Measurement of the Hoyle State Radius using single and mutual excitation inelastic scattering

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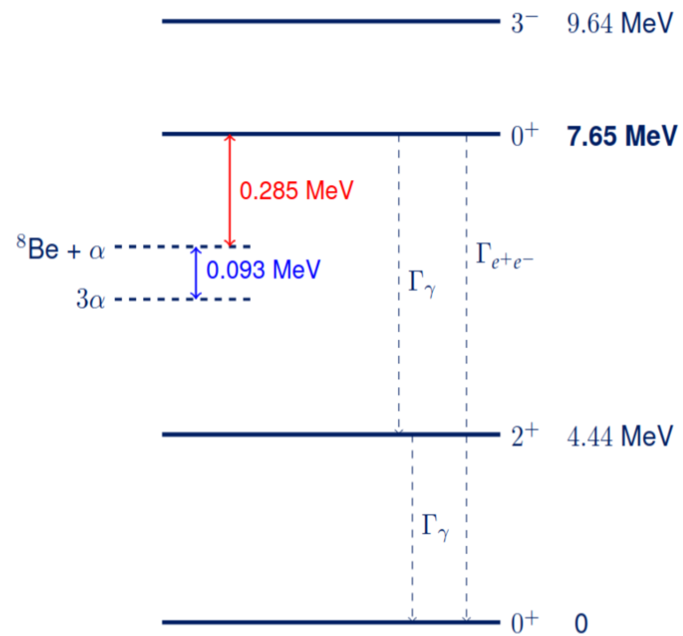
Colloque GANIL, 2026

Hoyle state ^{12}C (0_2^+) :

Resonant state of ^{12}C at 7.65MeV excitation energy.
Slightly above the 3α threshold (~ 0.285MeV).
Explains the abundance of ^{12}C by considering
the 3α process (α + α → ^8Be & ^8Be + α → ^{12}C + γ).

Hoyle state Decay :

- Sequential Decay : Multi-step decay process
($^{12}C^*$ → ^8Be + α & ^8Be → α + α).
- Direct Decay : Directly to 3α bypassing the ^8Be
intermediate state ($^{12}C^*$ → α + α + α)
- γ- emission : Transition to 4.44 MeV and then
to the ground state.
- e^+ - e^- production : direct decay to the ground state.



Spatial Configuration :

- *Nuclear Lattice EFT [1] :*
  Obtuse triangle for the Hoyle state.
- *Monte Carlo SM [2] :*
  Compact 3α structure for the Hoyle state.

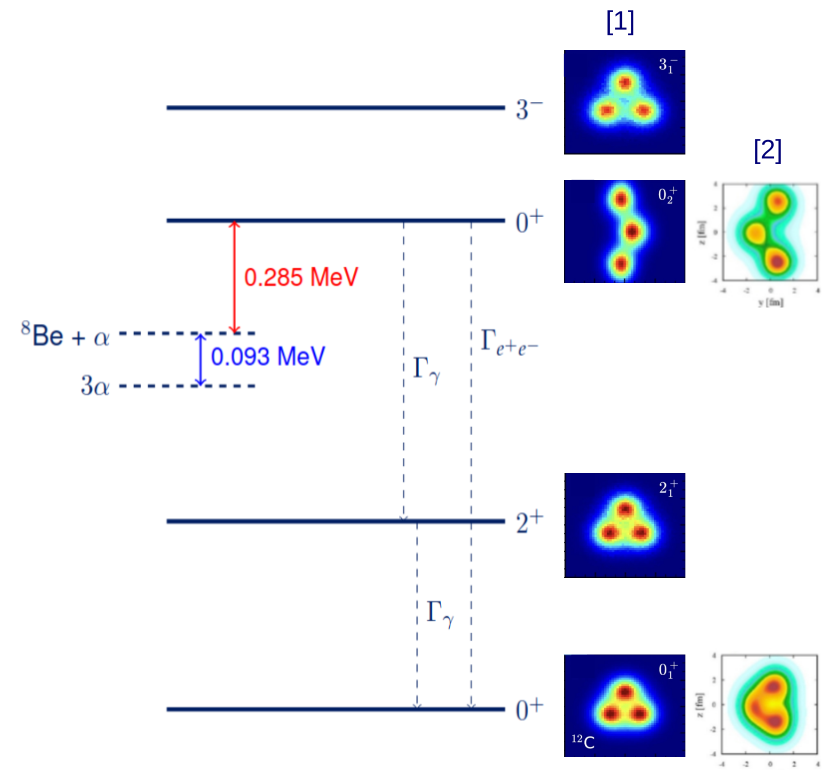
➔ No **consensus** on the Hoyle state **spatial configuration**.

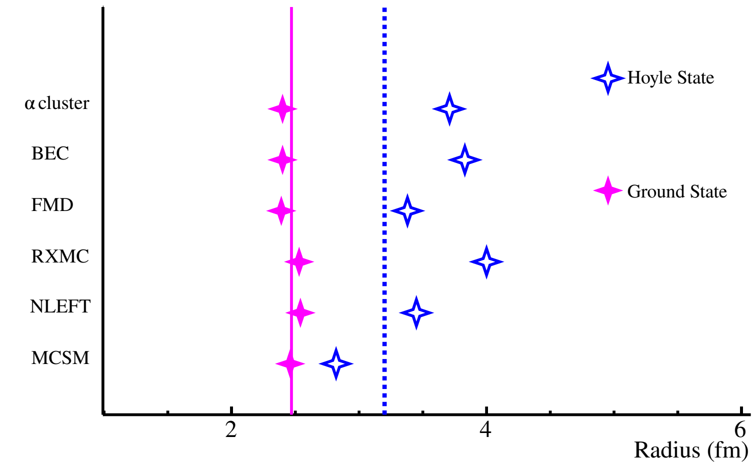
Matter Radius :

All the theoretical frameworks predict the Hoyle State to be larger than the ground state.

Different models predict different Hoyle state radius values from 2.82 fm to 4 fm.

➔ No **consensus** on the Hoyle state **radius** from the theoretical point view.





[1] : S. Shen, Nature Com. 14, 2777

[2] : T. Otsuka et al., Nature Com. 13, 2234

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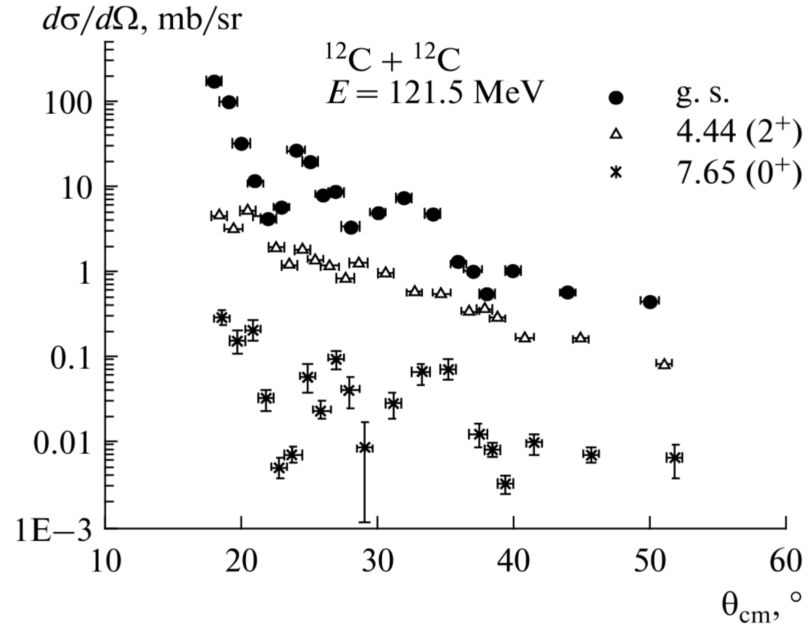

