New direct measurement of $^{12}C + {}^{12}C$ reaction near astrophysical energies at LUNA

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INFN-Laboratori Nazionali del Gran Sasso (LNGS)

Nuclear Physics in Astrophysics XII (NPA-XII)

September 8, 2026

Why this $^{12}C+^{12}C$ reaction

- Triggers carbon burning after hydrogen and helium exhaustion.
- Determines the temperature and density for carbon ignition.
- Acts as a gateway to Ne, O, and Si burning stages.
- Controls the fate of massive stars (($M \gtrsim 8\,M_\odot$)) and supernova progenitors.
- Reaction rate uncertainty directly impacts nucleosynthesis yields and stellar evolution models.

Understanding $^{12}\mathrm{C} + ^{12}\mathrm{C}$ fusion is essential to understand later stages of star evolution.

Previous Measurement & Present Status

Author(s)	Energy range	Measurement Type	Detector / Setup
Mazarakis et al. 1973	2.5–5.1 MeV	particle spectroscopy	Si detectors at 10°-90°
Becker et al. 1981	2.8–6.3 MeV		9 Si detectors at 10°-90°
High et al. 1977	2.5–5.9 MeV	γ-ray spectroscopy	2 Ge(Li) detectors placed at 90°
Aguilera et al. 2006	4.4–6.5 MeV		Ge detector placed at 55^o and 125°
Spillane et al. 2007	2.1–4.7 MeV		Ge detector (115 %) placed at 0°
Jiang et al. 2018	3.5–4.0 MeV	particle–γ coincidence technique	Gammasphere (array of about 100 Compton-suppressed Ge spectrometers) with three annular double-sided silicon strip detectors
Tan et al. 2020	2.2–5 MeV		Ge detector (119 %) silicon-detector array at Notre Dame (SAND)
Fruet et al. 2020	2.2–5.4 MeV		STELLA setup (36 lanthanum bromide [LaBr3(Ce)] scintillator detectors with three annular silicon detectors
Tumino et al. 2020	0.8-2.7 MeV	Indirect measurement (THM): ^{12}C(^{14}N, α^{20}Ne)^{2}H and ^{12}C(^{14}N, p^{23}Na)^{2}H	Two silicon telescopes(detection of α–d and p–d coincidences)

Previous Measurement & Present Status

Author(s)	Energy range	Measurement Type	Detector / Setup
Mazarakis et al. 1973	2.5–5.1 MeV	p	
Becker et al. 1981	2.8–6.3 MeV		
High et al. 1977	2.5–5.9 MeV		
Aguilera et al. 2006	4.4–6.5 MeV	γ	
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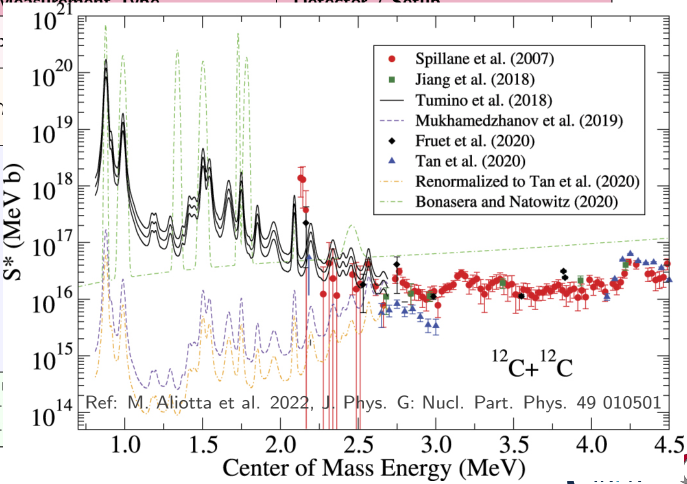
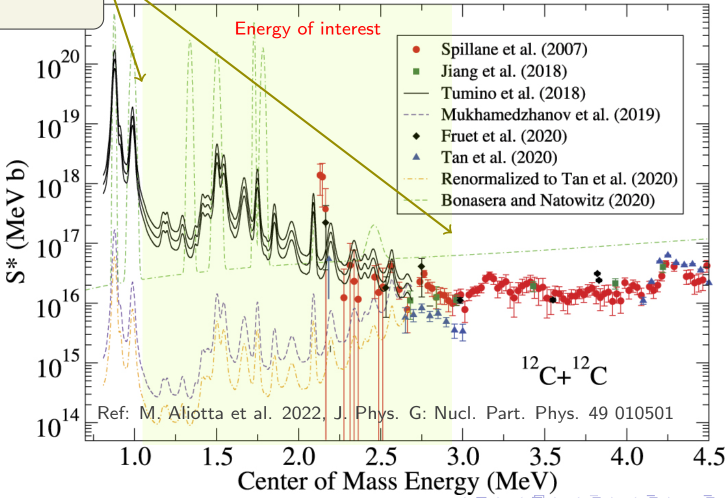


