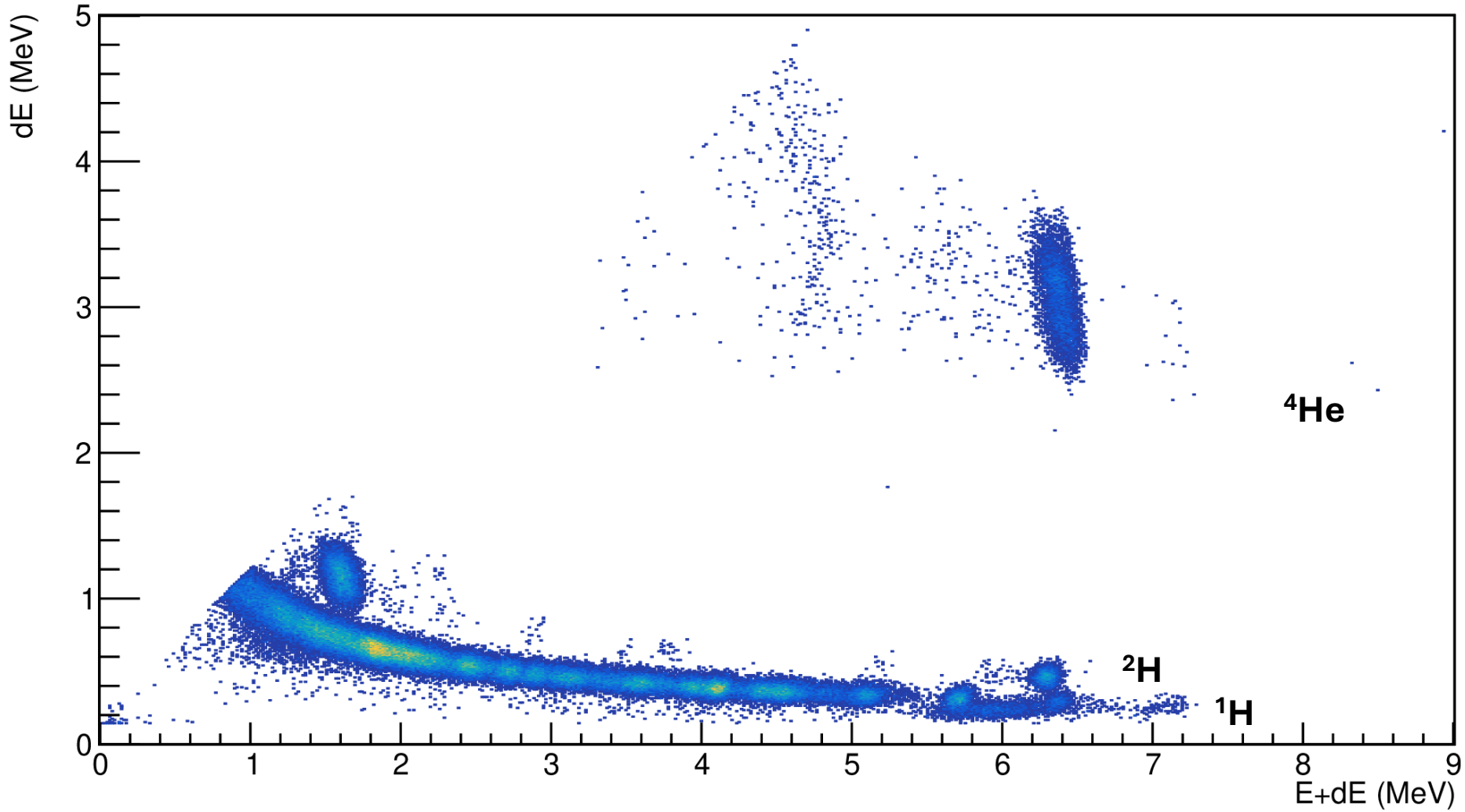
**~ 15%**

$$E_{corr} = \frac{\Delta x}{20\ \mu m} \cdot E$$

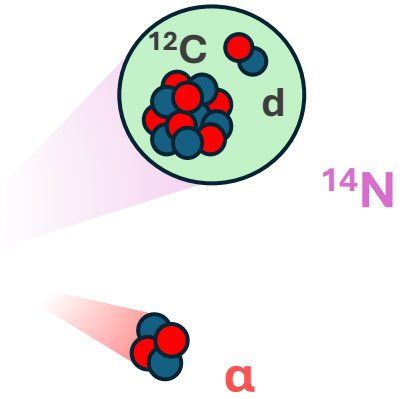


# Channels identification

$^{6}Li + {}^{12}C$ @ **6MeV** ( $\theta_{lab.}$~ 130º) telescope configuration




**Deuteron transfer**
$^{12}C(^{6}Li, \alpha)^{14}N$

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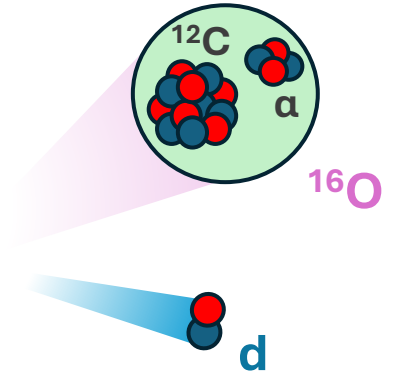

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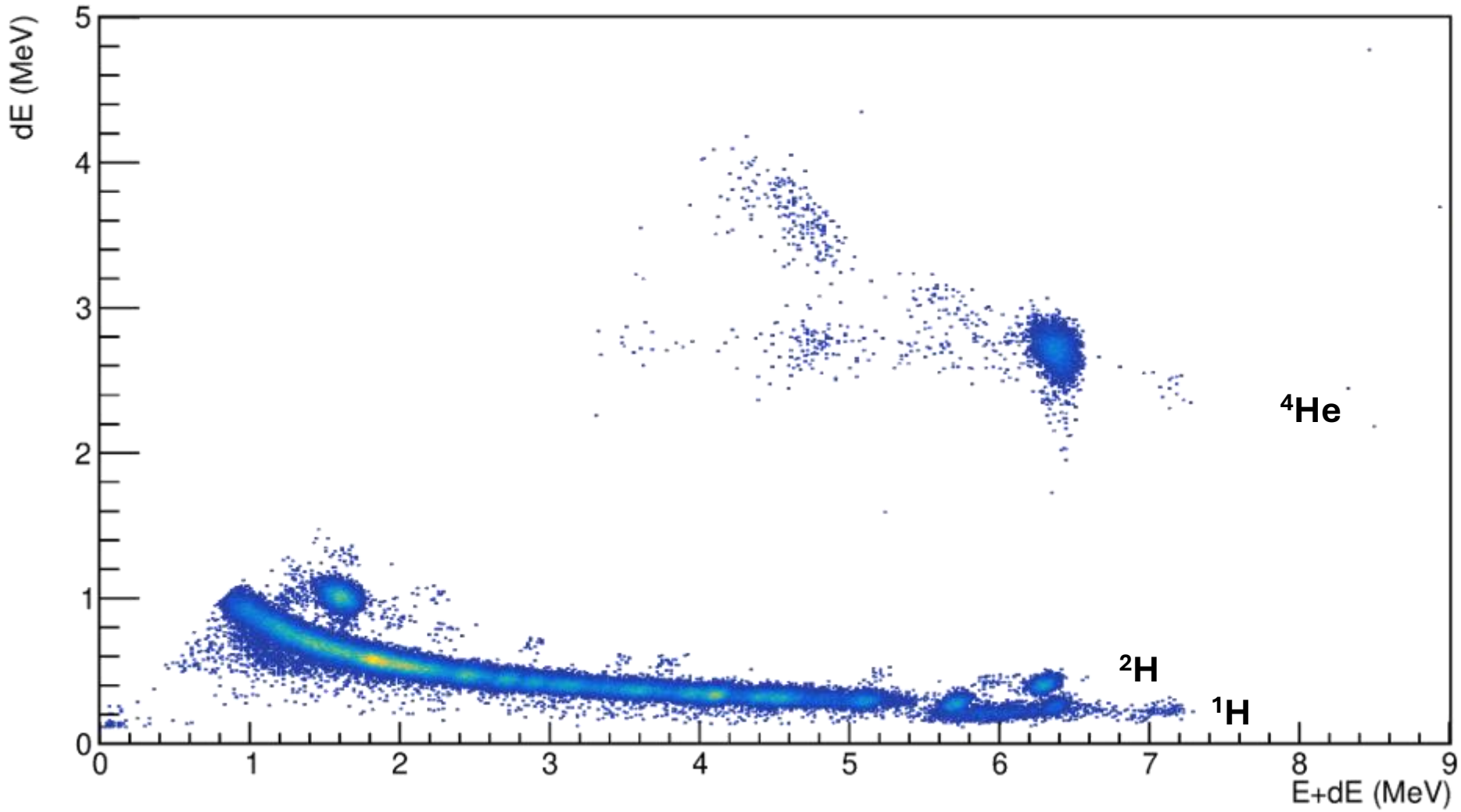
$^{6}Li + {}^{12}C$ @ **6MeV** ( $\theta_{lab.}$~ 130º) telescope configuration