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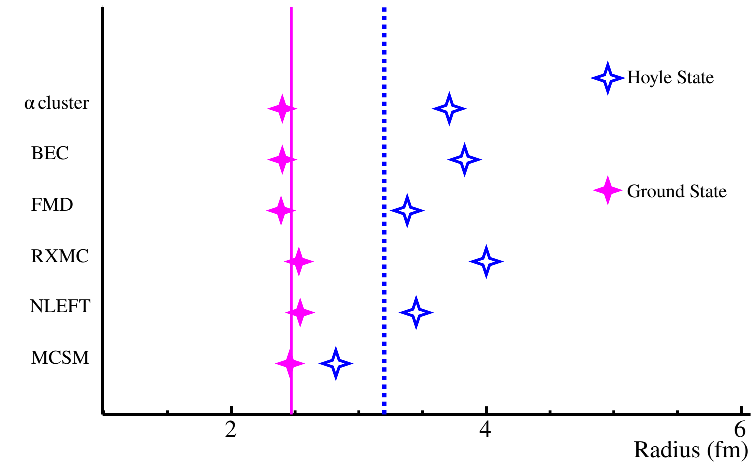

[3] : Maslov et al., Physics of Particles and Nuclei Letters 8 (2011).

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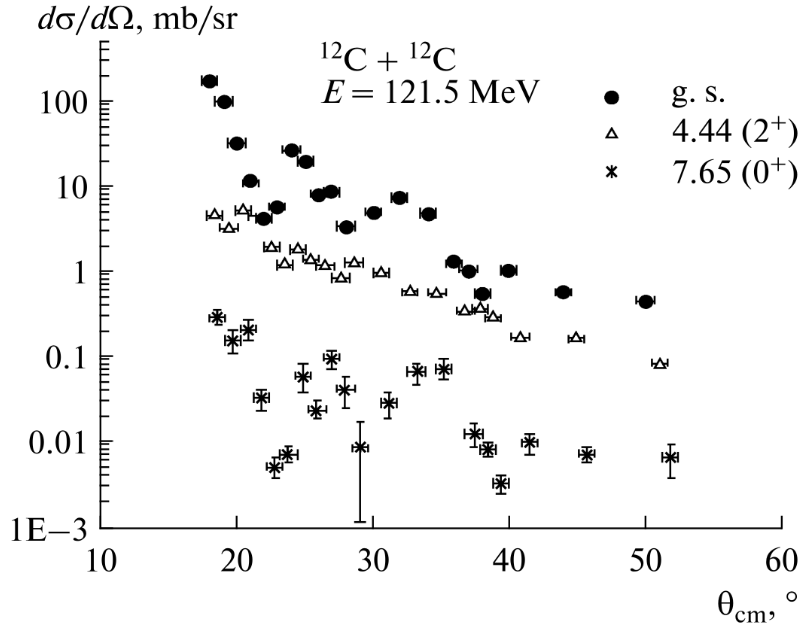
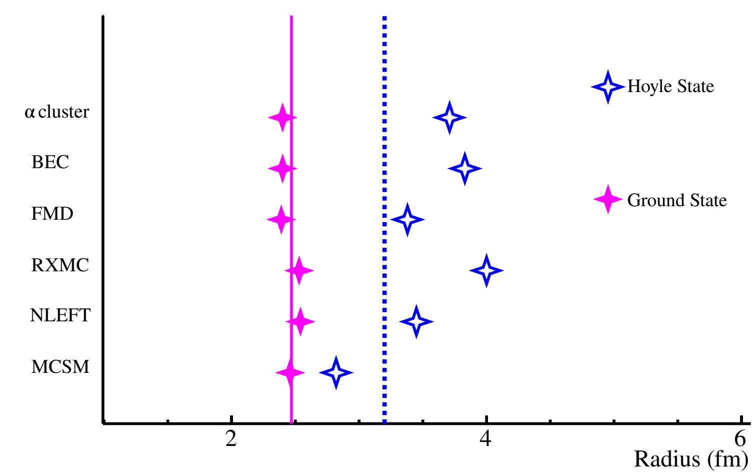
➔ **Inelastic** cross sections need to be **remeasured** to serve as reliable input for **advanced** modeling**.**





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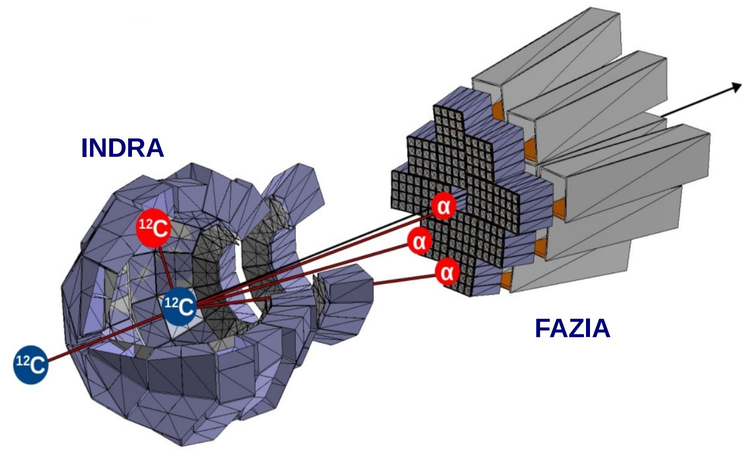
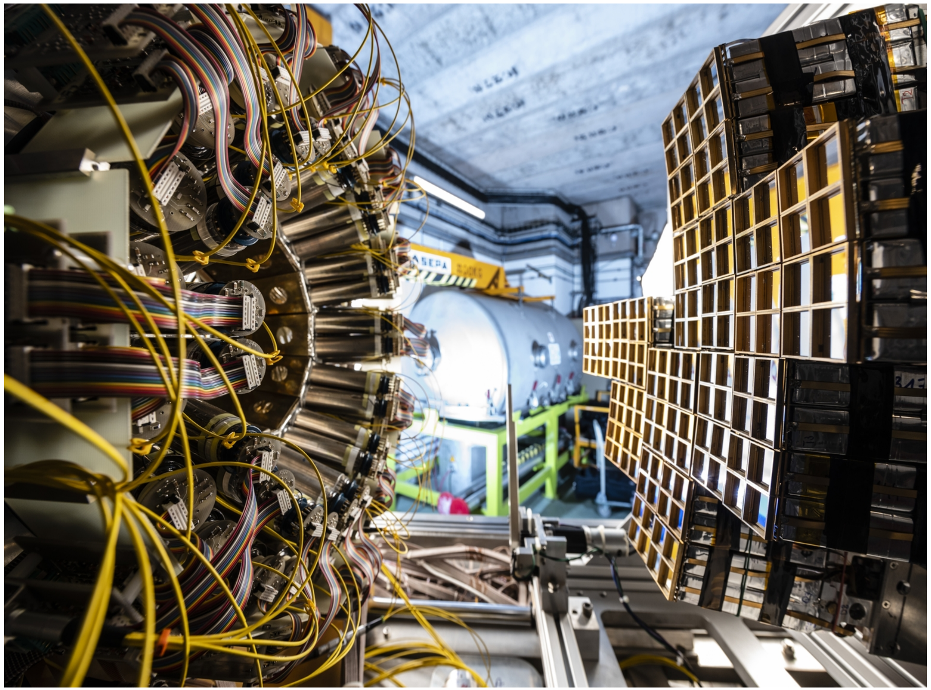




How can we measure these cross sections ?

