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

Ilham Dekhissi

LPC Caen

dekhissi@lpccaen.in2p3.fr

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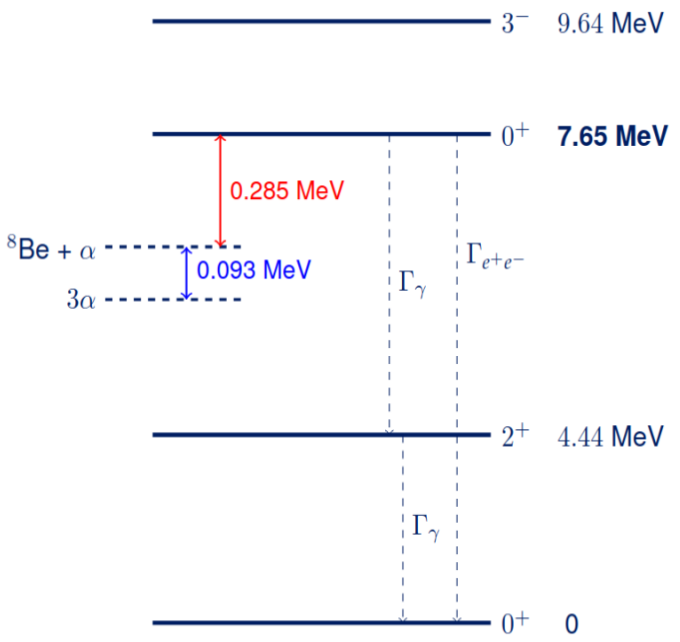
Hoyle state ^{12}C (0_2^+) :

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 → ^{8}Be & ^{8}Be + α → ^{12}C + ɣ).

Hoyle state Decay :

- Sequential Decay : Multi-step decay process ($^{12}C^*$ → ^{8}Be + α & ^{8}Be → α + α).
- Direct Decay : Directly to 3α bypassing the ^{8}Be intermediate state ($^{12}C^*$ → α + α + α)
- ɣ- 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] :

  Compact structure for the ground state.

  Obtuse triangle for the Hoyle state.

- *Monte Carlo SM* [2] :

  Superposition of independent particles and α clusters for the ground state.

  Compact 3α structure for the Hoyle state.

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

Matter Radius :

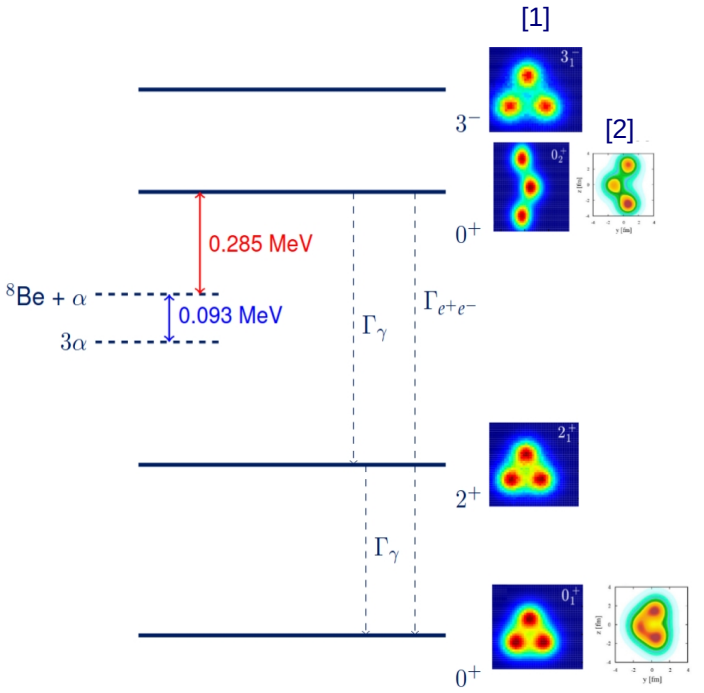
All the theoretical frameworks predict the Hoyle State to be larger than the ground state.

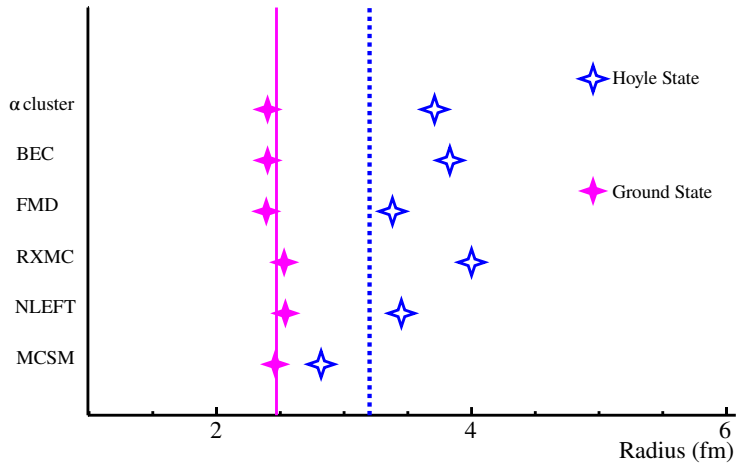
Different models predict different Hoyle state radius values from 2.82 fm to 4 fm.

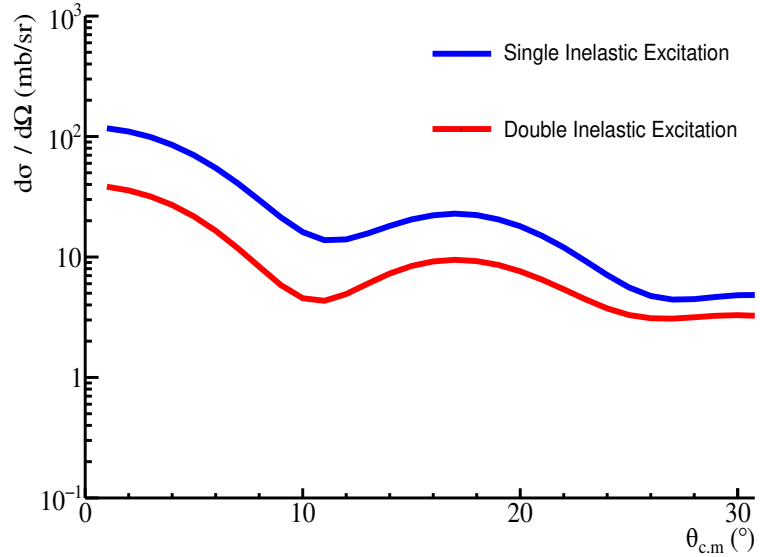
➔ No **consensus** on the Hoyle state **radius** from the theoretical point view.