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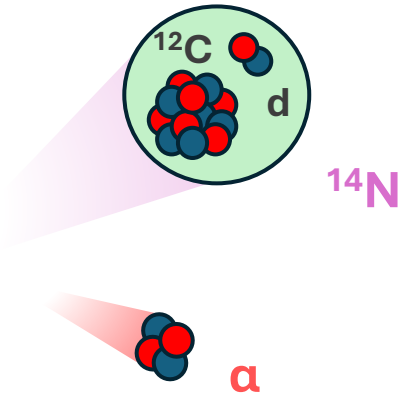
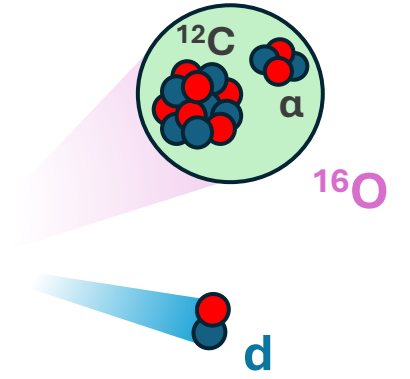
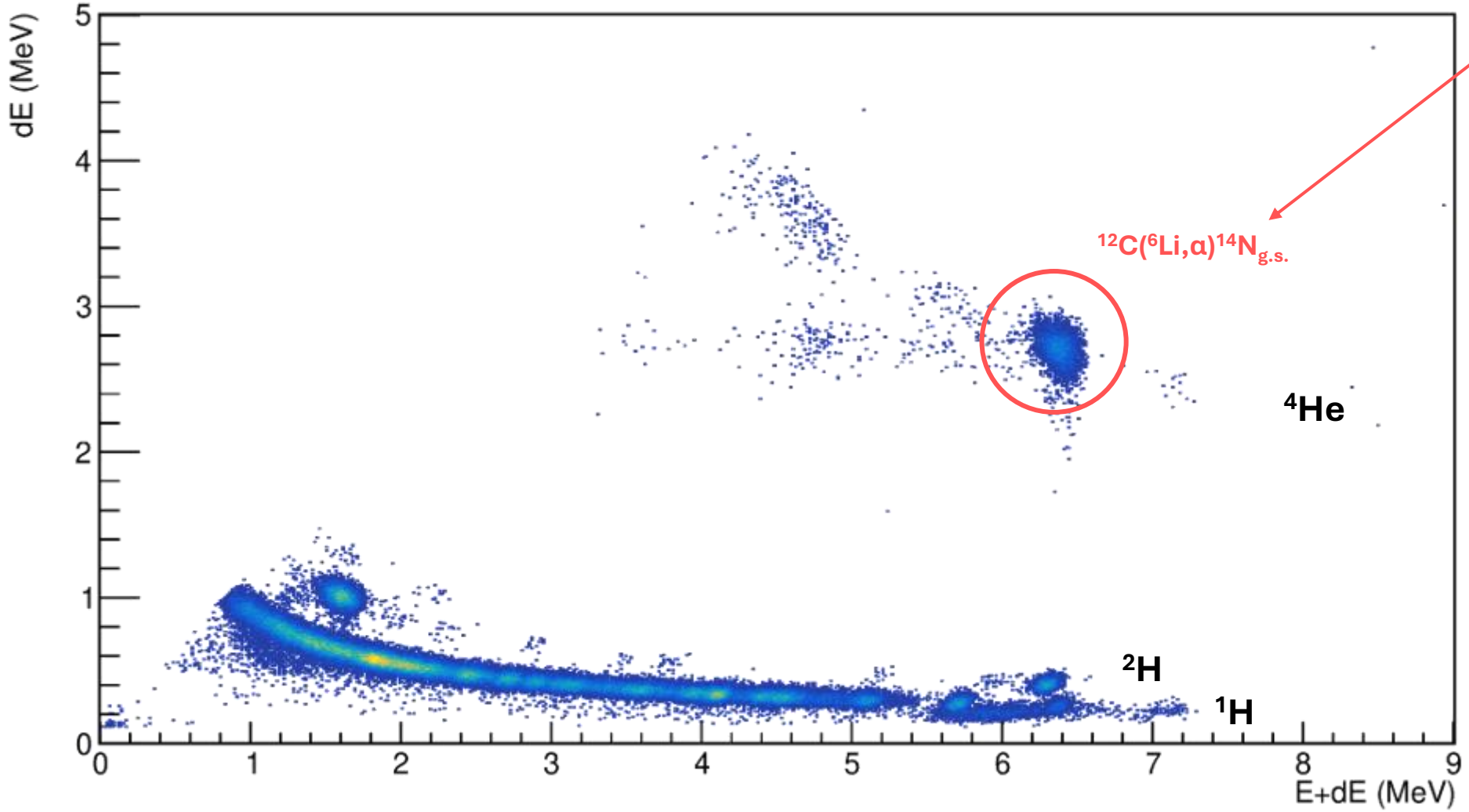



**Alpha transfer**
$^{12}C(^{6}Li,d)^{16}O$



# Channels identification

$^{6}Li + {}^{12}C$ @ **6MeV** ( $\theta_{lab.}$~ 130º) telescope configuration

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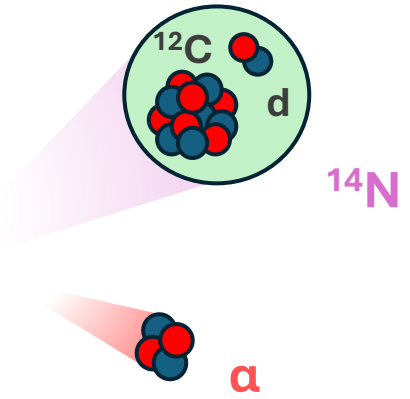


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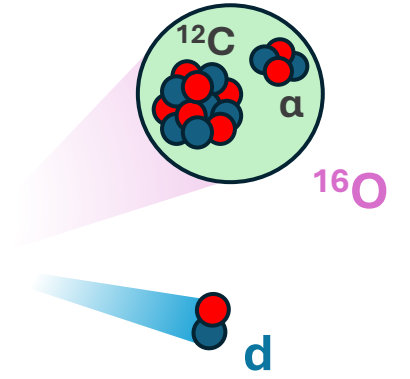

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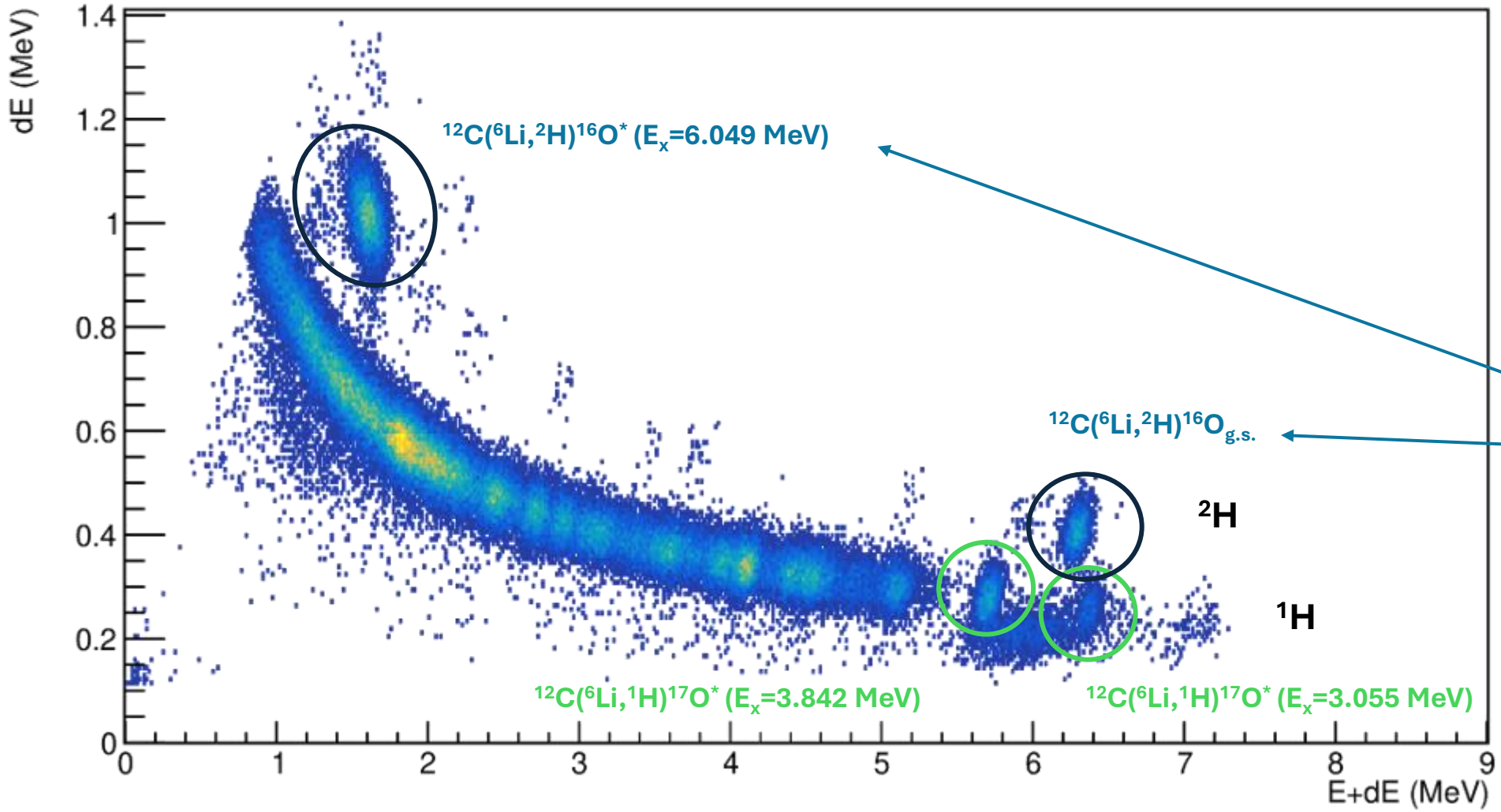