E881 Experiment :

A ^{12}C target was irradiated with a ^{12}C beam at an energy of 8.81 MeV/A at GANIL in April 2025.

The diffused ^{12}C or three α particles resulting from the decay of the projectile-like are detected using the FAZIA detector placed from 2° to 13.6°.

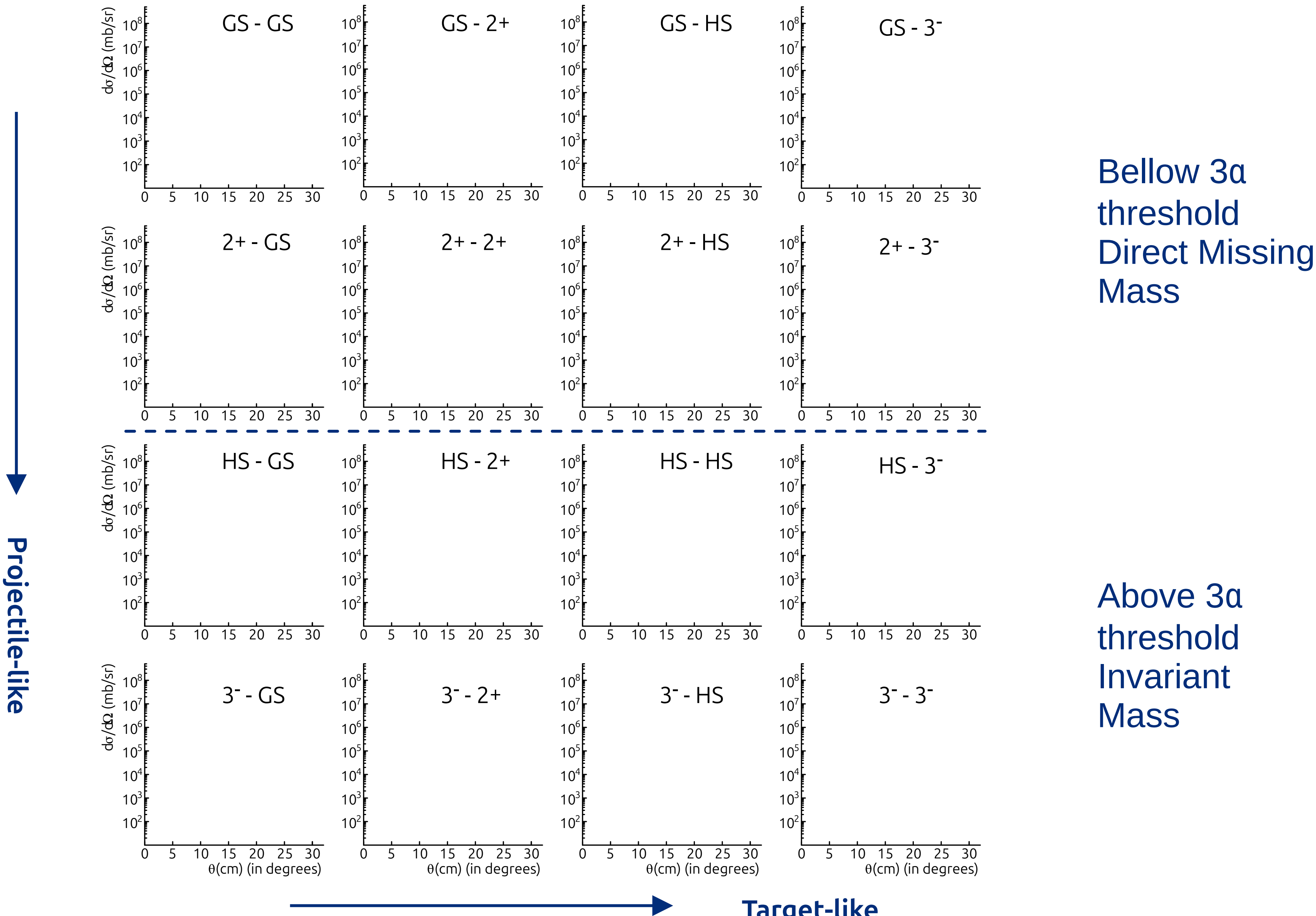
FAZIA :

12 blocks consisting of 16 three stages telescopes (2x2 cm²)

- Si1 (300 µm), Si2 (500 µm) and CsI (10 cm)

Allows for the use of multiple identification methods :

- PSA (Pulse Shape Analysis) , ΔE – E method


GS - GS
GS - 2+
GS - HS
GS - 3⁻
2+ - GS
2+ - 2+
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2+ - 3⁻
HS - GS
HS - 2+
HS - HS
HS - 3⁻
3⁻ - GS
3⁻ - 2+
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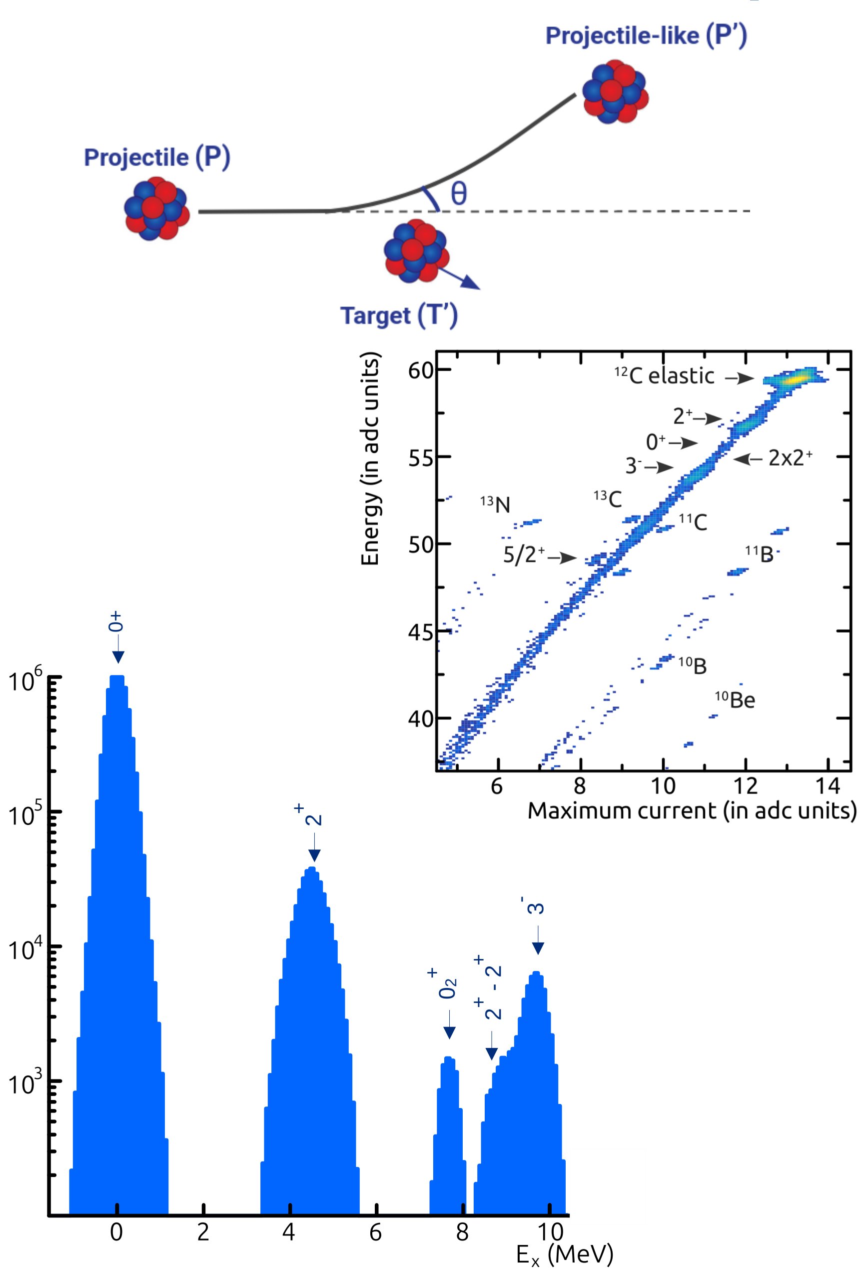
3⁻ - 3⁻
dσ/dΩ (mb/sr)
θ(cm) (in degrees)
Projectile-like
Target-like
Bellow 3α threshold Direct Missing Mass
Above 3α threshold Invariant Mass