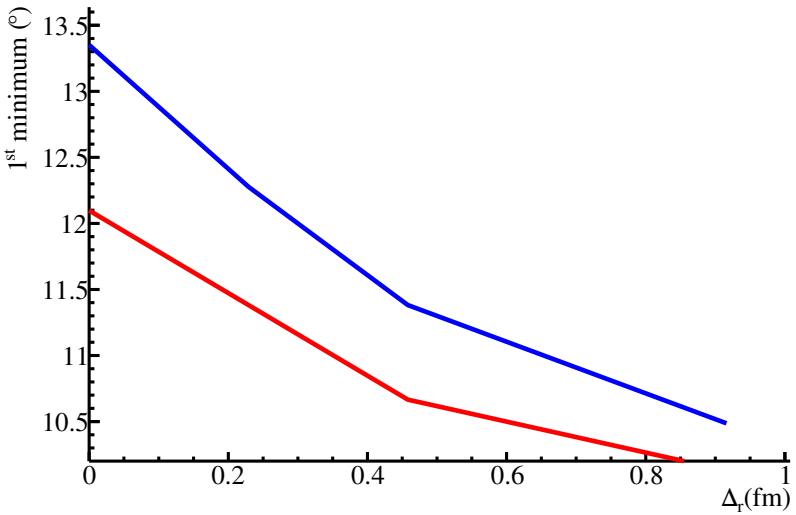
[1] : S. Shen, Nature Com. 14, 2777

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









How can we measure the Hoyle state radius ?

Theoretical Calculations :

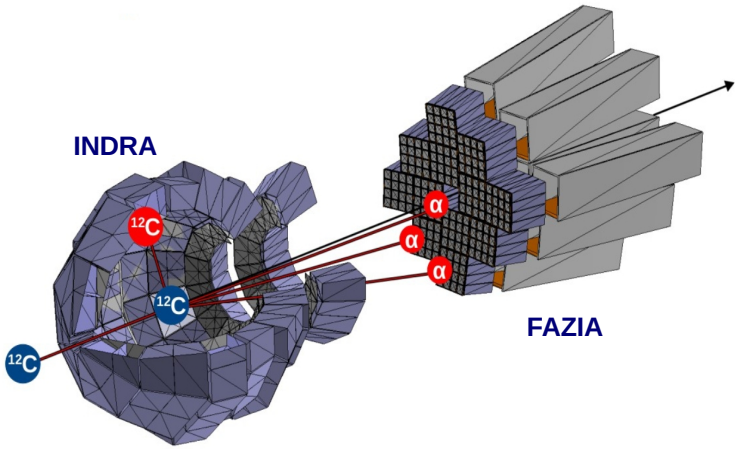
Coupled channel calculations performed for ^{12}C + ^{12}C at 100 MeV.

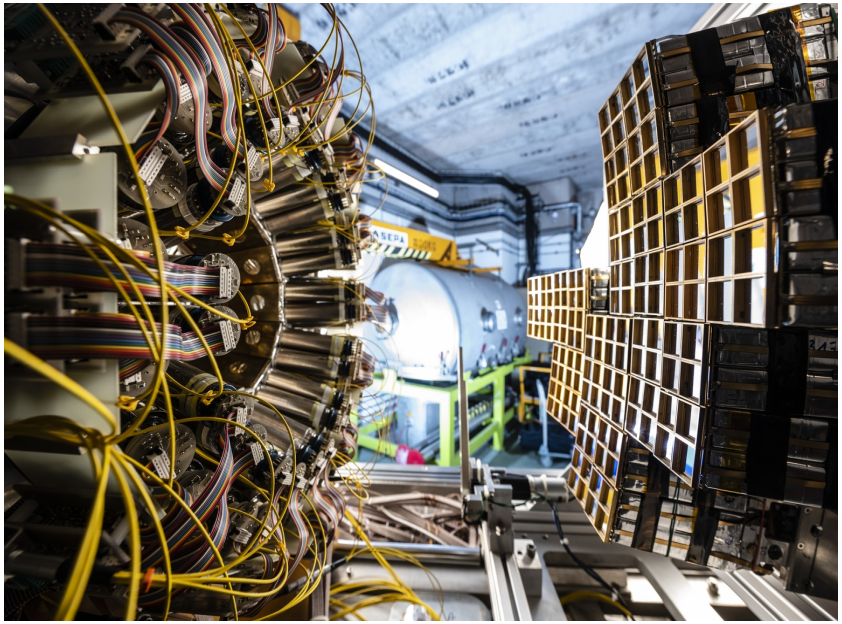
Single and mutual excitation inelastic scattering of the Hoyle state computed with CHUCK3 code by varying the difference between the ground and Hoyle states radii Δ_r = 0 – 0,92fm.

Observable sensitivity to the Hoyle state radius :

The position of the first and second minima decreases with Δr increasing.

- **Single- and mutual- excitation inelastic cross sections** show a **sensitivity** to the Hoyle state radius.





How can we measure these cross sections ?

Experimental Framework E881 :

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 cm^2)

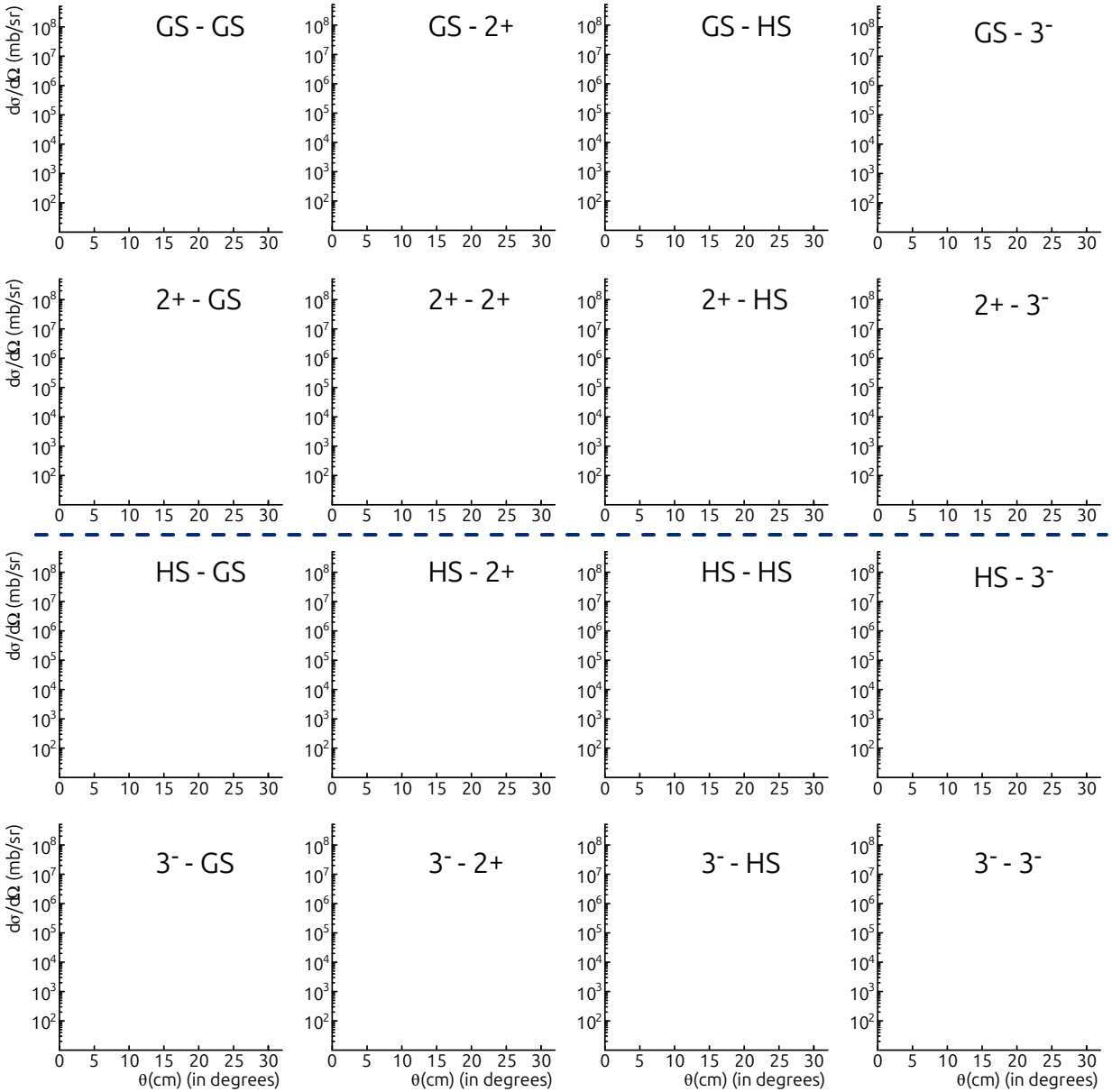
- Si1 (300 µm), Si2 (500 µm) and CsI (10 cm)