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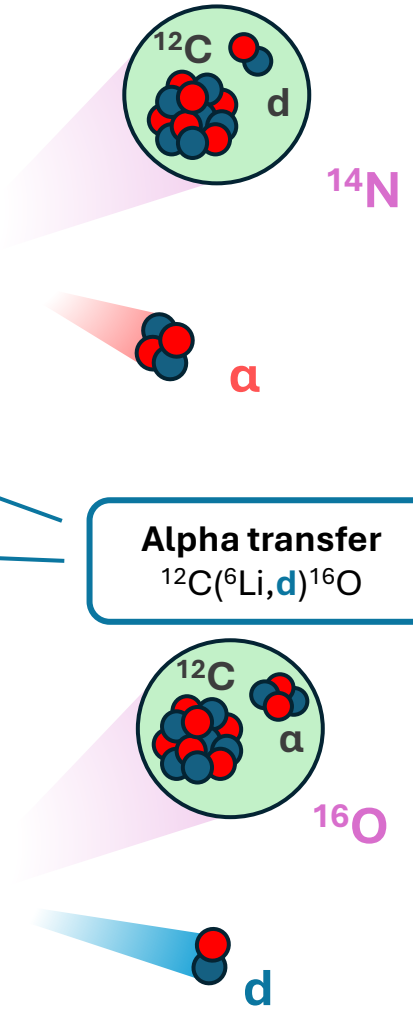
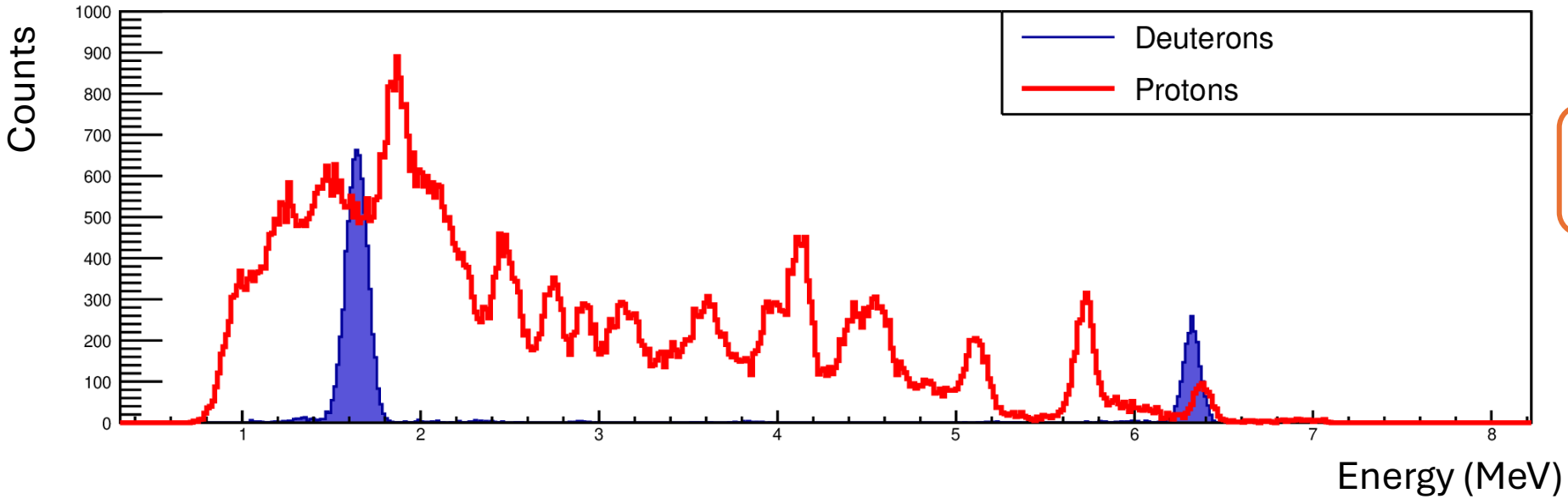
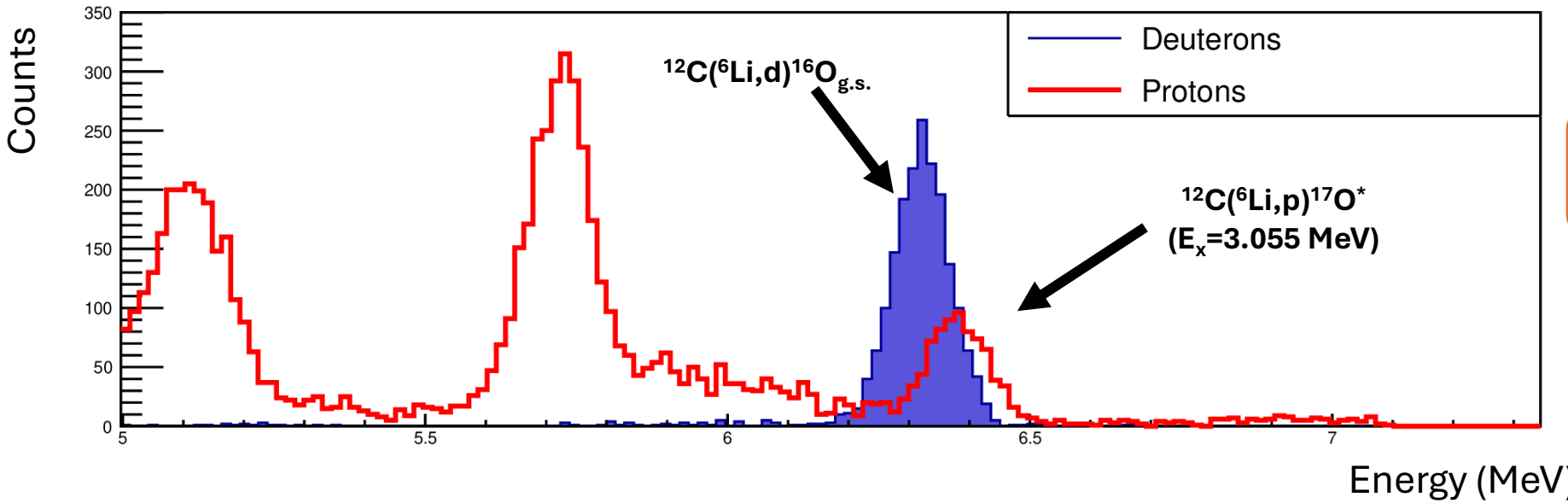