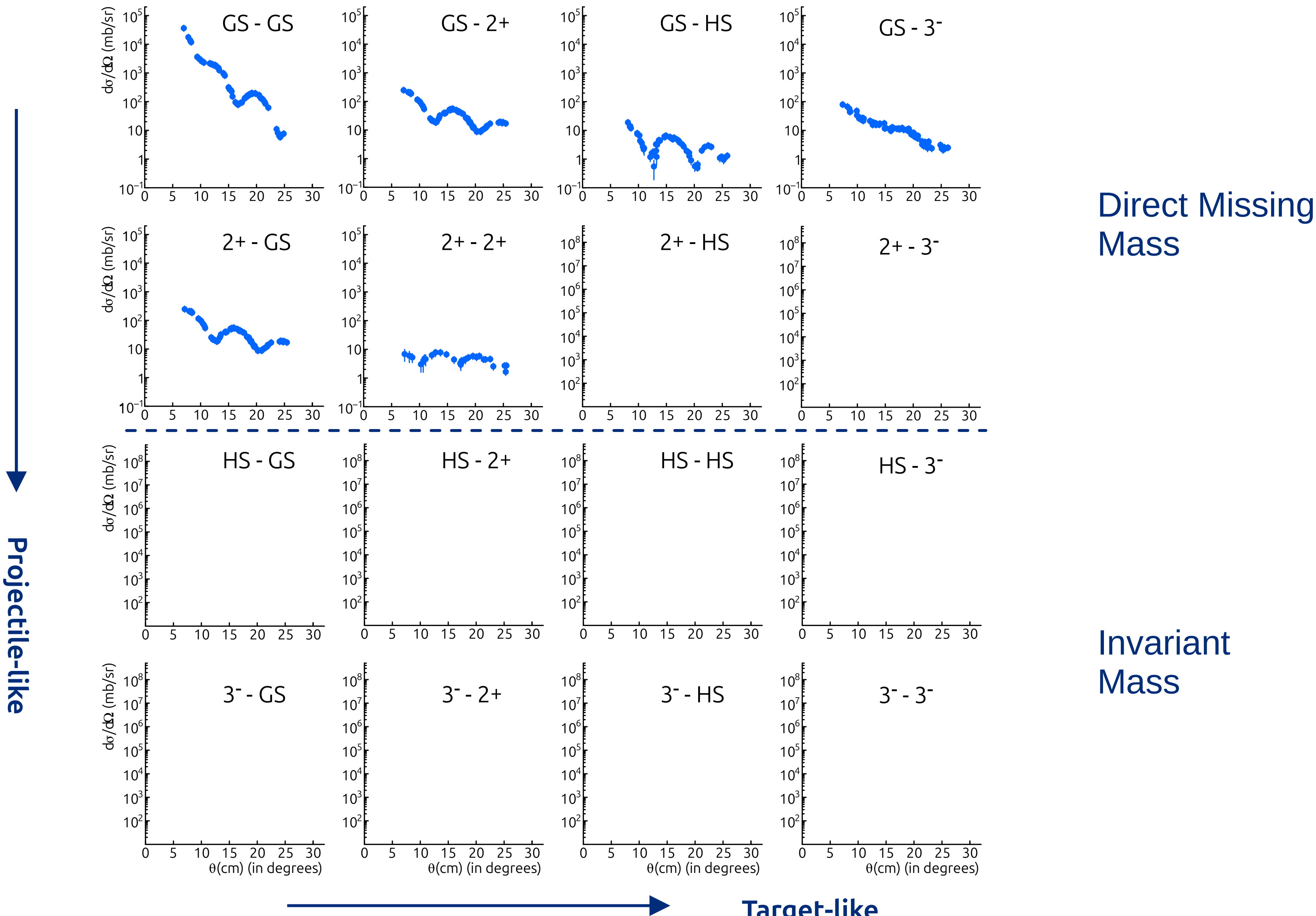
Direct missing mass :

Non decaying projectile-like ^{12}C are directly detected in the first silicon stage and identified using PSA.

On the line corresponding to ^{12}C : we can also spot the elastic peak + some excited states (2^+, 0_2^+ , 3^-).

Using 2-body kinematics, we reconstruct the dissipated energy.

- Probe projectile-like excited states **below** the particle emission threshold.
- Cross sections of multiple inelastic channels are extracted and evaluated to compare with theoretical models.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dσ/dΩ (mb/sr)
θ(cm) (in degrees)
Direct Missing Mass
Invariant Mass
Projectile-like
Target-like

What if the projectile-like decays ?

Invariant mass :

Apply the invariant mass method on the detected 3α to extract the projectile-like propreties.

➔ **Projectile-like** excitation energy and angle.

Indirect missing mass :

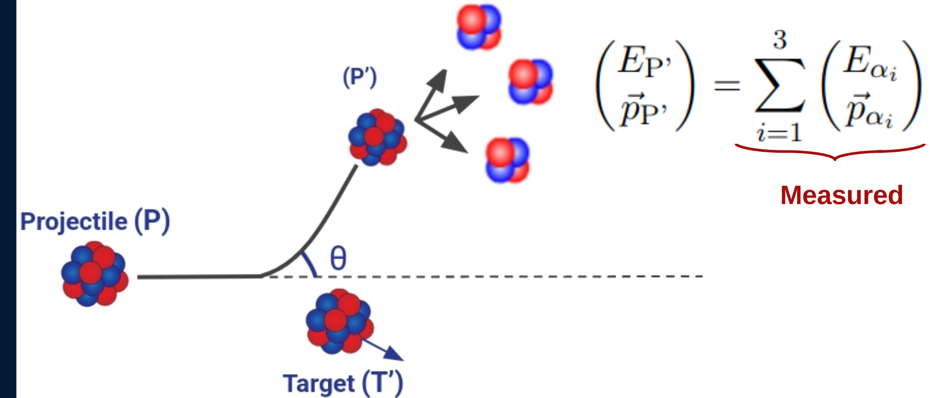
Apply the missing mass method on the reconstructed $^{12}C^*$ to extract the target-like propreties.

➔ **Target-like** excitation energy.