Allows for the use of multiple identification methods :

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

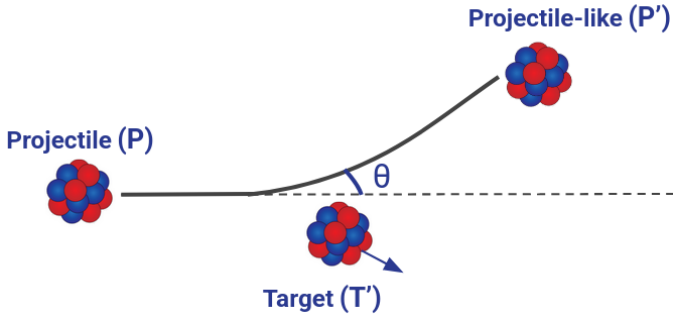
➔ Process 1 : ^{12}C is diffused without decaying into 3α

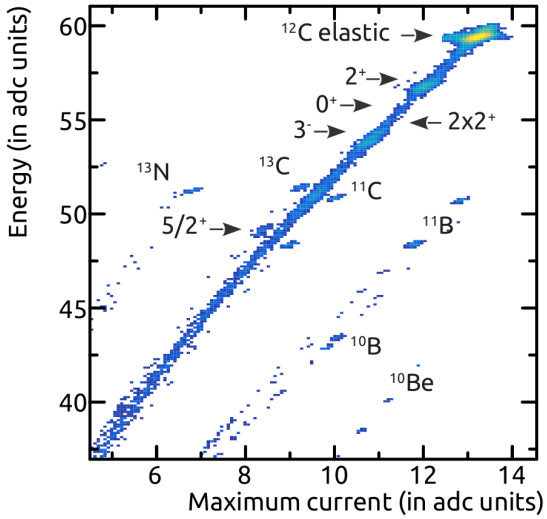
➔ Process 2 : $^{12}C^*$ decays into 3α.

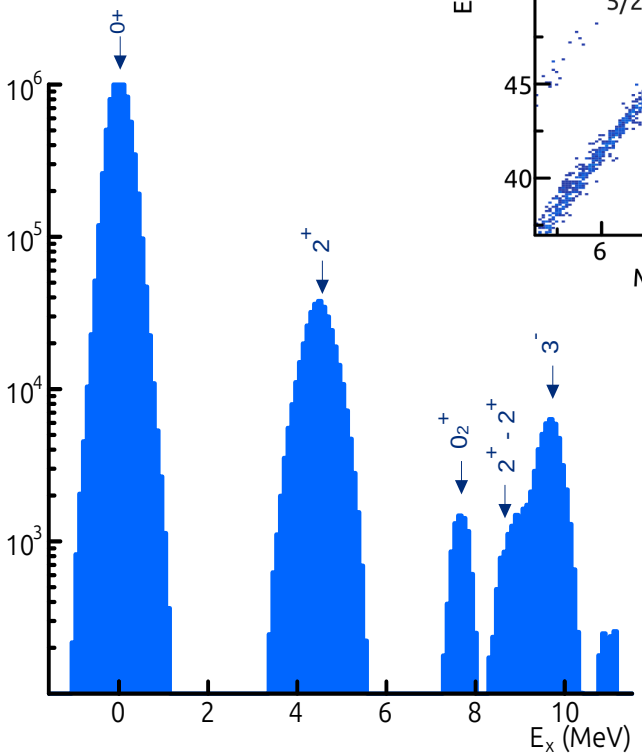


Bellow 3α threshold Direct Missing Mass

Above 3α threshold Invariant Mass







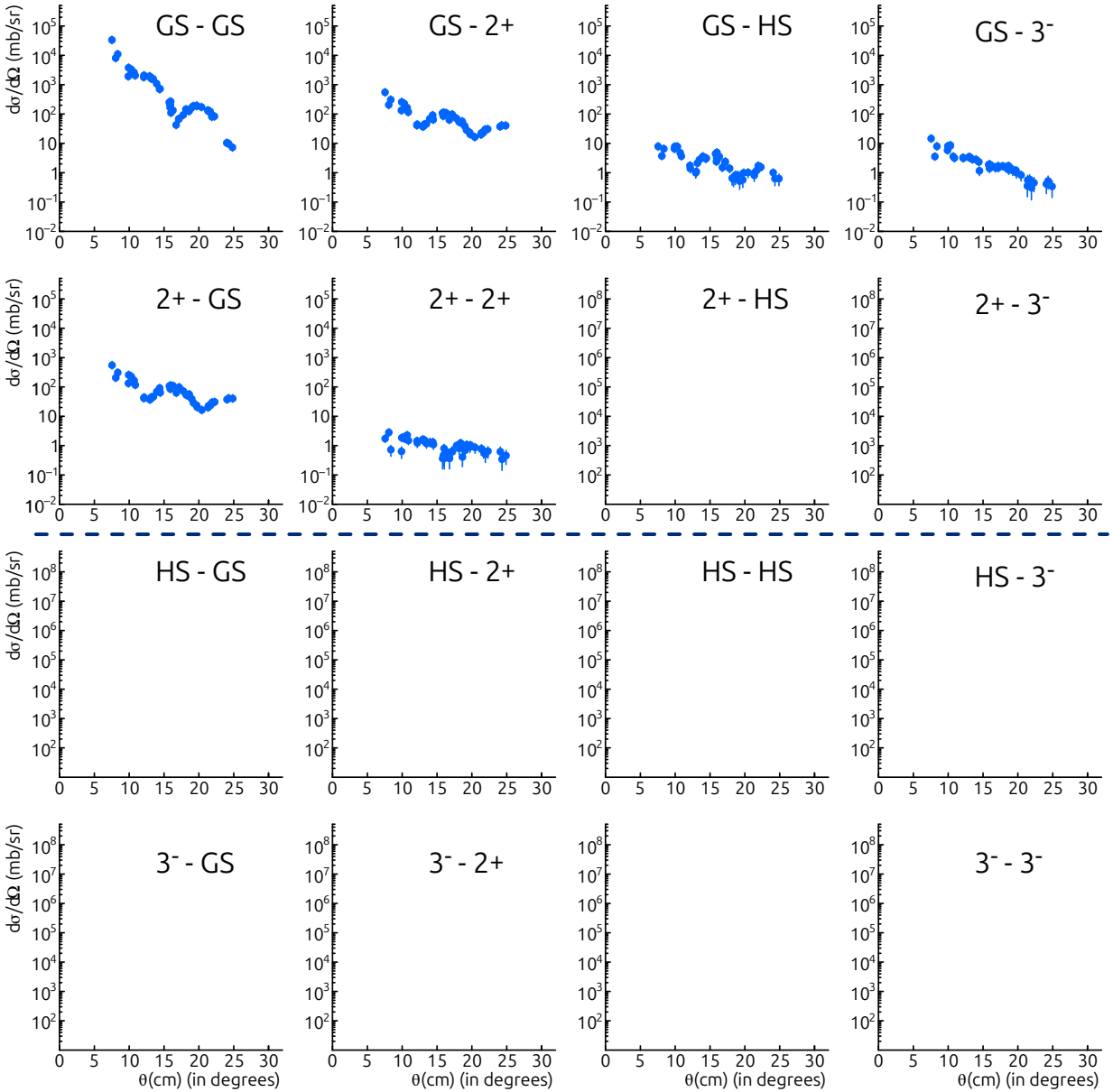
Direct missing mass :