Ref: M. Aliotta et al. 2022, J. Phys. G: Nucl. Part. Phys. 49 010501

Previous Measurement & Present Status

Stellar burning occurs E∼1-3 MeV, lies far below the Coulomb barrier (∼6 MeV)



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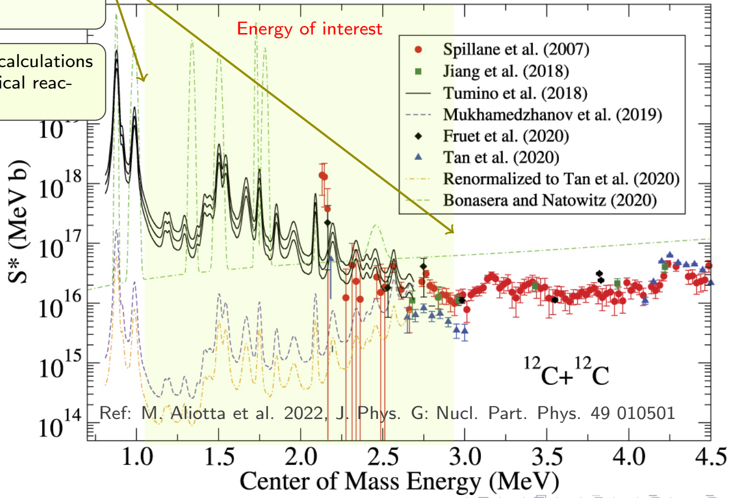
Phenomenological extrapolations or model calculations are needed in order to obtain the astrophysical reaction rate



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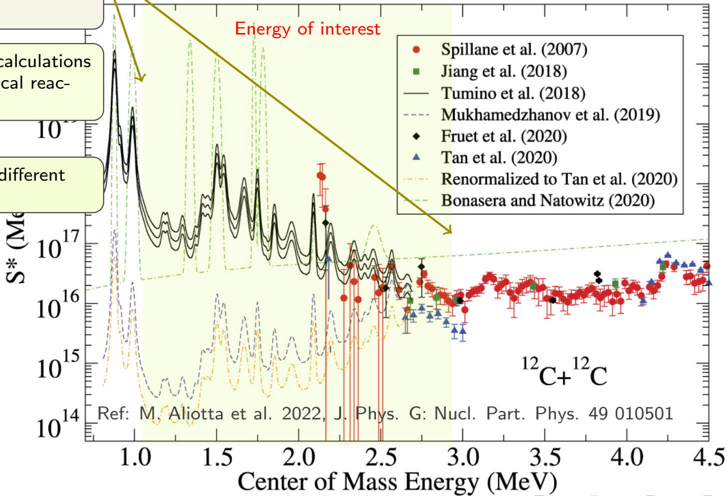
Strong discrepancies between datasets and different model



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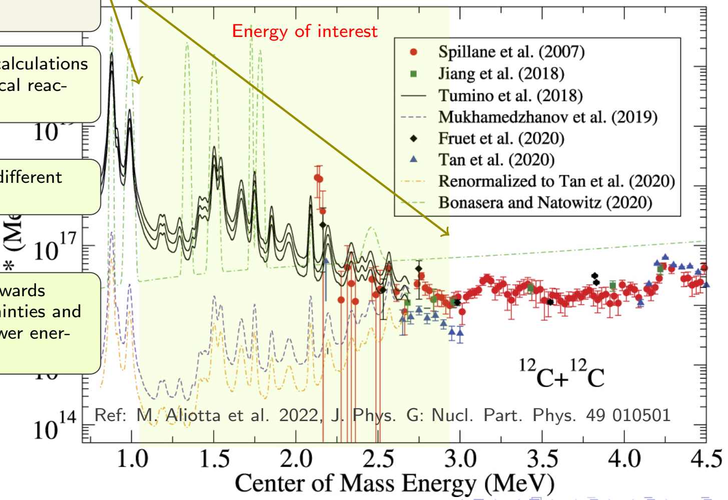
Strong discrepancies between datasets and different model