Projectile-Target Channels :

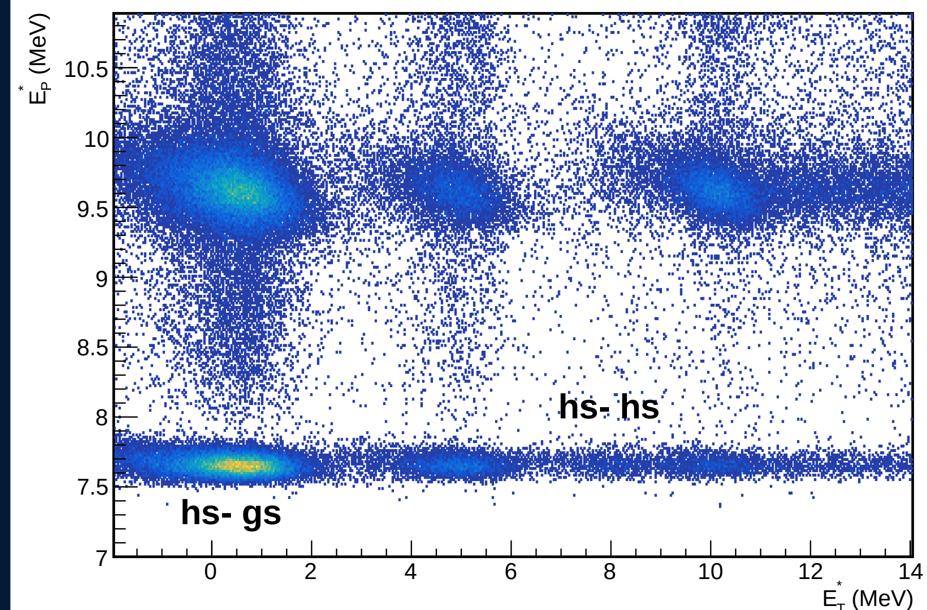
Multiple channels such as the HS - GS ,
HS – HS, 3^- - GS, 3^- - GS …,

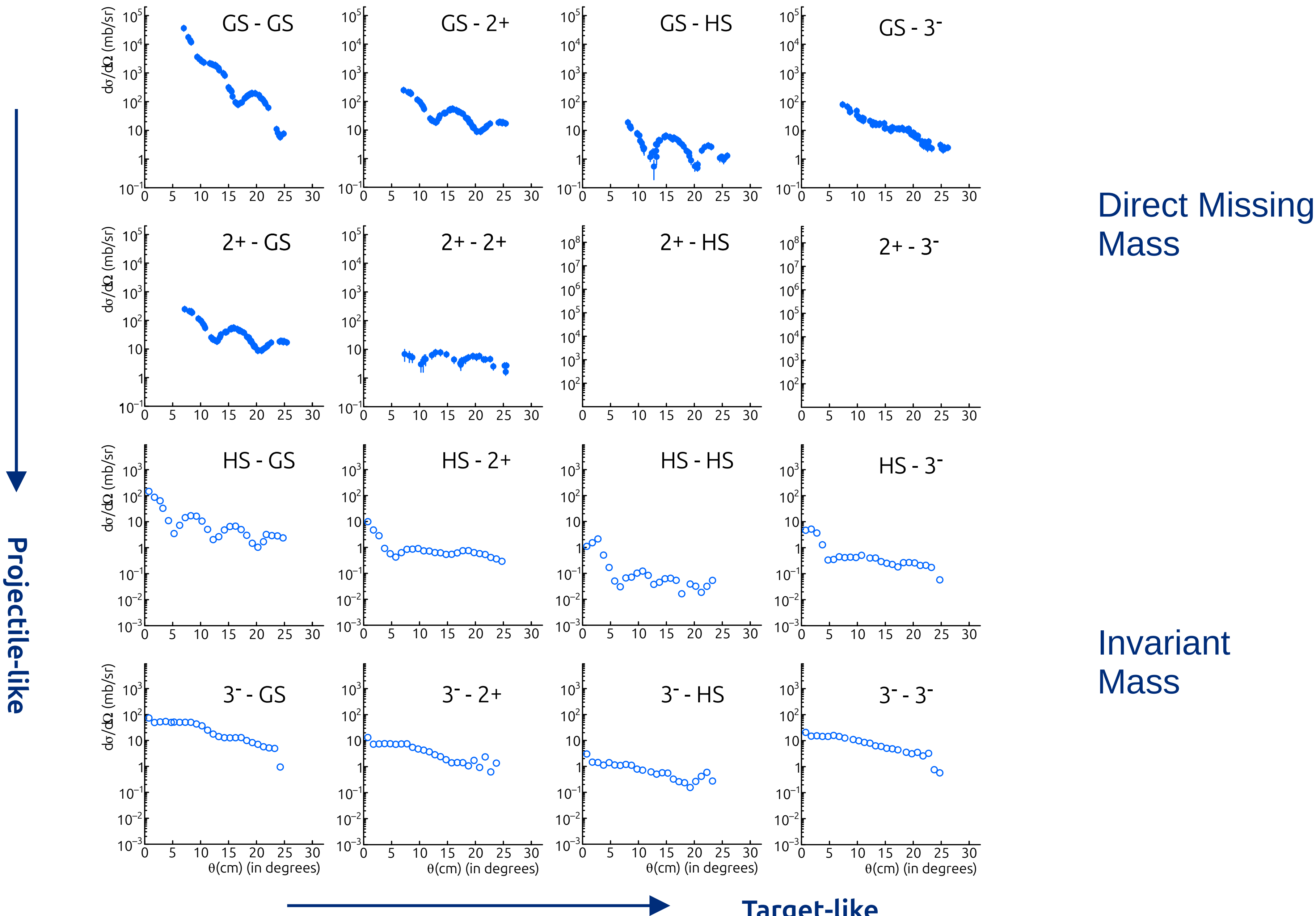
➔ Extract the **angular distribution** corresponding to each (Projectile-like – Target-like) reaction channel.



$$\begin{pmatrix} E_{P'} \\ \vec{p}_{P'} \end{pmatrix} = \underbrace{\sum_{i=1}^{3} \begin{pmatrix} E_{\alpha_i} \\ \vec{p}_{\alpha_i} \end{pmatrix}}_{\text{Measured}}$$

$$\begin{pmatrix} E_p \\ \vec{p}_p \end{pmatrix} + \begin{pmatrix} E_T \\ \vec{p}_T \end{pmatrix} = \begin{pmatrix} E_{P'} \\ \vec{p}_{P'} \end{pmatrix} + \begin{pmatrix} E_{T'} \\ \vec{p}_{T'} \end{pmatrix}$$