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.



Direct Missing Mass

Invariant Mass

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 :

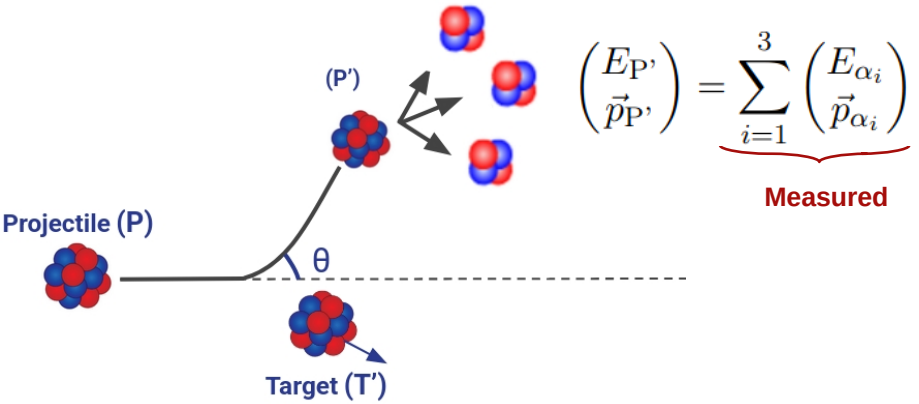
Apply the missing mass method on the reconstructed $^{12}C^*$ to extract the target-like propreties.

➔ **Target-like** excitation energy.

Projectile-Target Channels :

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

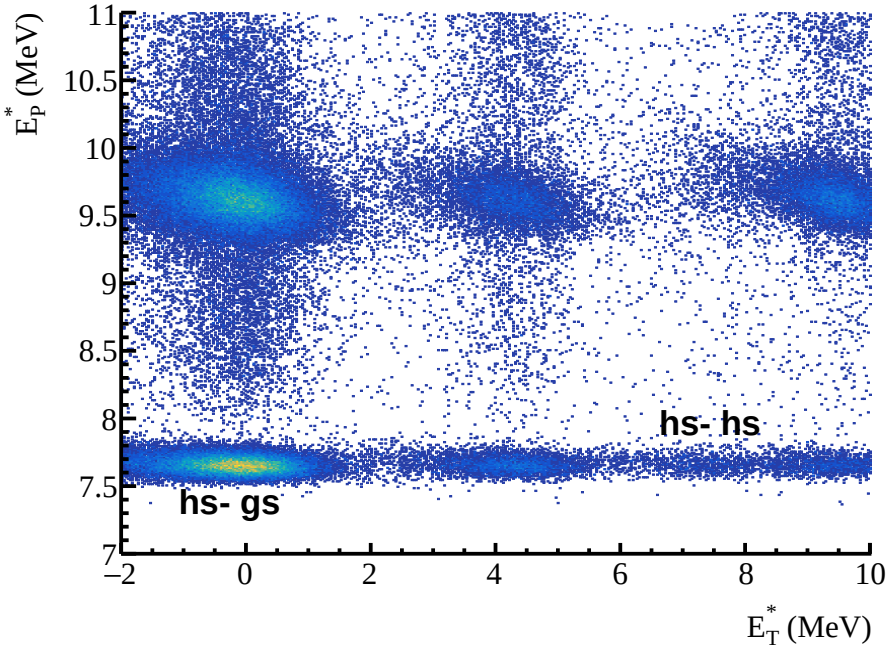
➔ Extract the **angular distribution** corresponding to each (Projectile-like – Target-like) reaction channel.