Extending high-quality experimental data towards lower energies is crucial for reducing uncertainties and giving more robust extrapolation towards lower energies



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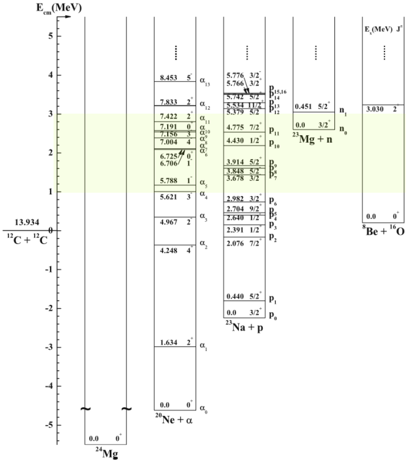
Direct measurement towards low energies



Ref: Y. J. Li et al. Chinese Phys. C 44 (2020) 115001

Direct measurement towards low energies

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* &\rightarrow {}^{20}\mathrm{Ne} + \alpha \ (\mathrm{Q} = +4.62\ \mathrm{MeV}) \\
&\rightarrow {}^{23}\mathrm{Na} + p \ (\mathrm{Q} = +2.24\ \mathrm{MeV}) \\
&\rightarrow {}^{23}\mathrm{Mg} + n \ (\mathrm{Q} = \text{-}2.60\ \mathrm{MeV}) \\
&\rightarrow {}^{16}\mathrm{O} + {}^{8}\mathrm{Be} \ (\mathrm{Q} = \text{-}0.20\ \mathrm{MeV})
\end{aligned}
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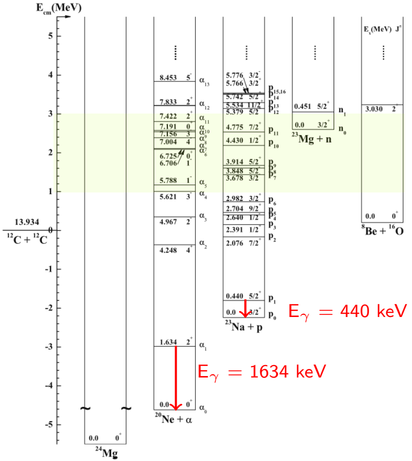

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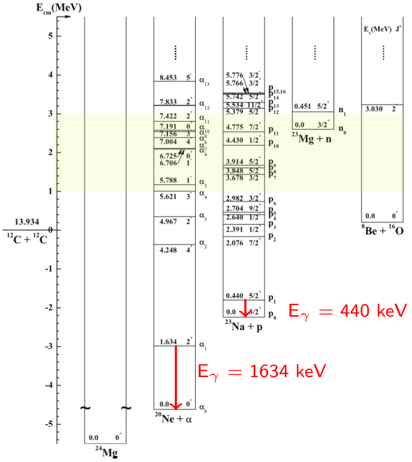
Measurement approach

- Charge particle detection
- γ-ray spectroscopy : count photons emitted (isotropically) in the de-excitation of the final nucleus



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Direct measurement towards low energies

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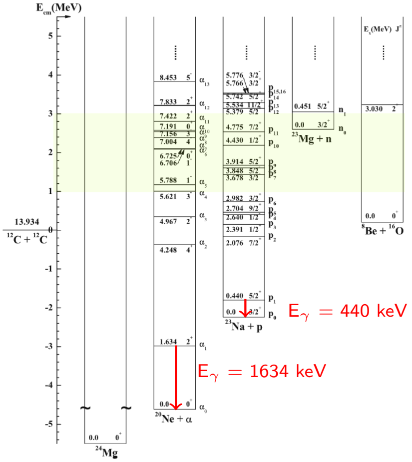
\begin{aligned}
{}^{12}C + {}^{12}C \rightarrow {}^{24}Mg^* &\rightarrow {}^{20}Ne + \alpha \ (Q = +4.62 \text{ MeV}) \\
&\rightarrow {}^{23}Na + p \ (Q = +2.24 \text{ MeV}) \\
&\rightarrow {}^{23}Mg + n \ (Q = -2.60 \text{ MeV}) \\
&\rightarrow {}^{16}O + {}^{8}Be \ (Q = -0.20 \text{ MeV})
\end{aligned}
$$

Measurement approach

- Charge particle detection
- γ-ray spectroscopy : count photons emitted (isotropically) in the de-excitation of the final nucleus