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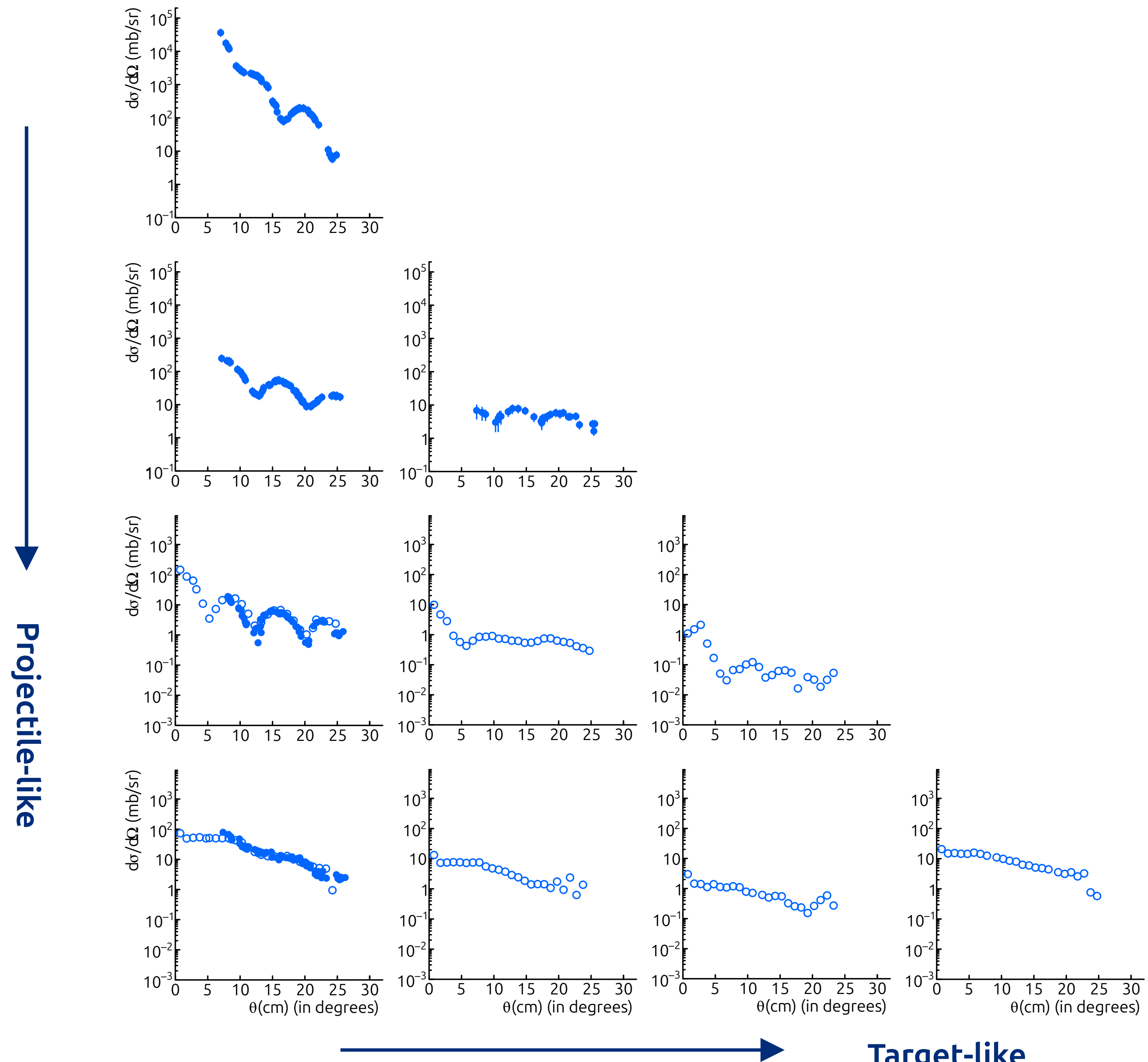
θ(cm) (in degrees)
Projectile-like
Target-like
Direct Missing Mass
Invariant Mass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Projectile-like
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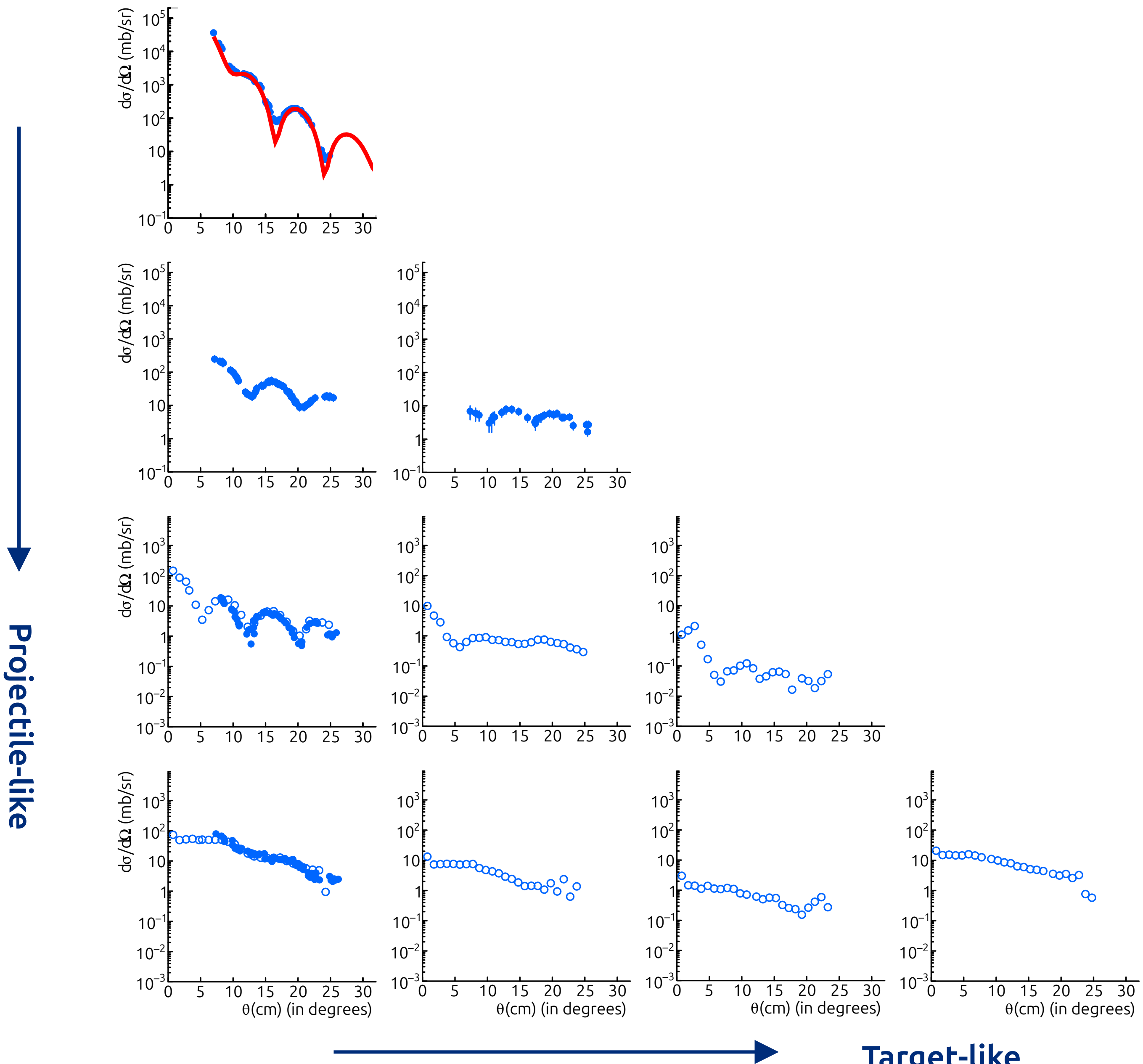