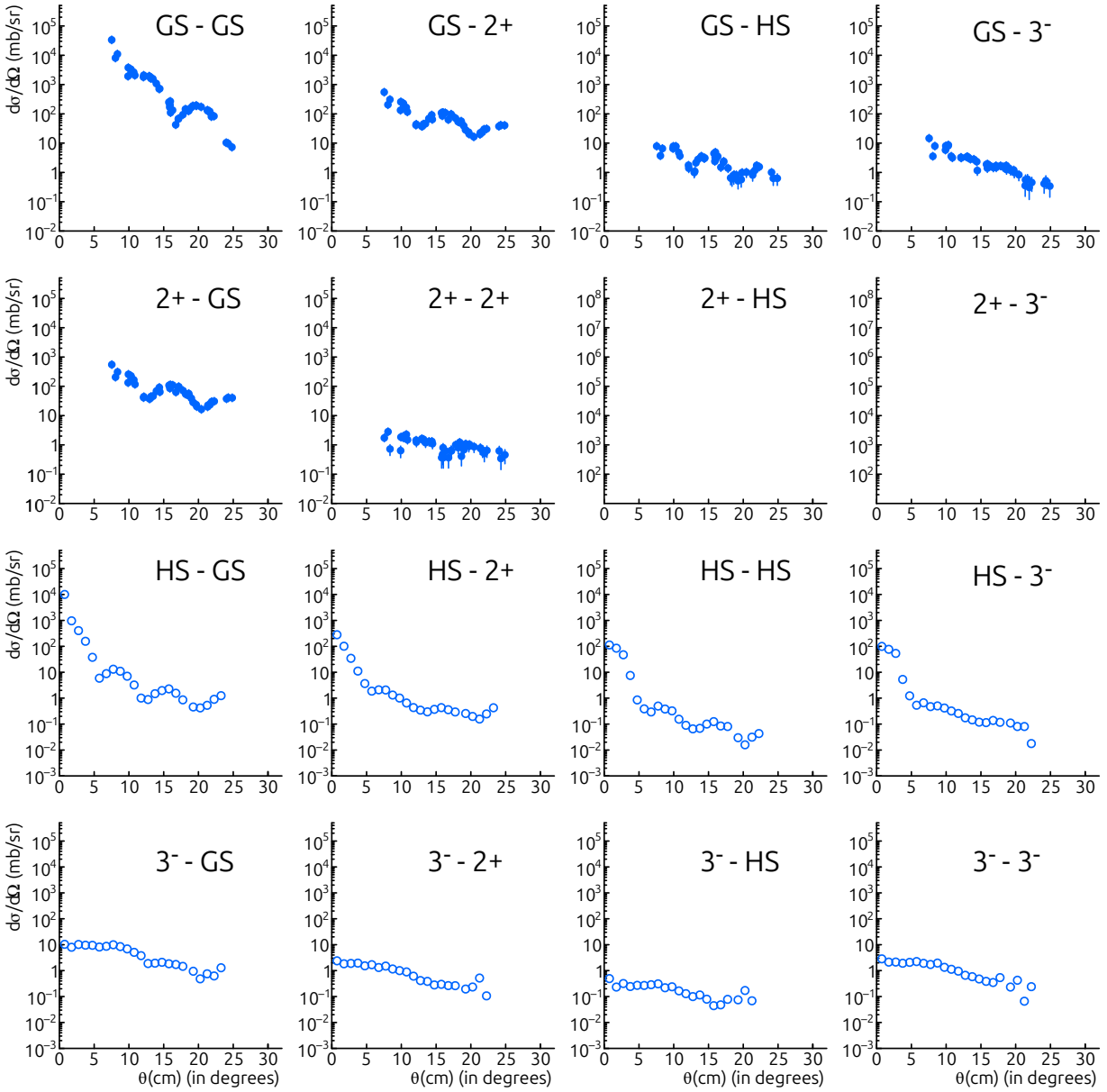


$$\begin{pmatrix} E_{P'} \\ \vec{p}_{P'} \end{pmatrix} = \sum_{i=1}^{3} \begin{pmatrix} E_{\alpha_i} \\ \vec{p}_{\alpha_i} \end{pmatrix}$$

Measured

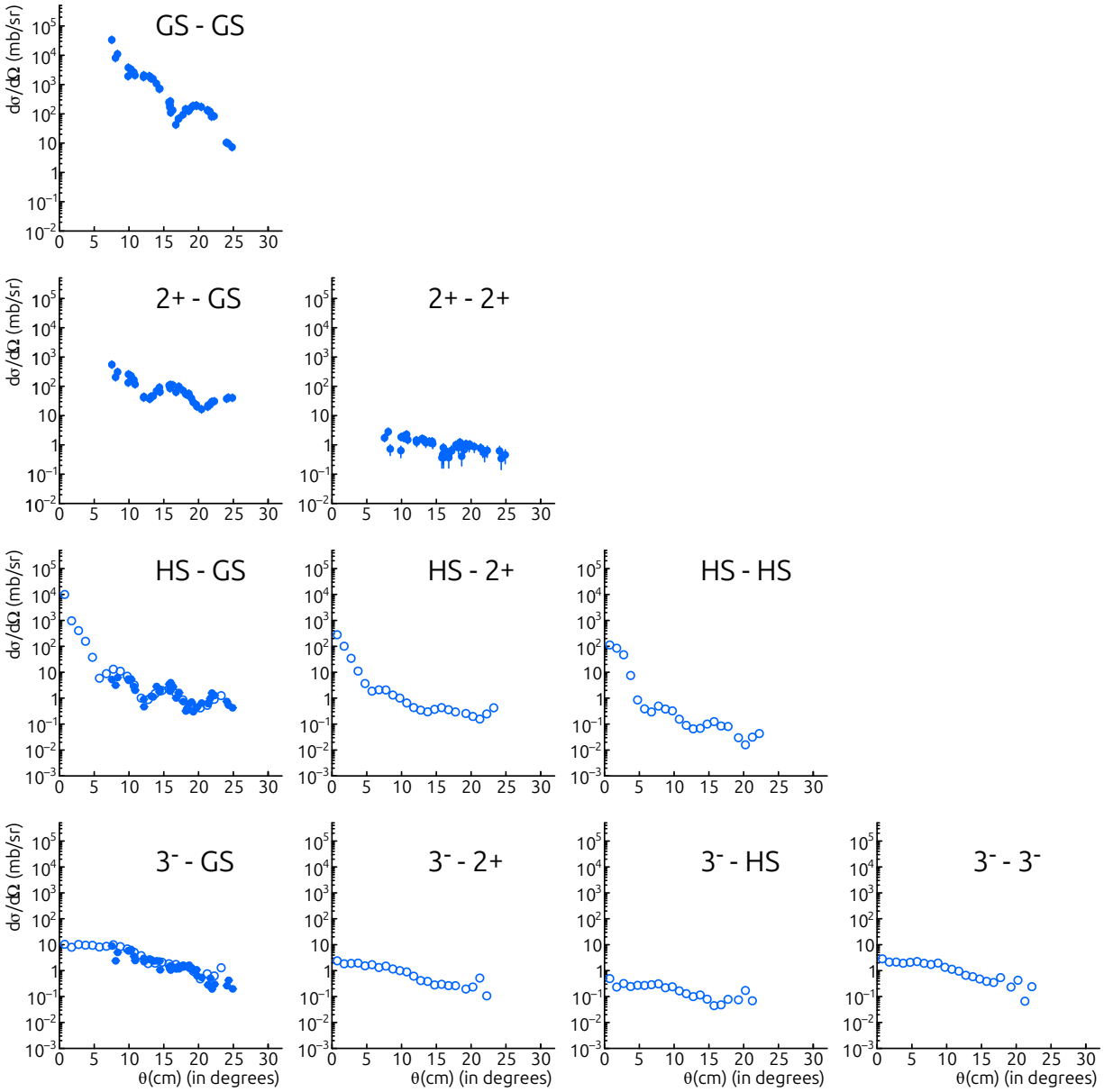
$$\begin{pmatrix} E_{P} \\ \vec{p}_{P} \end{pmatrix} + \begin{pmatrix} E_{T} \\ \vec{p}_{T} \end{pmatrix} = \begin{pmatrix} E_{P'} \\ \vec{p}_{P'} \end{pmatrix} + \begin{pmatrix} E_{T'} \\ \vec{p}_{T'} \end{pmatrix}$$