Difficulties

- At such low energies, the background inherent in detection techniques introduces extra uncertainty in the measured cross-section
- Reduction of background is necessary, using active and passive shielding



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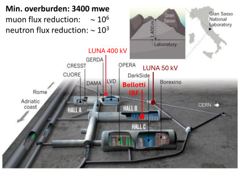
BELOTTI ION BEAM FACILITY

- Underground Laboratories: Provide a low-background environment by shielding experiments from cosmic rays and natural radiation
- **Belotti Ion Beam Facility** : 3.5 MV Singletron accelerators delivering high-intensity, low-energy ion beams (p, α, ^{12}C)



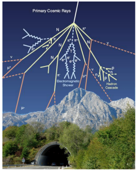


Image credit : R.M. Gesuè

BELOTTI ION BEAM FACILITY

More details: Federico Ferraro's talk on 11/09/2026

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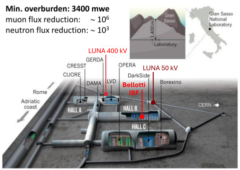

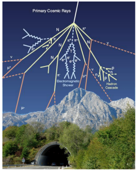

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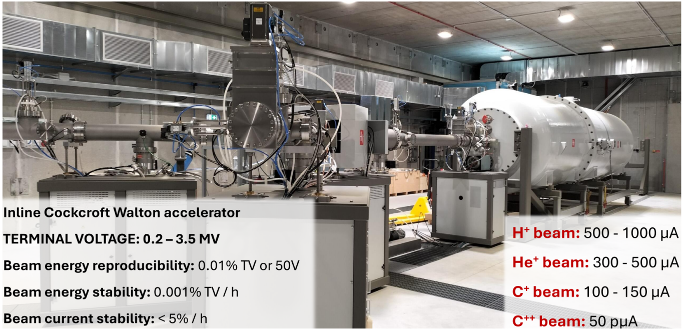

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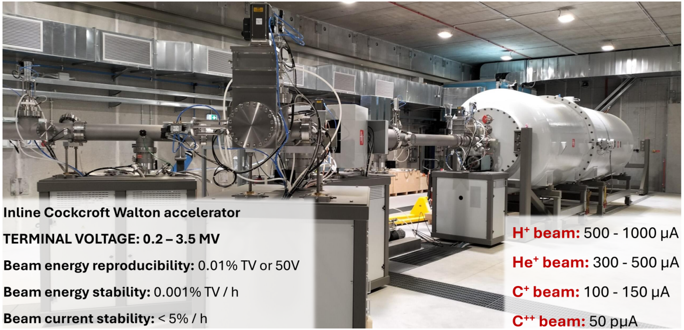

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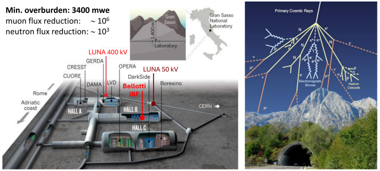

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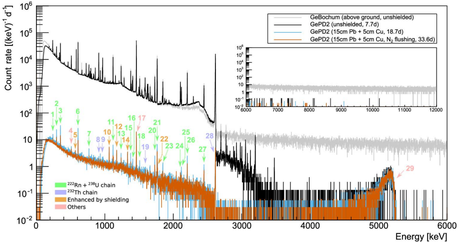


Ref: R M Gesuè et al 2025 J. Phys. G: Nucl. Part. Phys. 52 105103

$^{12}C + ^{12}C$ Experiment : Setup

- $^{12}C^{++}$ beam on thick Graphite target
- 25 cm Pb + 1 cm Cu passive shielding
- High purity Ge detector used (157 % relative efficiency)

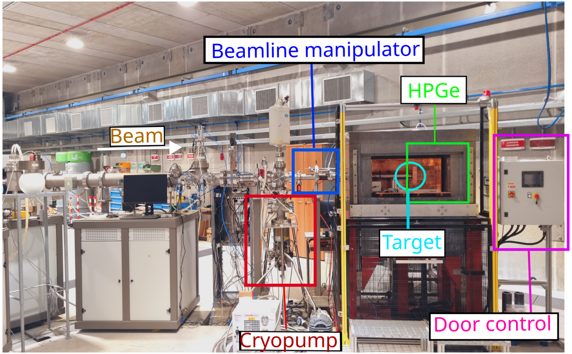
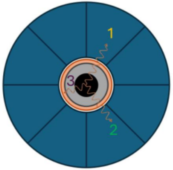