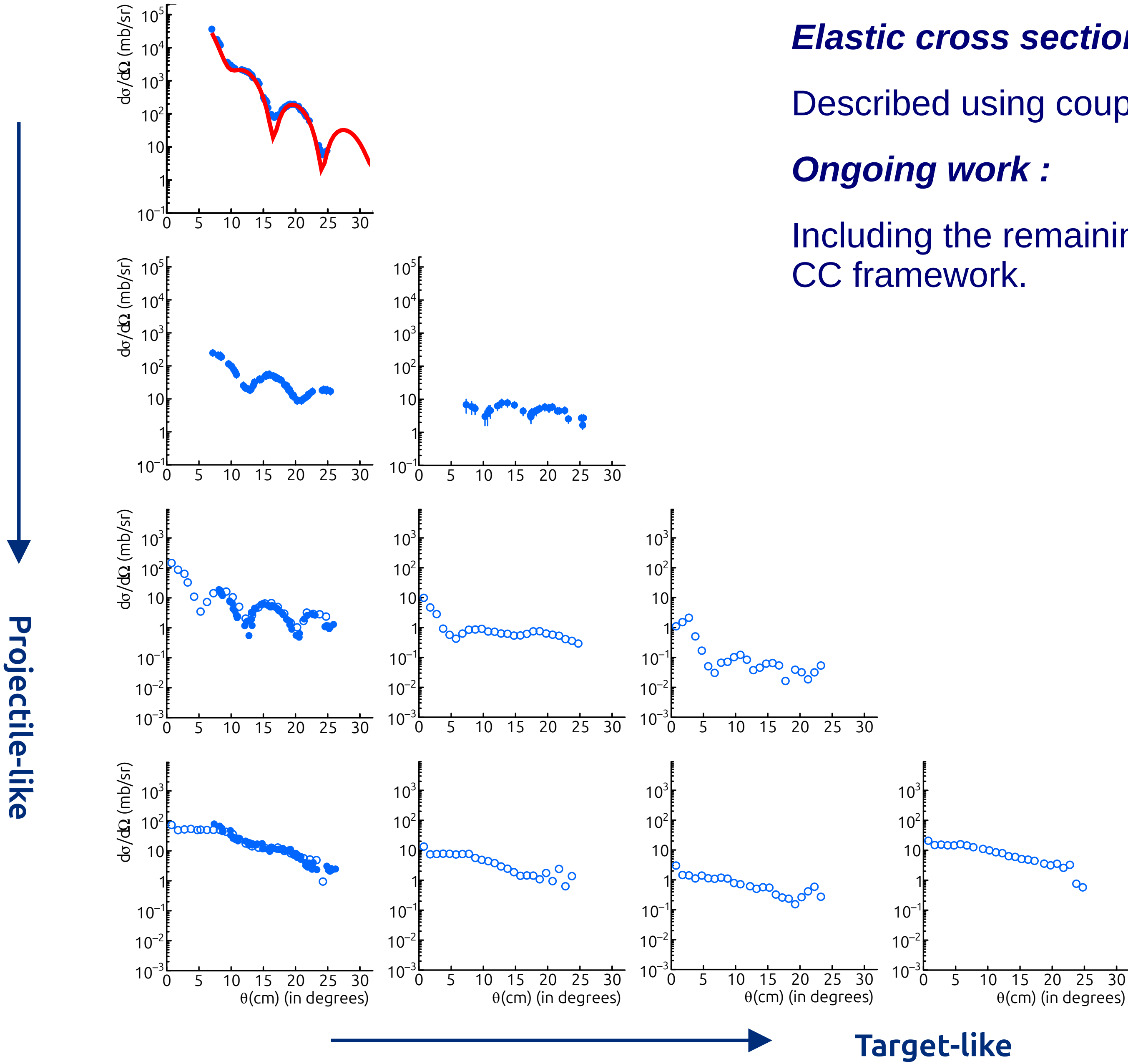
dσ/dΩ (mb/sr)
θ(cm) (in degrees)
Projectile-like
Target-like

Elastic cross section :

Described using coupled channels calculations.

Ongoing work :

Including the remaining inelastic channels in the CC framework.



Motivations :

In typical stellar conditions, ^{12}C formation via the 3α process proceeds mainly through the Hoyle state (7.65 MeV). At higher temperatures, the 3^- state (9.65 MeV) also contributes to ^{12}C production.

- Γɣ branching ratio being poorly constrained makes the resulting reaction rate highly uncertain.
- Γɣ should be **remeasured** with better accuracy.

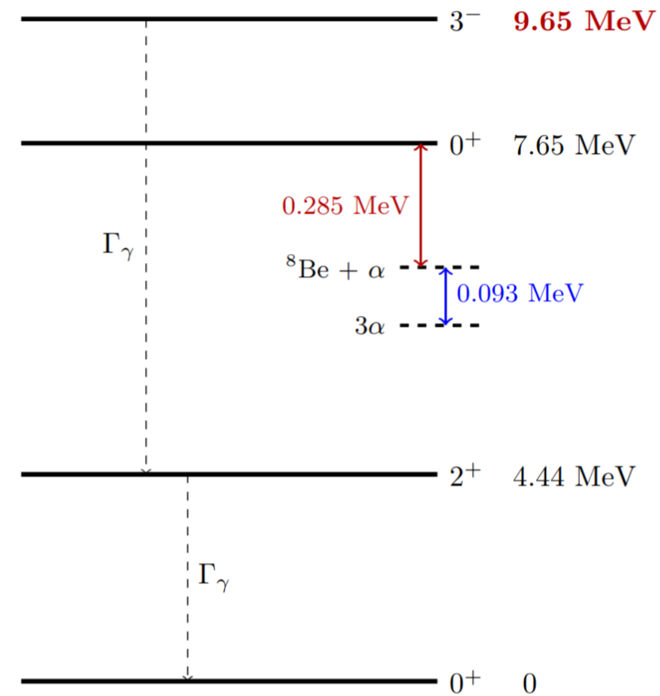
T26-01 Experiment :

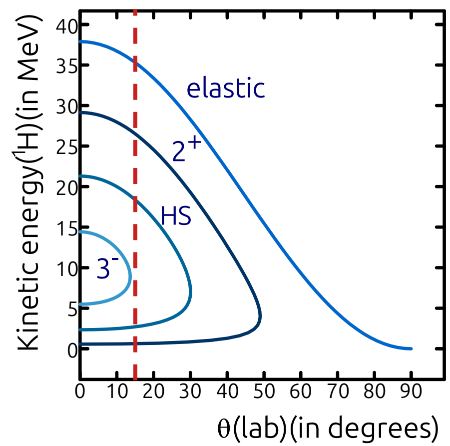
CH_2 target was irradiated with a ^{12}C beam at an energy of 11 MeV/A at GANIL in March 2026.

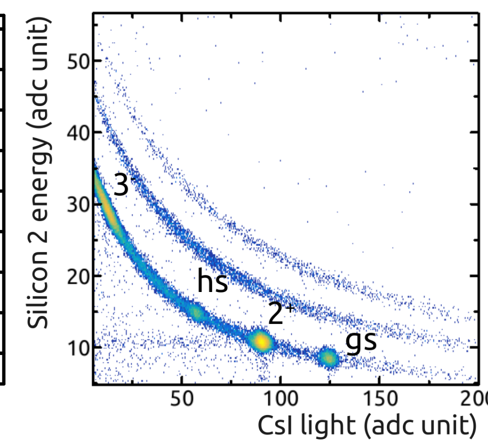
The diffused protons are detected using the FAZIA detector placed at forward angles.

The emitted ɣ are detected using INDRA multi-detector benifiting from its good efficiency.