# Channels identification

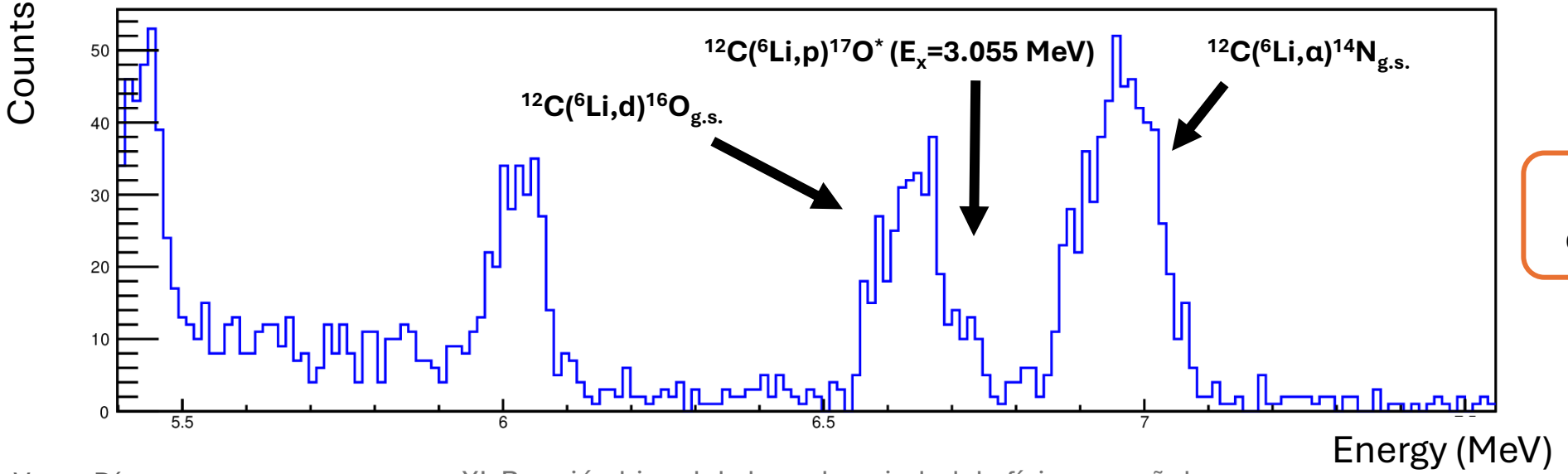



**Telescope projections**

# Channels identification




**Telescope projections**

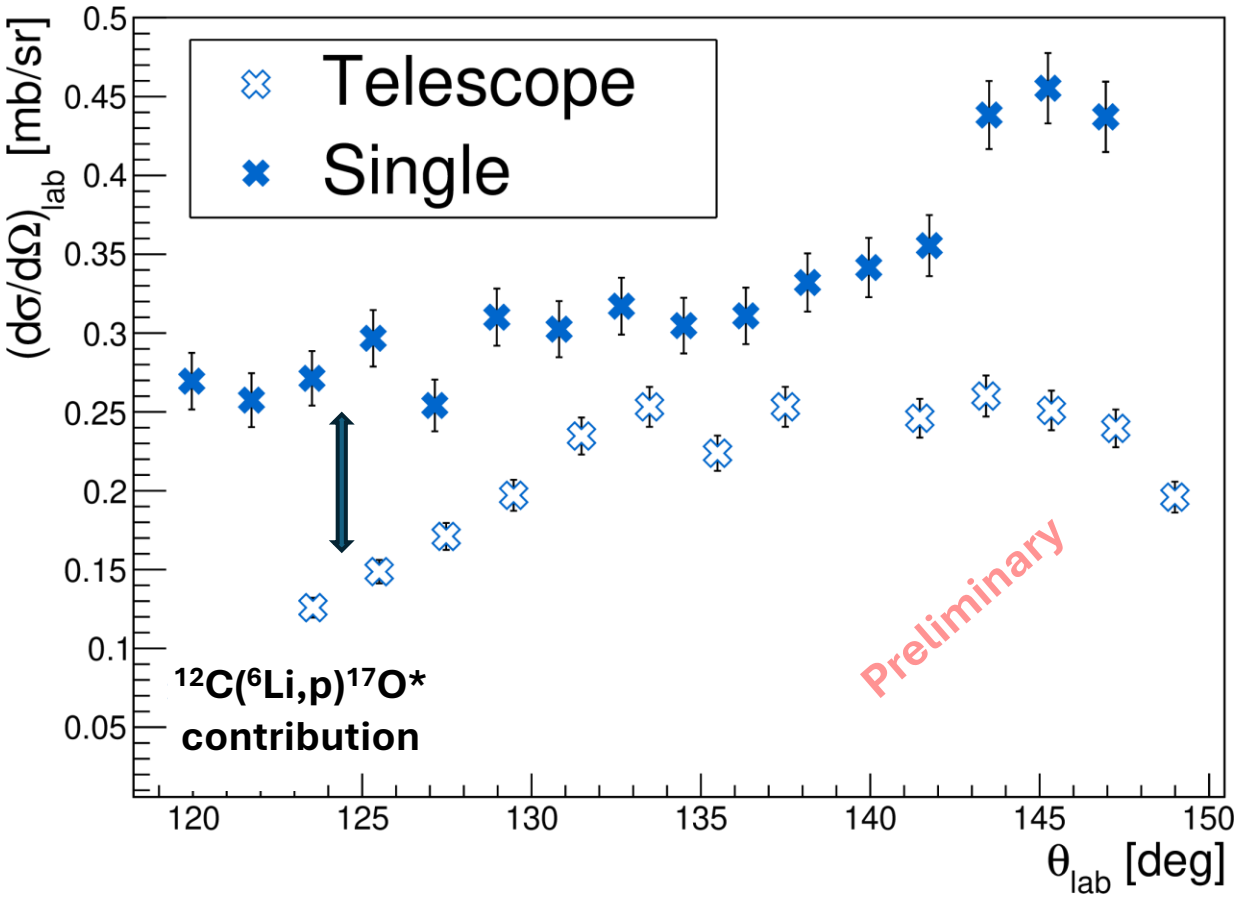



**Single configuration**

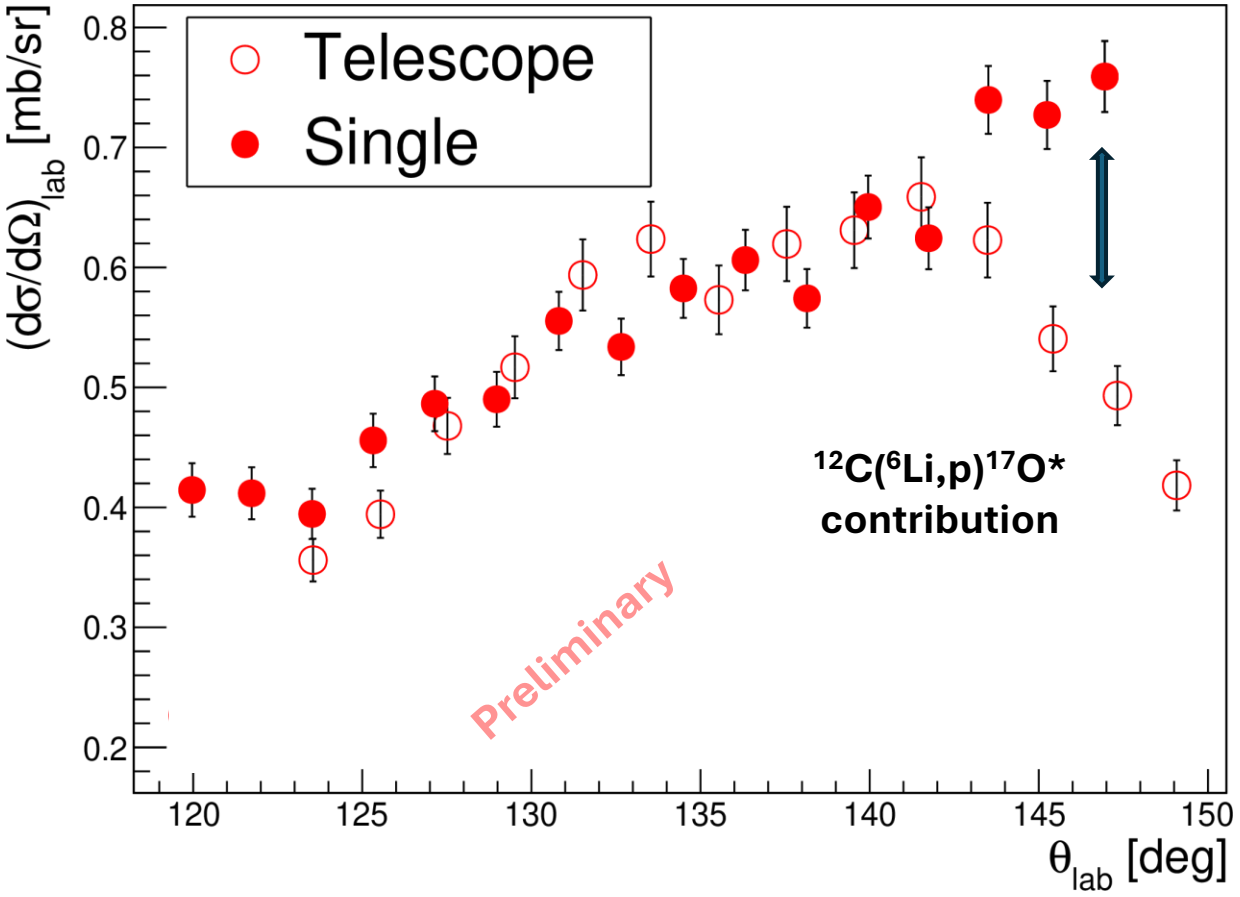
# Cross section angular distribution

$^{6}Li + {}^{12}C$ @ **6MeV**

$^{12}C(^{6}Li,d)^{16}O_{g.s.}$



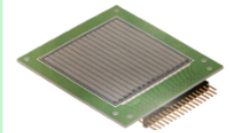

$^{12}C(^{6}Li,\alpha)^{14}N_{g.s.}$



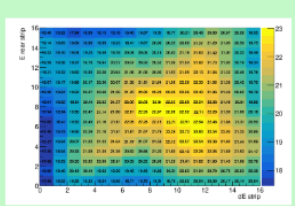
# Summary

$^{6}Li+^{12}C$

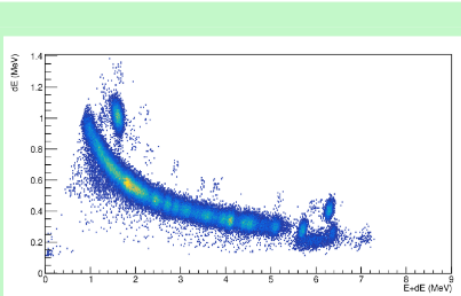
S/DSSSD



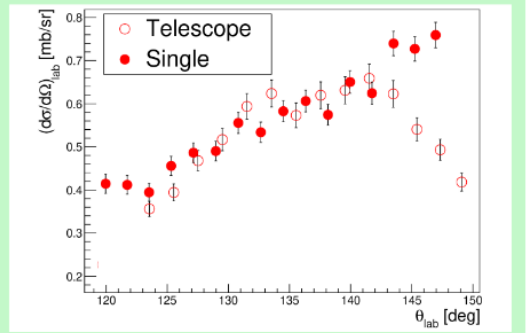
Detector thickness



Telescope configuration



Angular distribution




Setup development

Acquisition system characterization

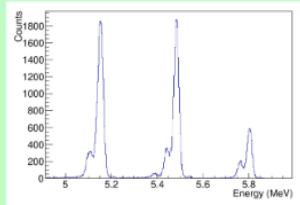
Measurements

Cross section

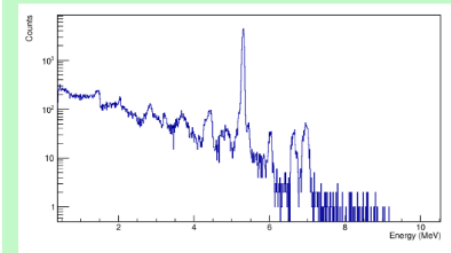
Low-energy indirect reactions

New reaction chamber

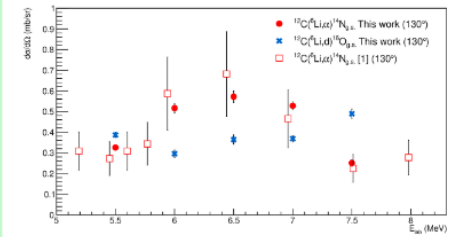
Energy resolution




Single configuration




Excitation functions



# Outlook

- Repeat the **$^{6}$Li+$^{12}$C measurements** with telescope and analyze the data.
- **Improve and enlarge** the acquisition system with digitizers.
- New **detectors holders** and **target controller**.
- **Low energy indirect measurement with astrophysical interest.**

# Acknowledgments

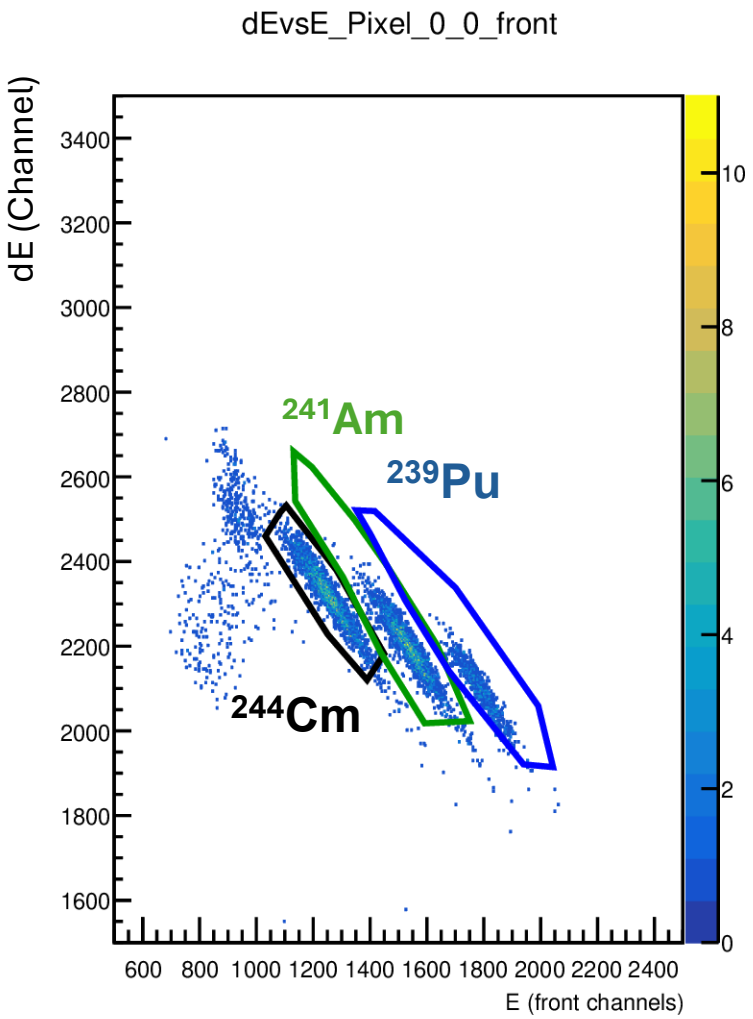

- This project has received funding from the *Ministerio de Ciencia, Innovación y Universidades* under grant agreement No **PID2024-155965OB-I00** and **PID2021-123879OB-C21.**