Direct Missing Mass

Invariant Mass

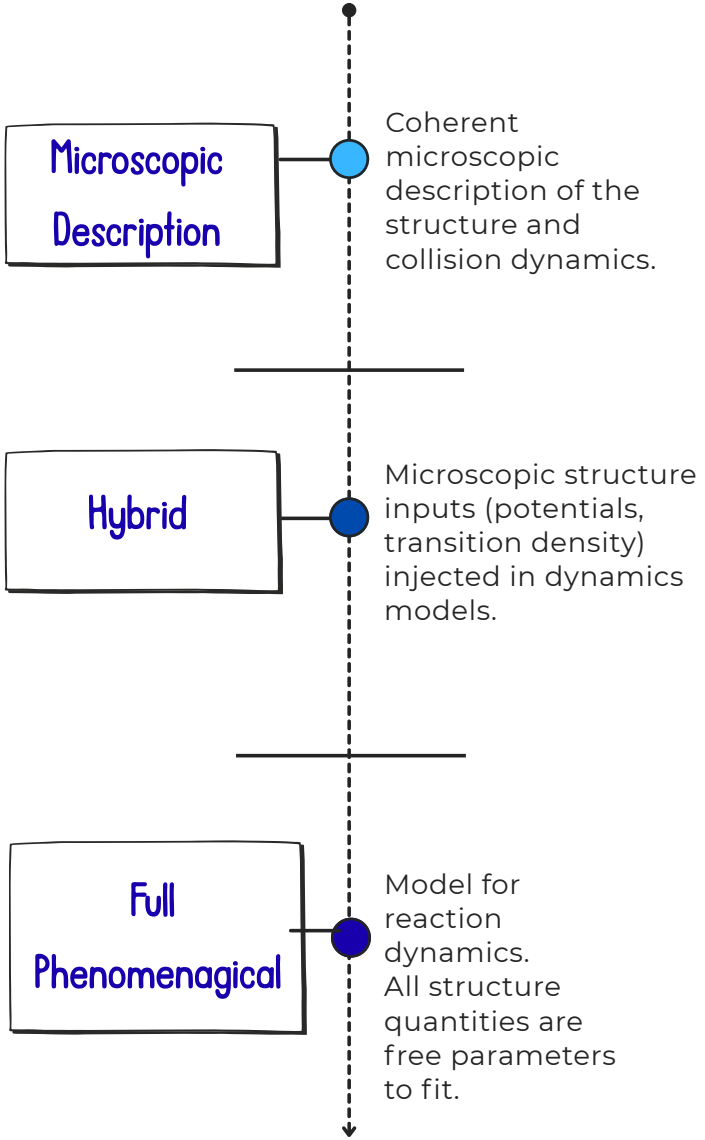


Experimental Output :

- Cross sections (Elastic & Inelatsic) all combination of projectile and target excitation.

Next steps :

- Theoretical calculations can be conducted to compare with these experimental cross sections in order to extract the Hoyle state radius.


Microscopic Description
Coherent microscopic description of the structure and collision dynamics.
Hybrid
Microscopic structure inputs (potentials, transition density) injected in dynamics models.
Full Phenomenagical
Model for reaction dynamics. All structure quantities are free parameters to fit.

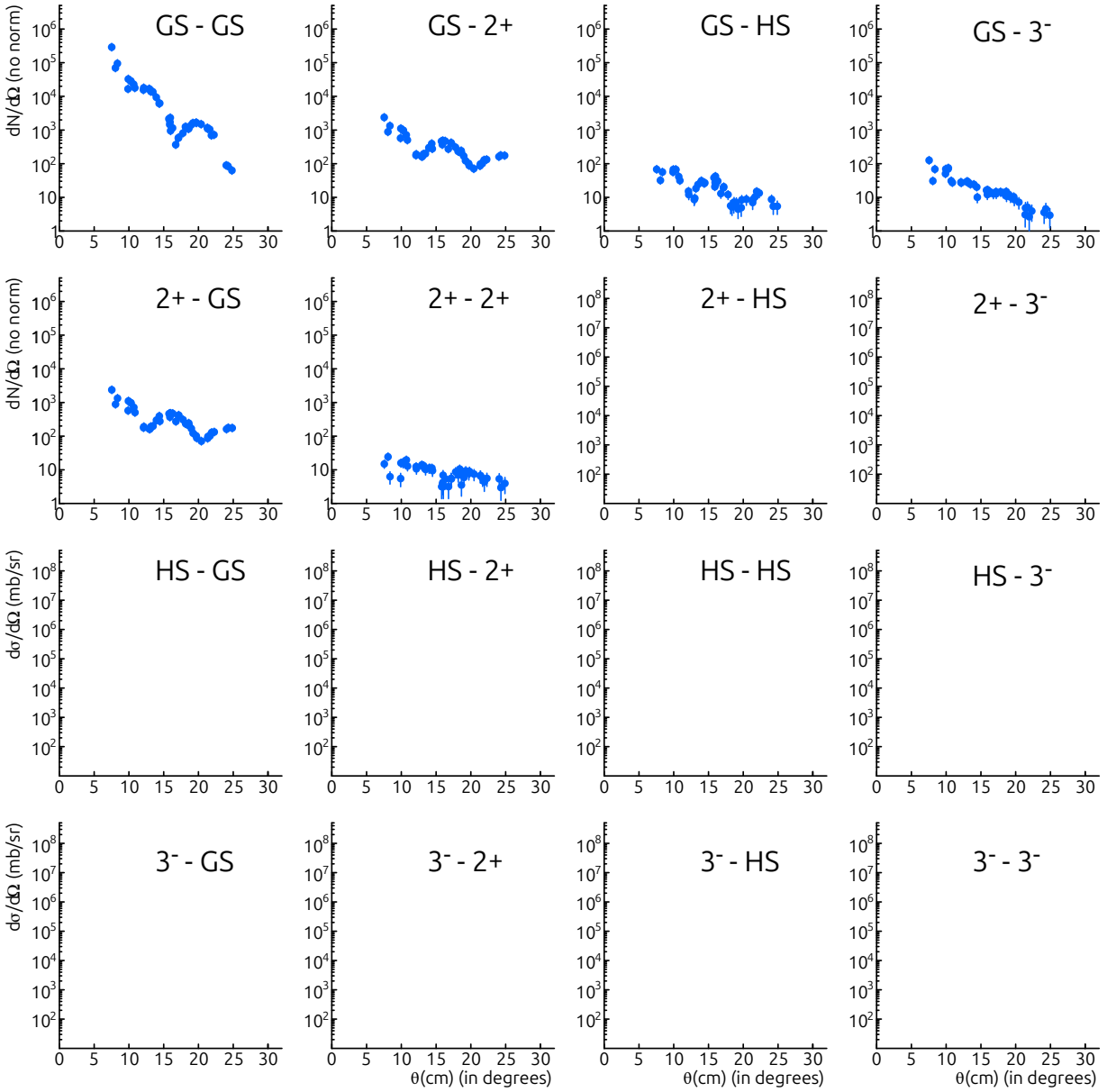
Thanks to the participants :

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, Abdou Chbihi, Caterina Ciampi, Enrico De Fillipo, Andrea De Rosa, Franck Delaunay, Laurie Dienis, Jose Duenas, Quentin Fable, John Frankland, Eulalia Gambera, Fabiana Gramegna, Maxime Henri, 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) :

Chloé Hebborn, Louis Heitz.

BACKUP SLIDES


GS - GS
GS - 2+
GS - HS
GS - 3-
2+ - GS
2+ - 2+
2+ - HS
2+ - 3-
HS - GS
HS - 2+
HS - HS
HS - 3-
3- - GS
3- - 2+
3- - HS
3- - 3-
dN/dΩ (no norm)
dσ/dΩ (mb/sr)
θ(cm) (in degrees)
Projectile-like
Target-like
Direct Missing Mass
Invariant Mass

Normalization Process :

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

Angular coverage ranges from 7° to 45° in the laboratory frame.