- p-ɣ-ɣ coincidence events are used to get the ɣ-decay branching ratio of the 3^- state. (**Work in progress**)







Thanks to the participants :

Ilham Dekhissi, Diego Gruyer, Daniele Dell'Aquila, Sandro Barlini, Lucia Baldesi, Jose Benlliure, Aldo Bonasera, Eric Bonnet, Bernard Borderie, Remi Bougault, Alberto Camaiani, Giuseppe Cardella, Giovanni Casini, Rosaria Cavallaro, Abdou Chbihi, Caterina Ciampi, Enrico De Fillipo, Andrea De Rosa, Franck Delaunay, Lou Dienis, Jose Duenas, Quentin Fable, John Frankland, Eulalia Gambera, Fabiana Gramegna, Maxime Henri, Alexia Hocine, Byungsik Hong, Sunji Kim, Giyeong Kim, Min Jung Kweon, Nicolas Le Neindre, Ivano Lombardo, Olivier Lopez, Nunzia Simona Martorana, Katarzyna Mazurek, Gabriella Naddeo, Seon Ho Nam, Nigel Orr, Jeonghyeok Park, Marian Parlog, Maria Grazia Pellegriti, Silvia Piantelli, Simone Valdre, Antonin Valente, Giuseppe Verde, Emmanuel Vient.

Collaborators (Theory) :

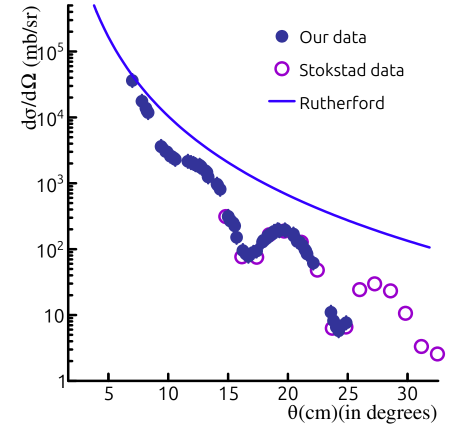
Chloë Hebborn, Louis Heitz, Franck Delaunay.

Thank you for your attention

Direct Missing Mass :

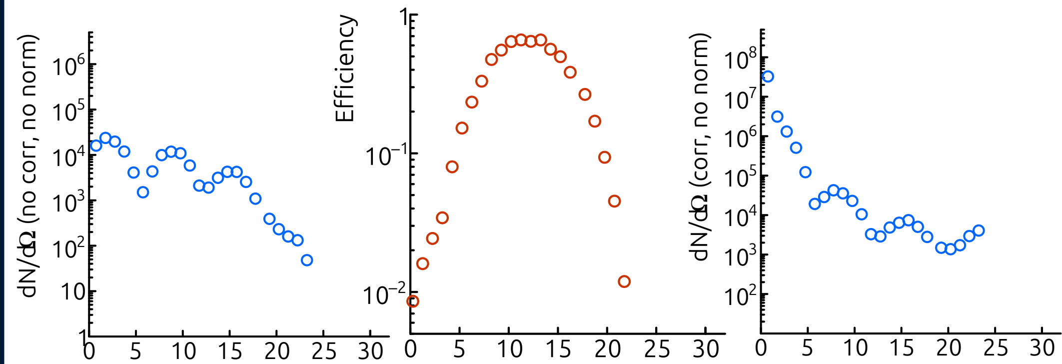
^{12}C + ^{12}C @ 105MeV elastic data & single excitation cross sections in mb/sr were found in the literatture [3] and used for nomalization purposes.

GS - GS

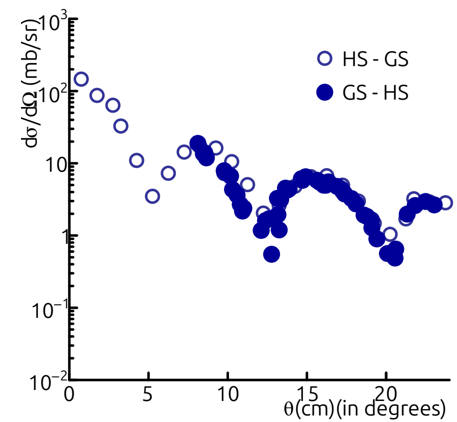


Invariant Mass :

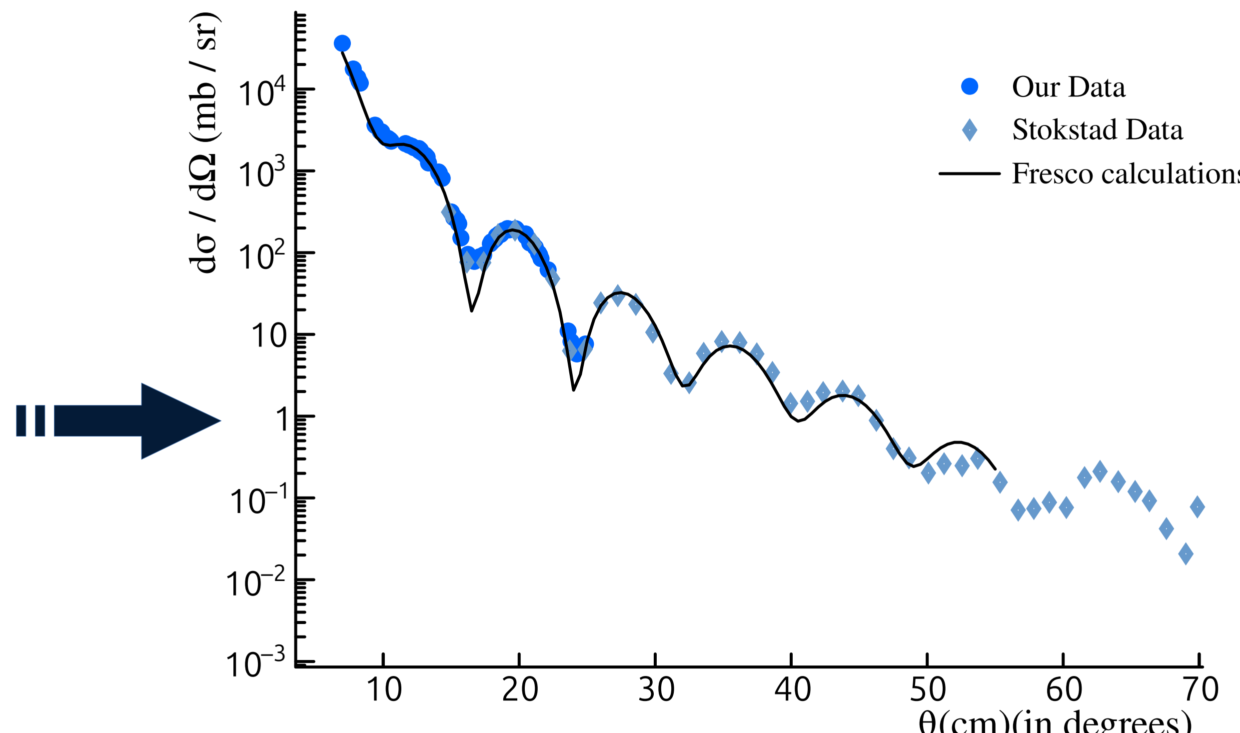
Evaluate the 3α detection efficiency using Monte Carlo simulations for each reaction channel.



Normalize the cross sections obtained through the invariant mass technique using the symmetric cross section obtained through the direct missing mass.



[3] : Stokstad et al., Phys Rev. C, 20, 1979.



dσ / dΩ (mb / sr)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10
20
30
40
50
60
70
θ(cm)(in degrees)
Our Data
Stokstad Data
Fresco calculations