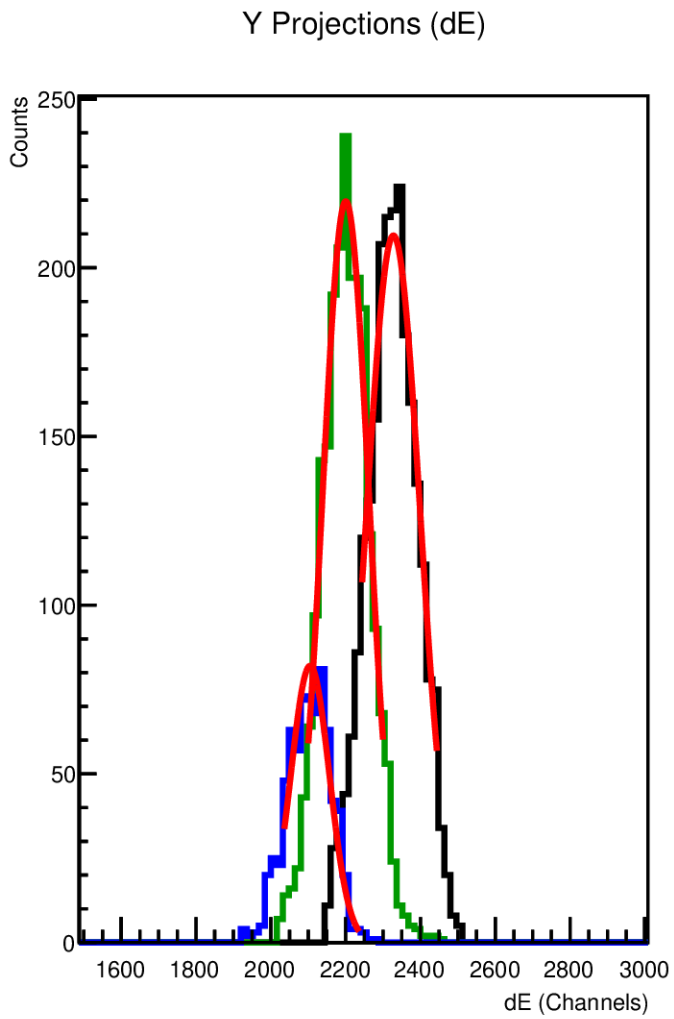
- Acknowledges funding from the *Agencia Estatal de Investigación (AEI)* through a predoctoral contract for the *Formación de Personal Investigador (**FPI**)*, Grant No. **PRE2022-102551**.