Image credit : R.M. Gesuè

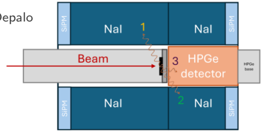
$^{12}C + {}^{12}C$ Experiment : Setup

- $^{12}C^{++}$ beam on thick Graphite target
- 25 cm Pb + 1 cm Cu passive shielding
- Ge detector encased by 5 cm Cu
- Two annulus NaI detectors (each segmented into eight sections) to use as an active anti-Compton veto



Front view

Image credit : R. Depalo



Lateral view

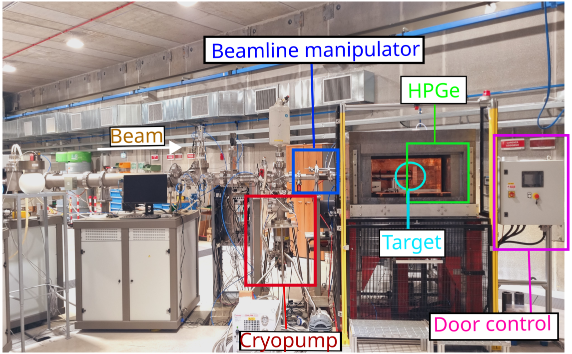


Image credit : R.M. Gesuè

Phase 1: Target Characterization

Phase 1

Phase 2

Phase 3

Phase 4

- Four target types tested: two sintered graphite variants, glassy carbon, and HOPG (highly oriented pyrolytic graphite)
- Approximately 1 mm thick with backing 1.5 mm Cu and few μm Ta on top

Phase 1: Target Characterization

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Phase 4

- Four target types tested: two sintered graphite variants, glassy carbon, and HOPG (highly oriented pyrolytic graphite)
- Approximately 1 mm thick with backing 1.5 mm Cu and few μm Ta on top
- Graphite targets withstood irradiation up to 10 C with no visible damage
- Glassy carbon and HOPG dameged after only 0.2-0.6 C

Image credit : F. Ferraro

Target	Charge (C)	Relative contamination
Graphite#1	0.97	1
Graphite#2	0.19	1.19
HOPG	0.62	0.14
Glassy carbon	0.23	0.03

Phase 1: Target Characterization

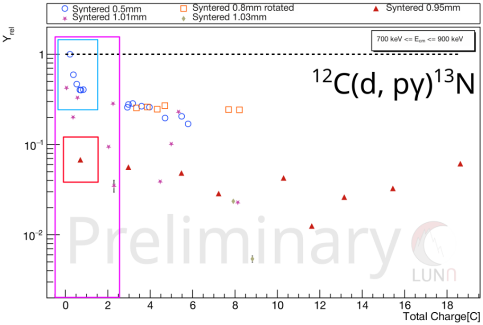
Phase 1

Phase 2

Phase 3

Phase 4

- ^{1}H and ^{2}H two major contamination
- Heating the target is an effective way to remove these contaminants
- Beam irradiation is not enough
- Backing the target at 200^{0}C in a vacuum oven for few days, reduced contamination by about one order of magnitude



Phase 2: ^{12}C + ^{12}C Measurement

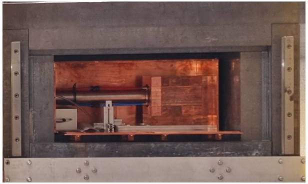
Phase 1 ✓

Phase 2

Phase 3

Phase 4

- Ge detector encased by 5 cm Cu
- Characterize the HPGe detector
- Measurements at $2.3 \leq E_{CM} \leq 3.5$ MeV in steps of $\sim$20 keV



Phase 3: ^{12}C + ^{12}C Measurement

Phase 1 ✓

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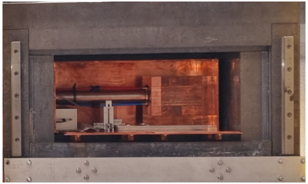

- Two annulus NaI detectors installed surrounding the beam-line and HPGe
- Characterization of NaI
- Measurements at $2.1 \leq E_{CM} \leq 2.3$ MeV in steps of 20 keV (**Ongoing**).