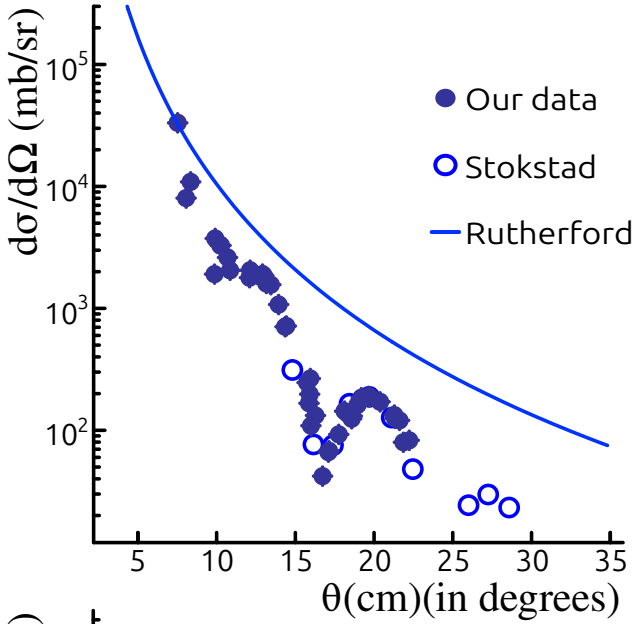
Elastic Data was used as a normalization referenece to the e881 elastic data.

Scaling process was then cross validated using the single excitation cross section.

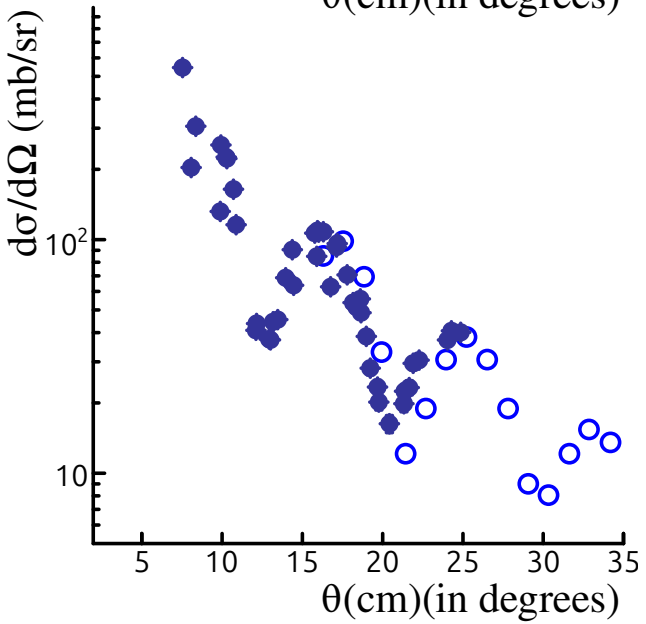
This normalization was then used for all cross sections obtained through the direct missing mass method.