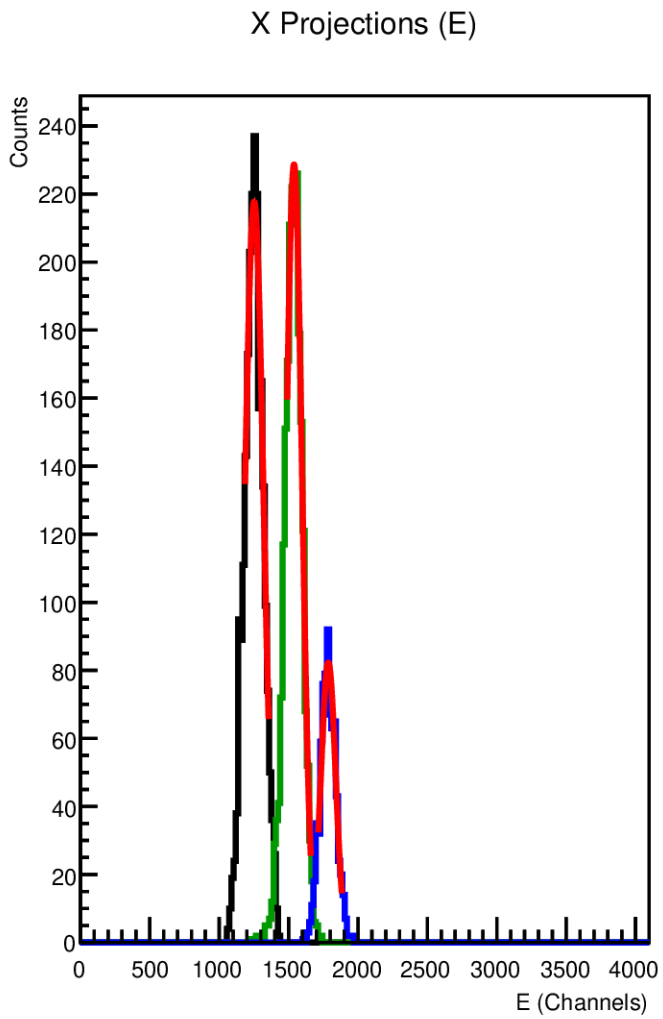



# Backup slides

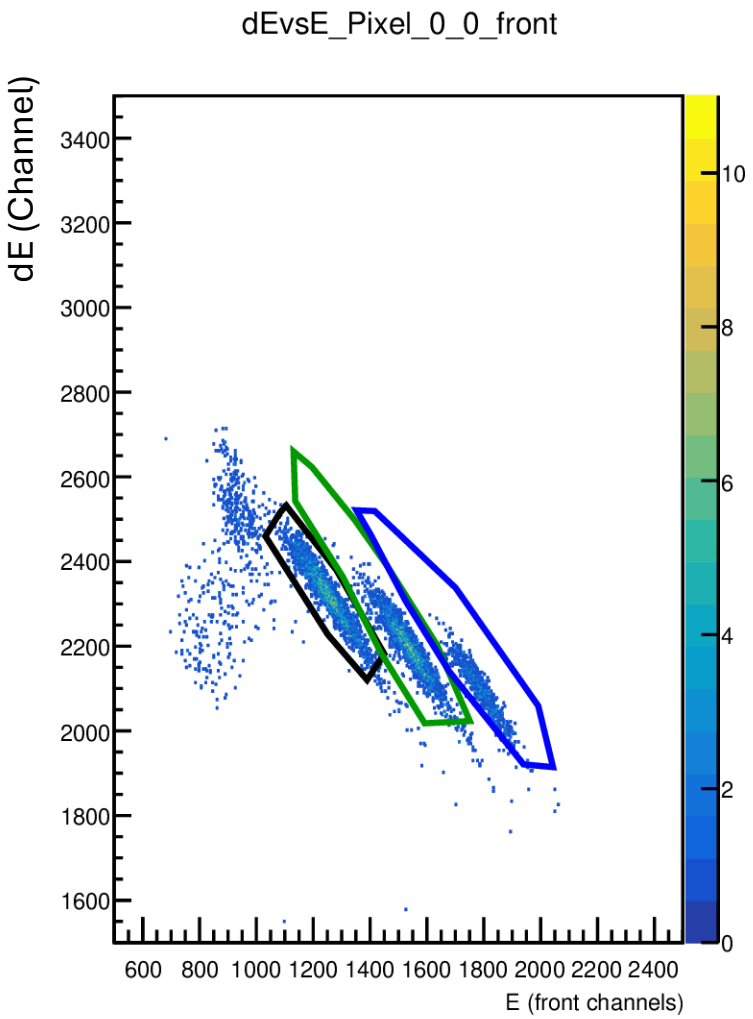
# Thickness characterization

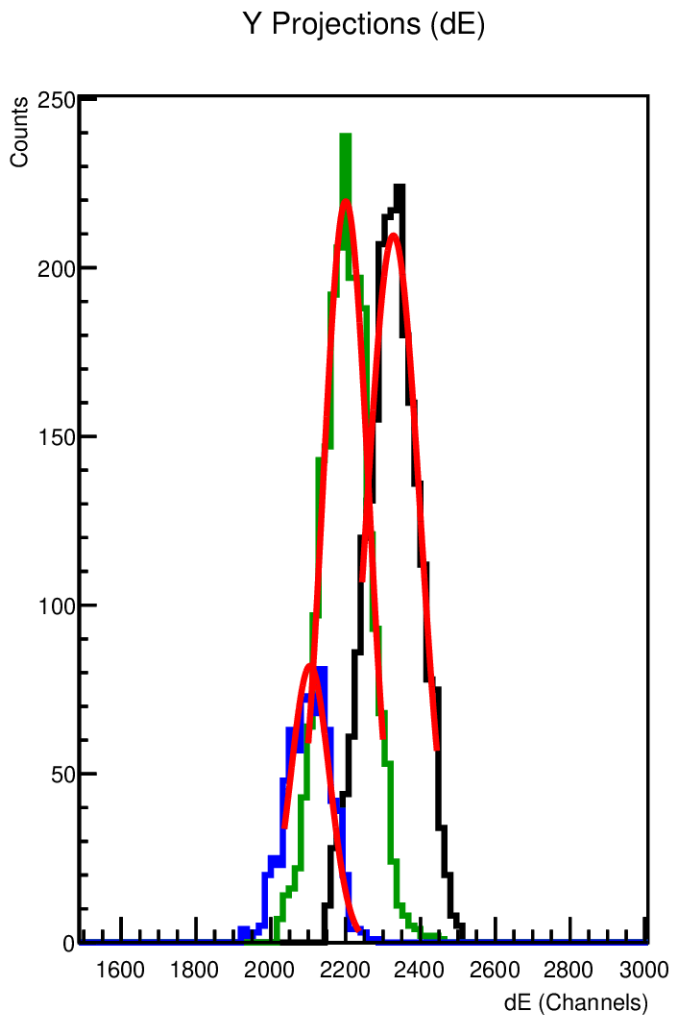


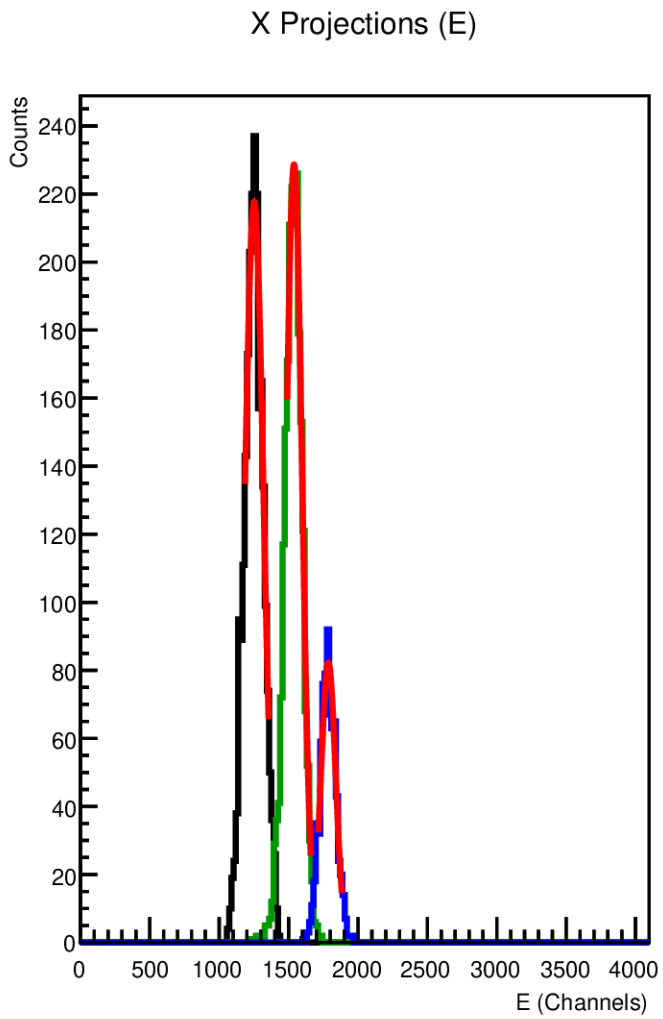



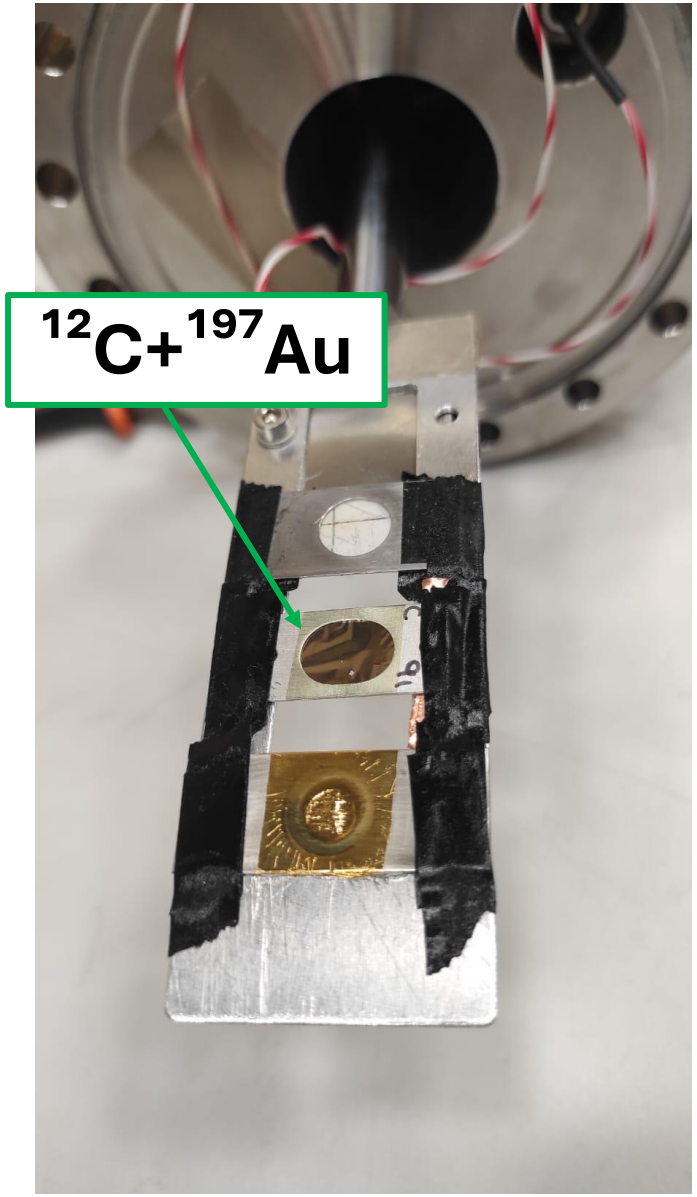
# Thickness characterization



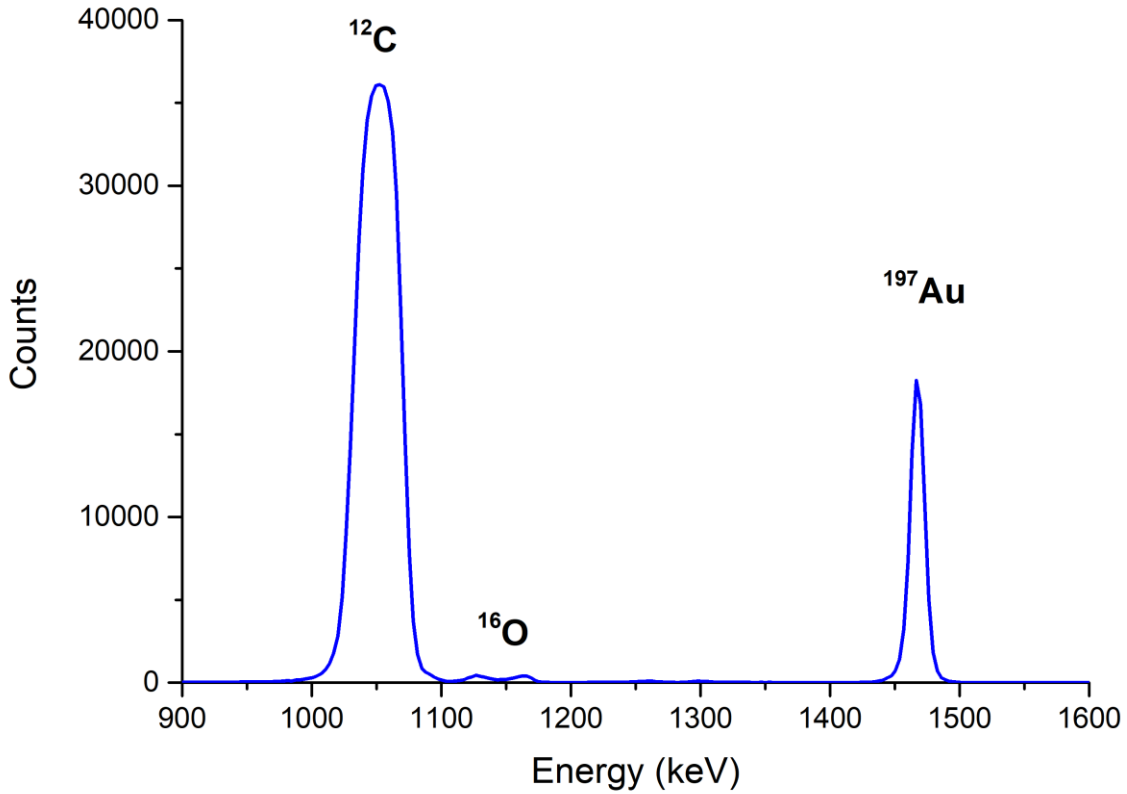



# Target characterization




**p-EBS characterization**




**Nominal thickness**

91 µg/cm² of $^{12}C$

**Characterized thickness**

115±2 µg/cm² of $^{12}C$

1.5±0.1 µg/cm² of $^{16}O$

12.2±0.2 µg/cm² of $^{197}Au$

# Cross section determination

$$\frac{\sigma_C^{el.}}{\sigma_C^{ruth.}}(\theta_{c.m.}) = F(\theta) \cdot K \cdot \frac{N_C^{el.}}{N_{Au}^{el.}}$$

$$\frac{d\sigma_{reac.}}{d\Omega}(\theta_{c.m.}) = \frac{N_C^{reac.}}{N_C^{el}} \cdot \frac{J_{reac.}^{lab\to c.m.}}{J_{el.}^{lab\to c.m.}} \cdot \sigma^{el.}(\theta_{c.m.})$$

$$K = \left(\frac{Z_{Au} \cdot A_C}{Z_C \cdot A_{Au}} \cdot \frac{A_{Li} + A_{Au}}{A_{Li} + A_C}\right)^2 \cdot \frac{\rho_{Au}}{\rho_C}$$

$$F(\theta) = \frac{sin^4\left(\frac{\theta_{c.m.}^C}{2}\right)}{sin^4\left(\frac{\theta_{c.m.}^{Au}}{2}\right)} \cdot \frac{J_C^{lab\to c.m.}}{J_{Au}^{lab\to c.m.}}$$

$$\frac{d\sigma_{reac.}}{d\Omega}(\theta_{c.m.}) = \frac{N_C^{reac.}}{N_{Au}^{el.}} \cdot \frac{J_{reac.}^{lab\to c.m.}}{J_{el.}^{lab\to c.m.}} \cdot F(\theta) \cdot K \cdot \sigma_C^{ruth.}$$