$^{12}C + {}^{12}C$: Peak Identification

Phase 1 ✓

↓

Phase 2 ✓

↓

Phase 3 ✓

↓

Phase 4

- $E_{cm} = 3.47 – 2.10$ MeV
- current 85-100 uA on target
- 5 Targets, About 58 C accumulated

$^{12}C + {}^{12}C$: Peak Identification

- Phase 1 ✓
- Phase 2 ✓
- Phase 3 ✓
- Phase 4

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$E_{CM} = 3.47$ MeV

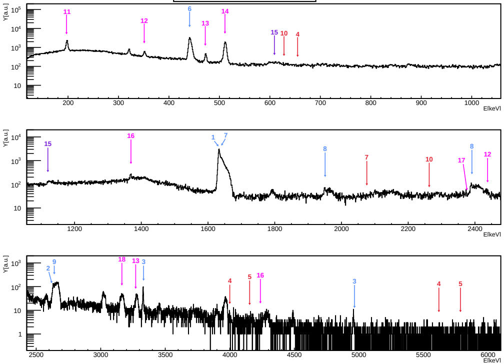

Image credit : R.M. Gesuè

Label	Source
1	α_1
2	α_2
3	α_3
4	α_4
5	α_5
6	p_1
7	p_2
8	p_3
9	p_4
10	p_5

Label	Source
11	^{19}F
12	$^{12}C(^{13}C, \alpha)^{21}Ne$
13	$^{12}C(^{13}C, p)^{24}Na$
14	Annih
15	^{214}Bi
16	$^{12}C(^{12}C, \gamma)^{24}Mg$
17	$^{12}C(p, \gamma)^{13}N$
18	$^{12}C(d, p\gamma)^{13}C$

- Identified the relevant peaks in the γ-spectrum
- Some transition were not observed (α_4, α_5, p_5)
- Identified and characterized different sources of beam-induced background (BIB)

$^{12}C + {}^{12}C$: Peak Identification

- $E_{cm} = 3.47 - 2.10$ MeV
- current 85-100 uA on target
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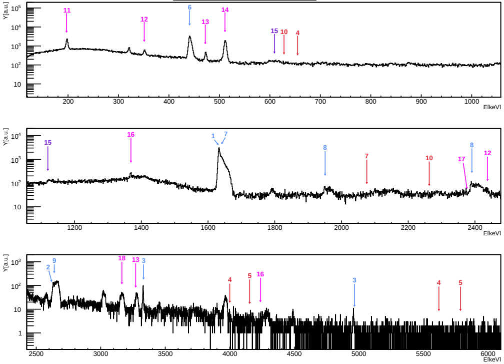
Phase 1 ✓

Phase 2 ✓

Phase 3 ✓

Phase 4

$E_{CM} = 3.47$ MeV



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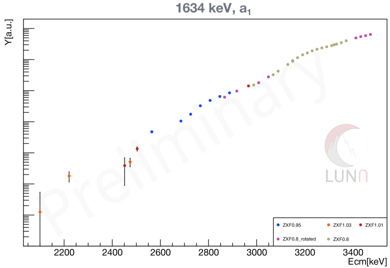

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Phase 2 ✓

Phase 3 ✓

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$E_{CM} = 3.47$ MeV

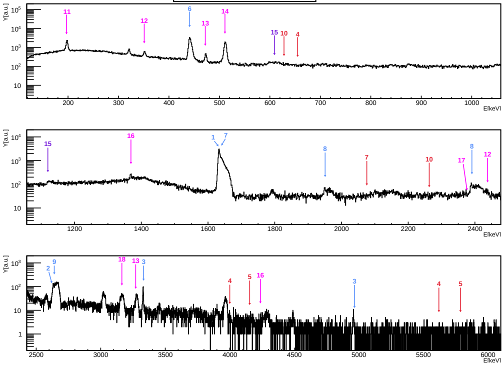
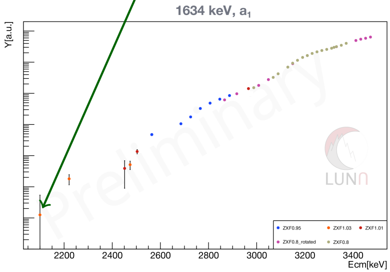


Image credit : R.M. Gesuè

Lowest energy ($E_{CM} = 2.1$ MeV) from direct measurement



Phase 4: Conclusion and Future outlook

Phase 1 ✓

Phase 2 ✓

Phase 3 ✓

Phase 4

- Suitable targets identified and used throughout the measurement campaigns
- The first measurement campaigns were successfully completed, the collected dataset is currently under analysis.
- Lowest energy reached $E_{CM} = 2.1$ MeV
- Measurements $E_{CM} \leq 2.1$ MeV will be performed in the next campaign.
- New promising results expected soon

LUNA COLLABORATION

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Thank you