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

GS - GS

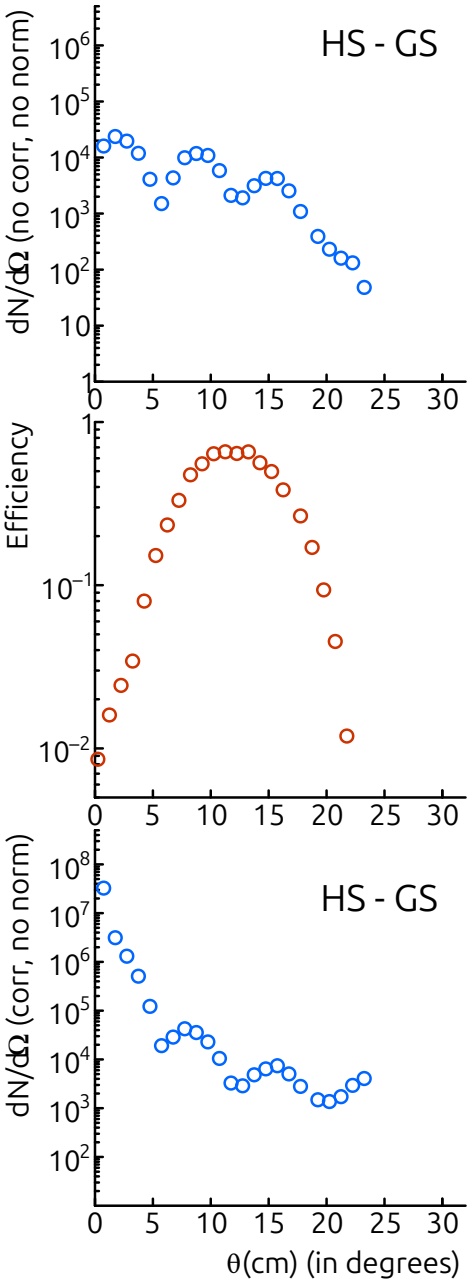


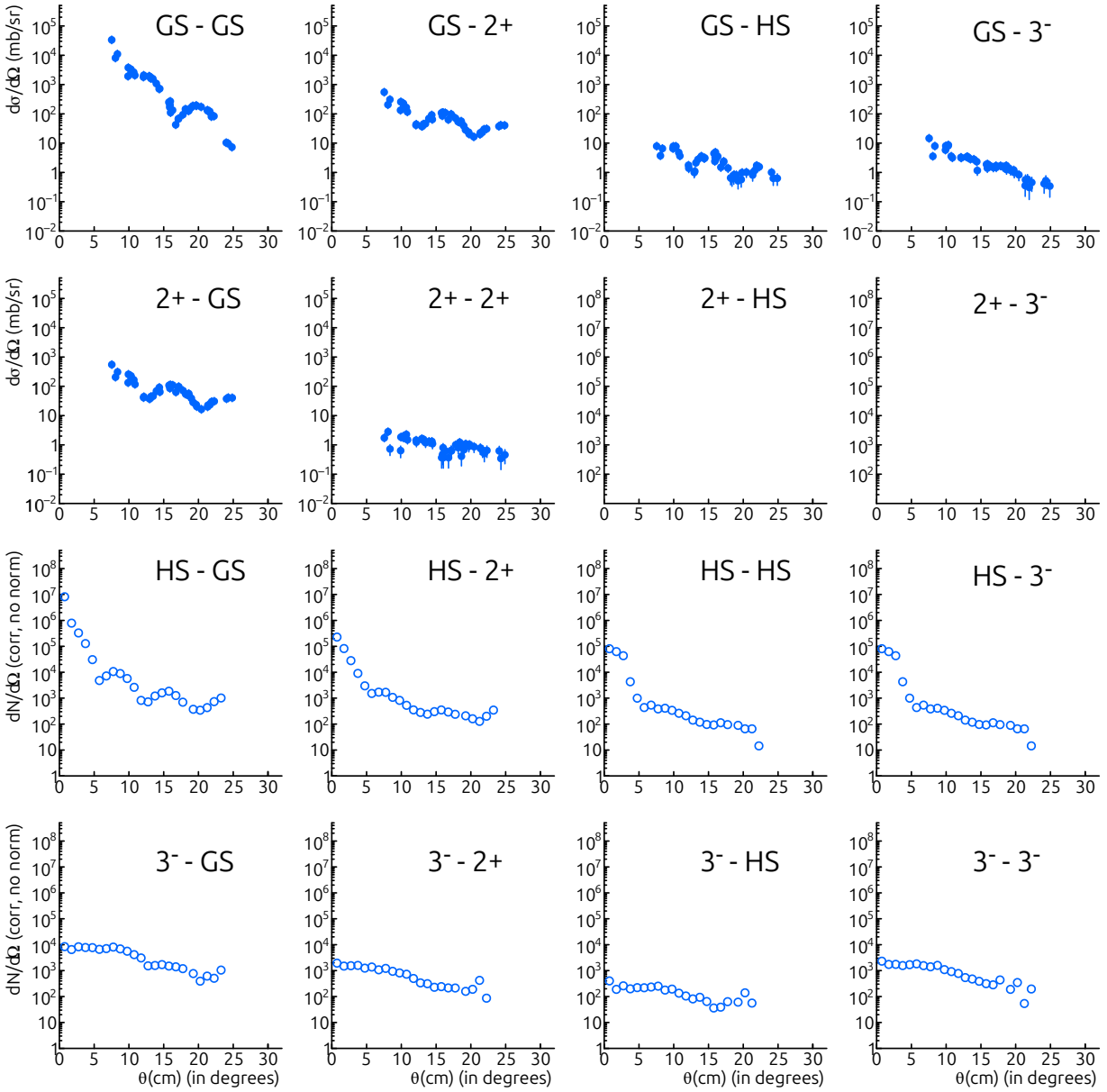
GS -2+



Efficiency correction :

- 3α dacays were simaulated for each reaction channel using Monte Carlo.
- Evaluate the events consisting of 3α using an experimental filter (geometry + detection threshold).
- Filtered events were then used to reconstruct the excited states of ^{12}C.
- Compute the detection efficiency for each reaction channel.
- No detectors at 0° → Efficiency drop at low angles.
- Correct the previous distributions using the computed efficiency.



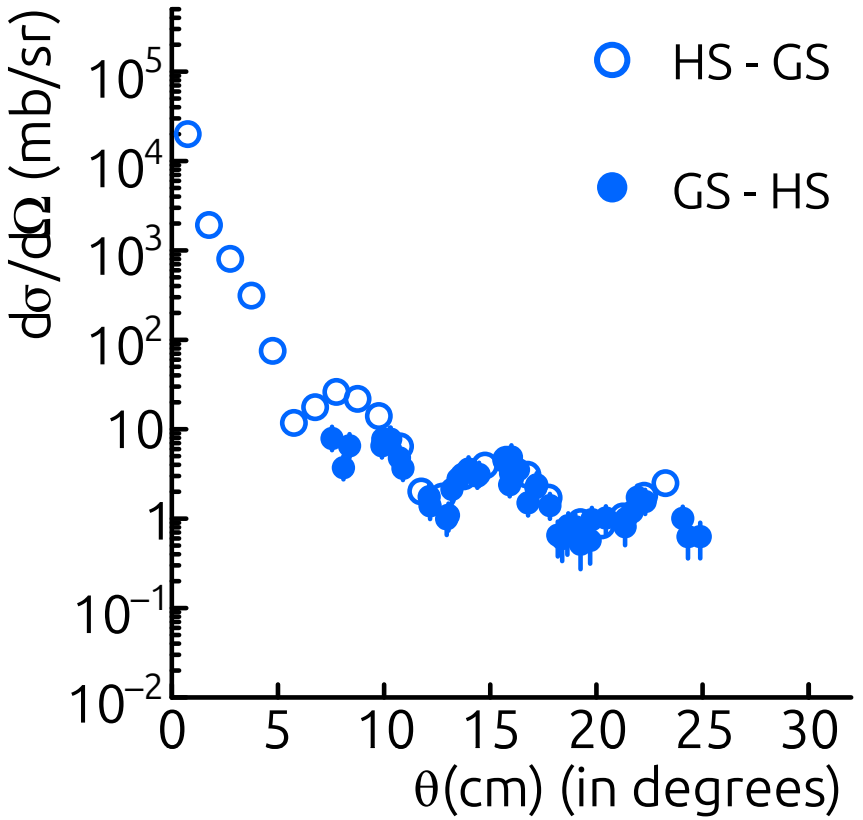


Direct Missing Mass

Invariant Mass

Normalization process :

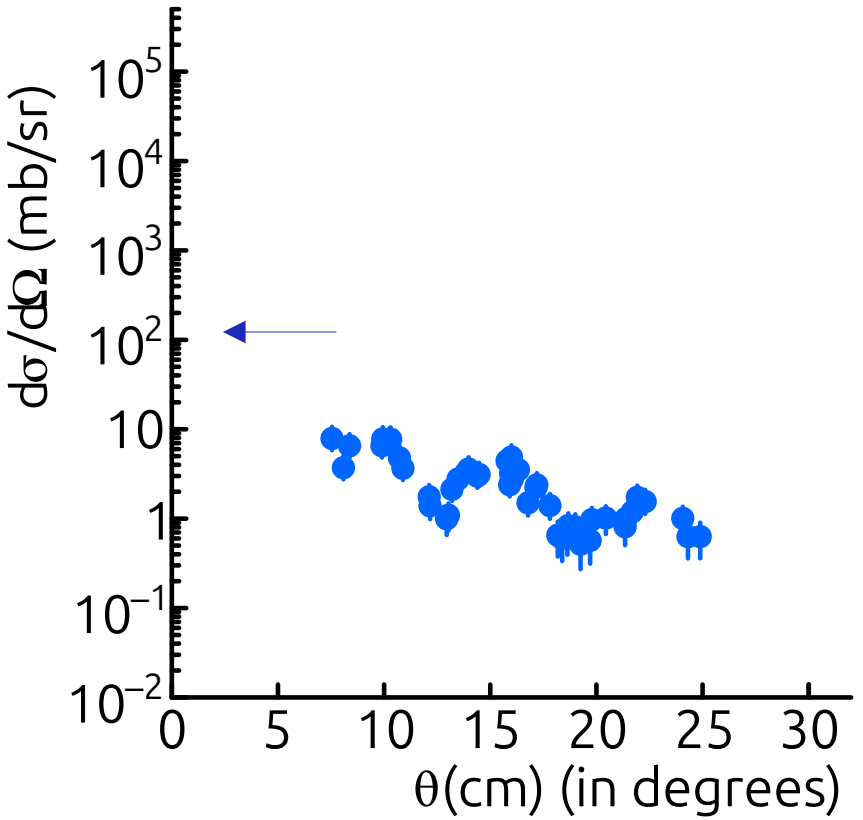
- Use the GS-HS normalized cross section obtained through the direct missing mass technique.
- Cross validate this normalizaton step with the GS - 3^- and the 3^-- GS.
- Use the deduce normalization factor for all cross sections obtained through invariant mass & indirect missing mass techniques.



Experimental Output :

- Angular distribution for (almost) all combination of projectile and target excitation.

Next steps :

- Include other data points at lower angles.

- Theoretical calculations can be conducted using these angular ditributions to compare with these experimental cross sections..