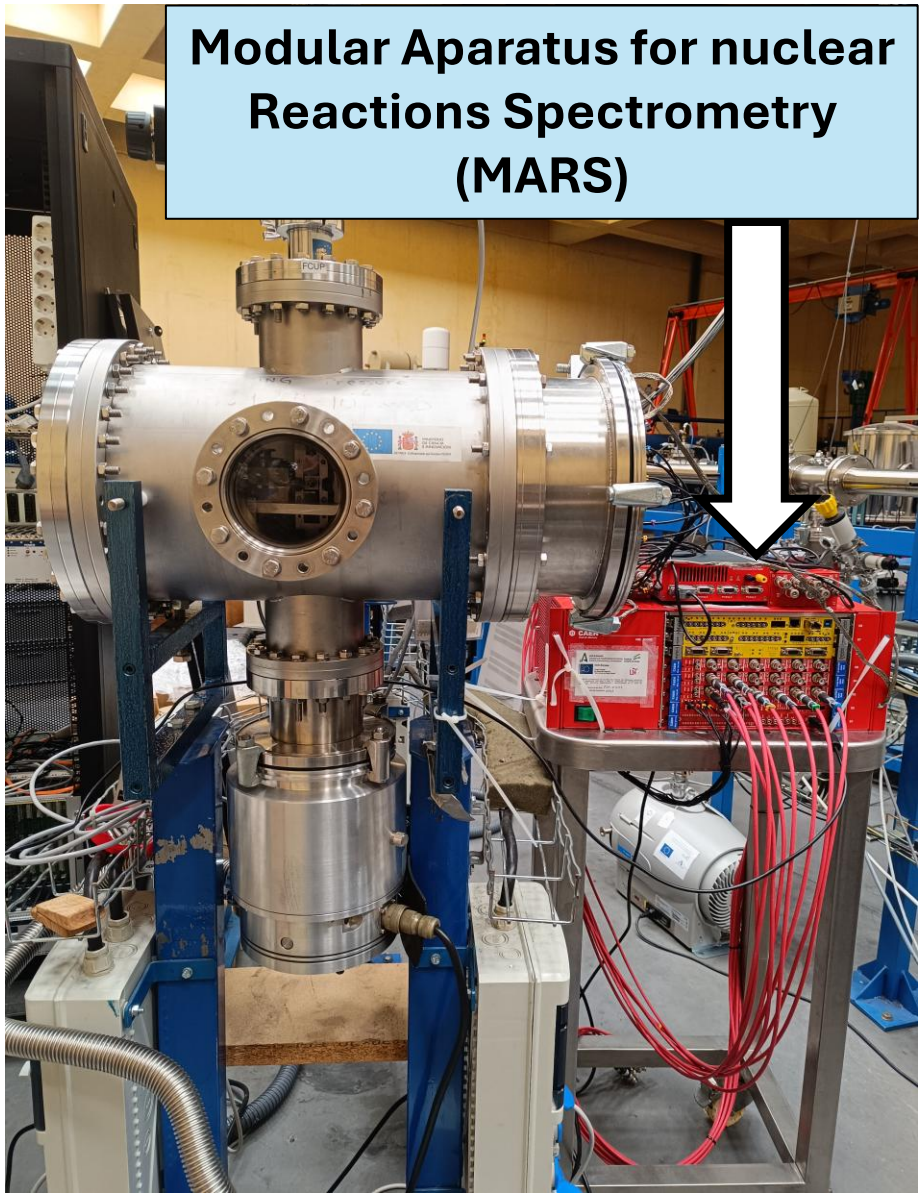
# MARS

## Detectors

8 Surface Barrier silicon Detectors

- 500 μm thickness
- 50 $mm^2$ active area

**Modular Aparatus for nuclear Reactions Spectrometry (MARS)**

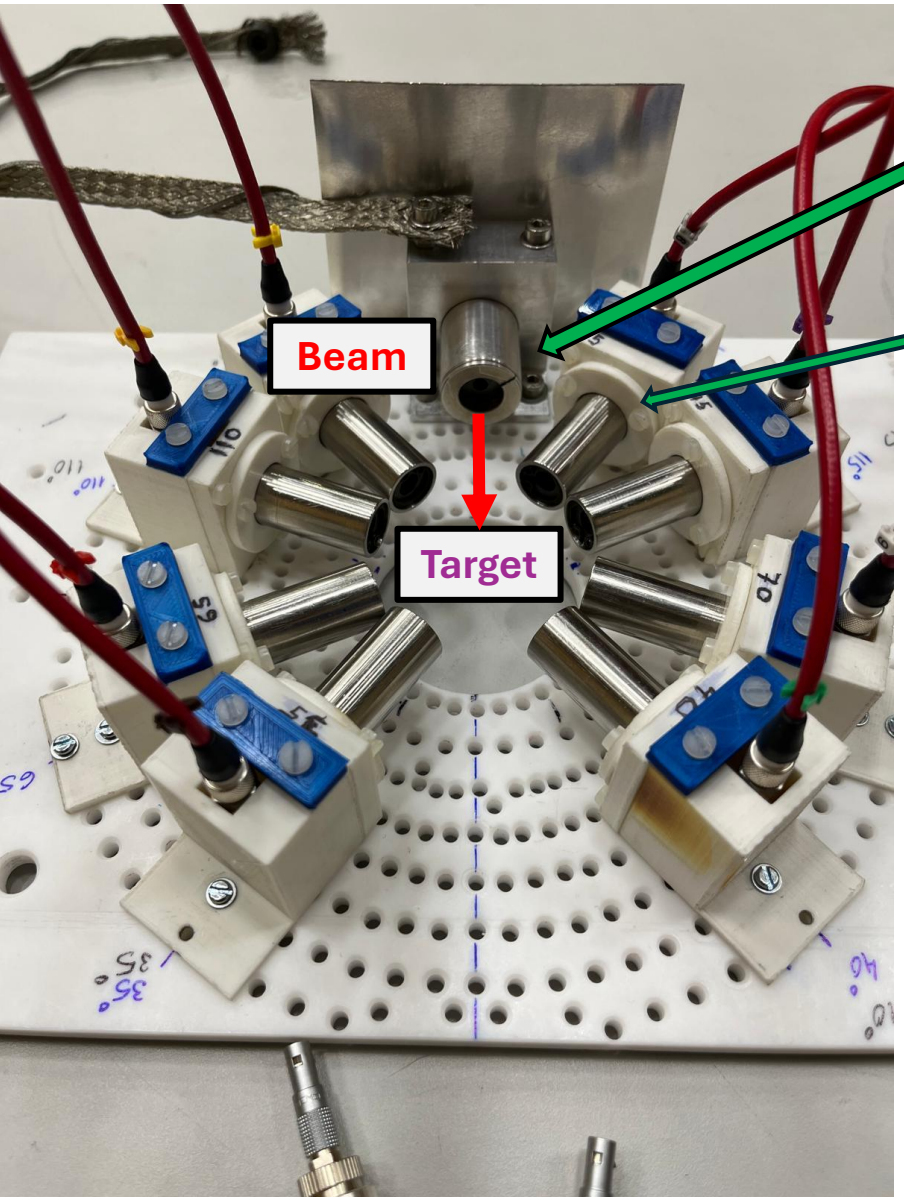


## DAQ

V1725S digitizer from CAEN

- 14 bit resolution
- Sample rate of 250 MS/s
- DPP-PHA firmware

# Experimental setup

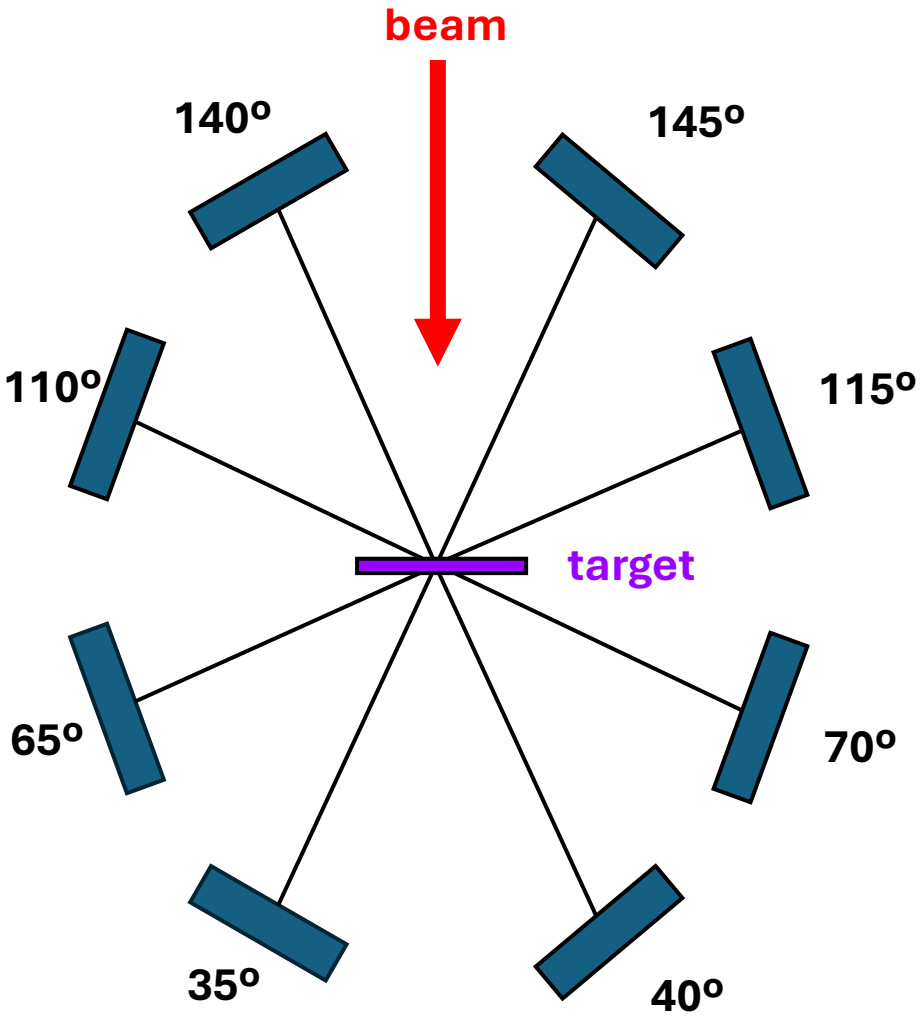



**Beam collimator**
**Ø=2 mm**

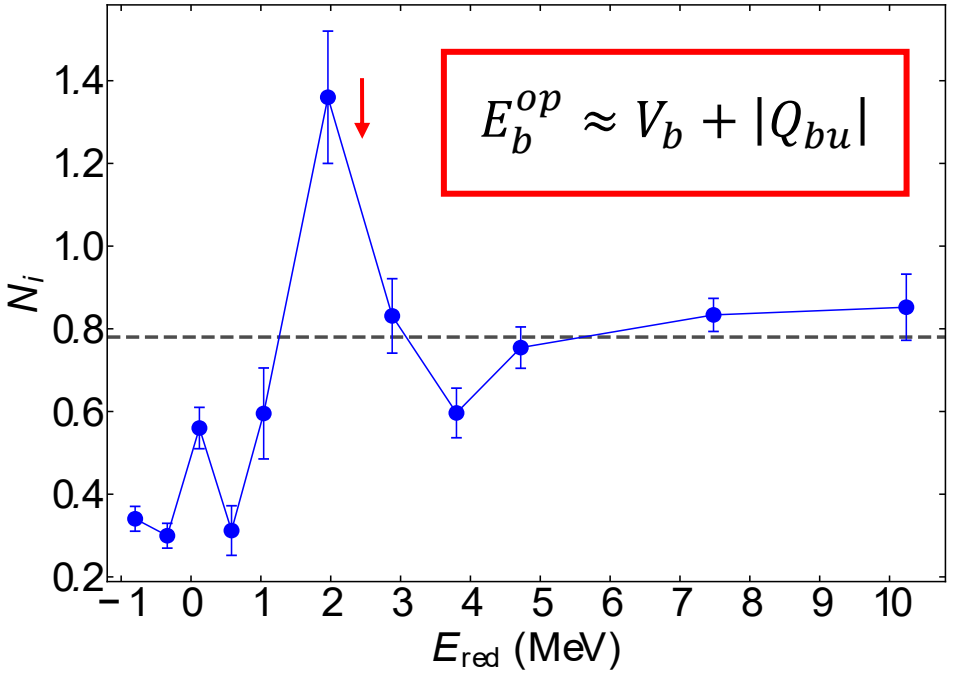
**Detectors collimator**
**Ø=6 mm**

**8 Surface Barrier silicon detectors (500μm)**

## Detectors setup



# Systematic study

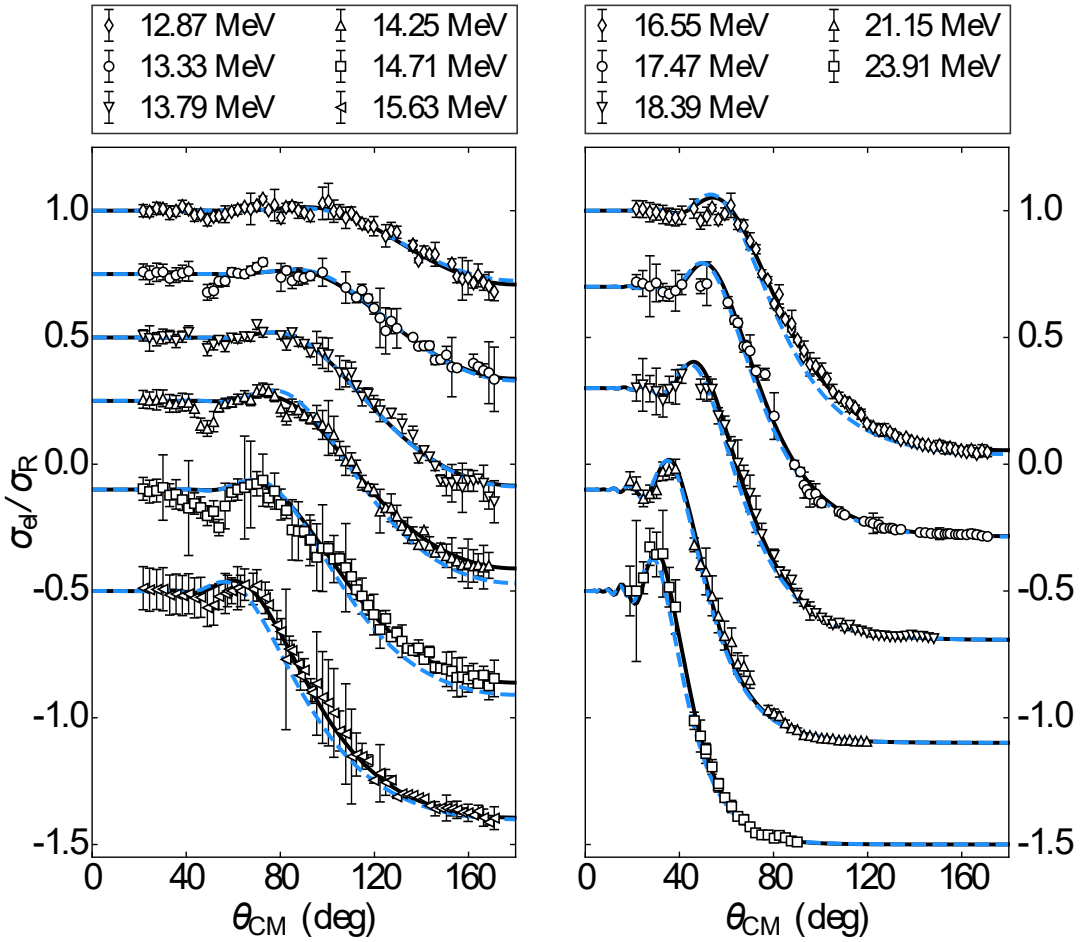



$$U_N = N_r\, V_{SPP2}(r) + i N_i V_{SPP2}(r)$$

$$V_{SPP2}(r) = \iint \rho_1(\vec{r}_1)\rho_2(\vec{r}_2)\, U_0 e^{-\left(\frac{r}{a}\right)^2} e^{-\frac{4v^2}{c^2}}\, d\vec{r}_1 d\vec{r}_2$$

L. Chamon *et al.* Comput. Phys. Commun. 267, 108061 (2021)

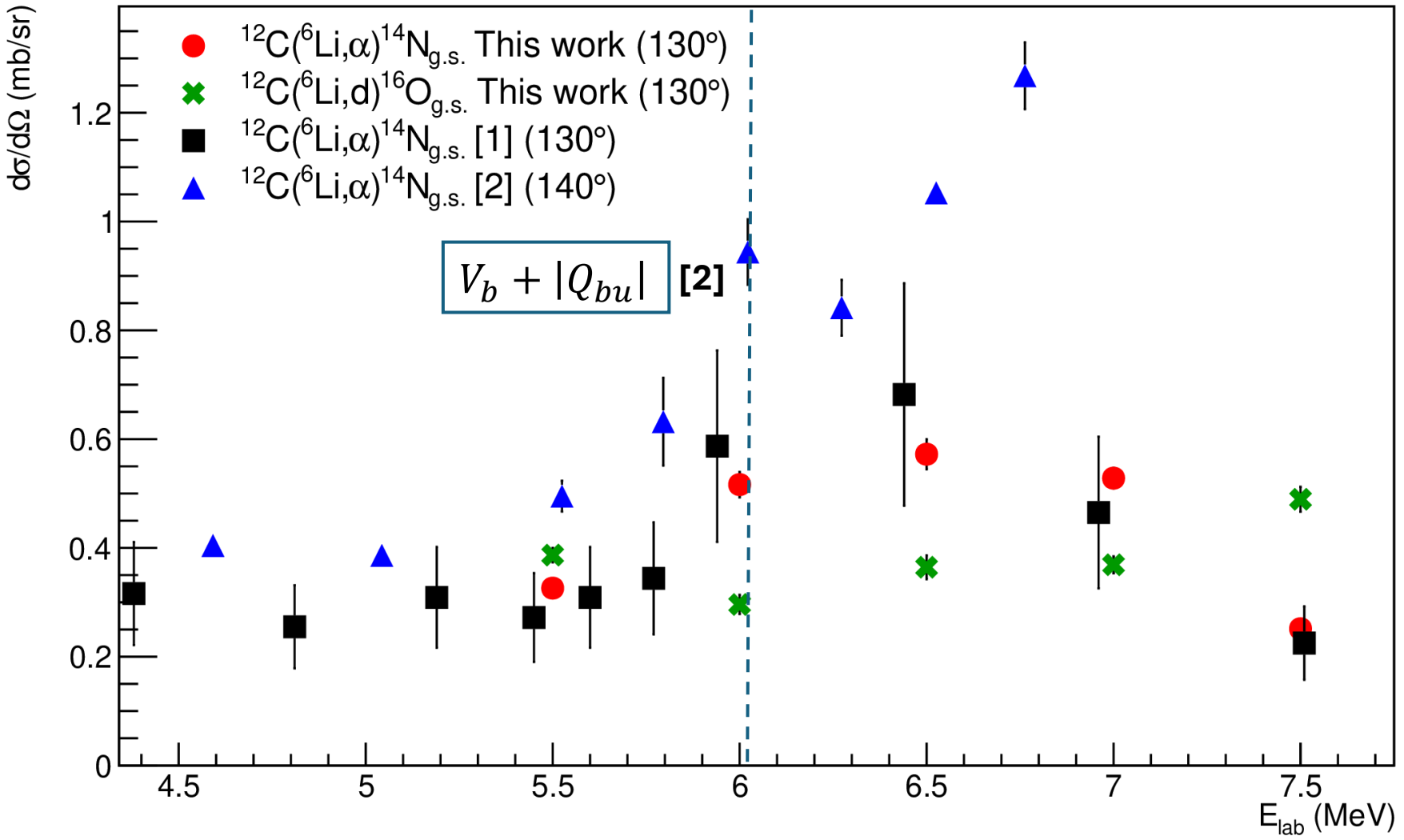
$^{7}$Li+$^{80}$Se elastic scattering cross section




L. Garrido-Gómez, A. Vegas-Díaz, J.P. Fernández-García and M.A.G. Alvarez, Phys. Rev. C 109, 054608 (2024)

# Excitantion functions

Excitation function of channels $^{12}C(^{6}Li,\alpha)^{14}N_{g.s.}$ and $^{12}C(^{6}Li,^{2}H)^{16}O_{g.s.}$ at 130º (lab.)





**[1]** J. Schwenzel et al.
*Nucl. Phys. A **367**, 145-156 (1981).*

**[2]** L. Garrido-Gómez et al.
*Phys. Rev. C **109**, 054608 (2024).*

# Systematic study

Weakly bound projectile & light target

| Projectile | Targets |
|---|---|
| $^{6}$Li, $^{7}$Li… | $^{12}$C, $^{14}$N… |

Weakly bound projectile & medium mass target

| Projectile | Targets |
|---|---|
| $^{6}$Li, $^{7}$Li, $^{9}$Be, $^{10}$B | $^{120}$Sn |
| $^{6}$Li, $^{7}$Li, $^{6}$He, $^{9}$Be, $^{11}$Be $^{10}$B | $^{64}$Zn |

**Measured at FNB experimental line**

**M. A. G. Alvarez, *et al.* Phys. Rev. C 100, 064602 (2019).**
**L. Garrido-Gómez, A. Vegas-Díaz, J.P. Fernández-García and M.A.G. Alvarez, Phys. Rev. C 109, 054608 (2024).**