

The direct determination of the cross section of the ¹²C + ¹²C reaction at astrophysical energies

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ChETEC-INFRA Experimental Plan Bellotti Ion Beam Facility, INFN-LNGS

Title of Experiment

Measurement of the $^{12}C+^{12}C$ cross section from E_{cm} = 2.5 MeV down to 2.3 MeV

Name of the PI, participants and institutions

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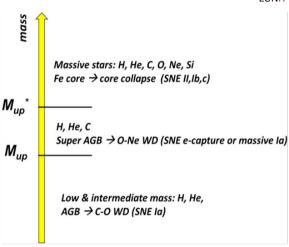
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Astrophysical motivations



- Carbon burning is the stage of stellar evolution that determines the final destiny of stars.
- Only stars with M > M^{*}_{up} ~ 10M_o can ignite C in non-degenerate conditions and proceed up to the formation of a gravitationally unstable Fe core.
- Less massive stars M < M_{up} ~ 7M_☉ never ignite C and will evolve into CO White Dwafs.
- Thus M_{up} and M_{up}^* are linked to the $^{12}\text{C} + ^{12}\text{C}$ reaction rate.

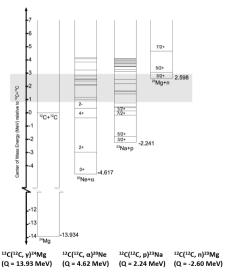


[Straniero et al., J. Phys. Conf. Ser. 665012008, 2016]

The ¹²C + ¹²C reaction

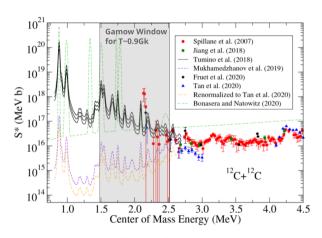


- Stellar C burning proceeds mainly through the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ and the $^{12}\text{C}(^{12}\text{C}, p)^{23}\text{Na}$ channels.
- ~ 50% of the reactions leave the final nucleus in an excited state.
- The cross-section can be measured either detecting the emitted charged particles or the γ-rays produced by the decay of the excited states of ²⁰Ne and ²³Na.



State of the art





[Aliotta et al., J. Phys. G. Nucl. Part. Phys. 49 010501, 2022]

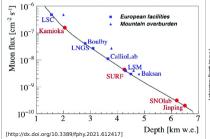
- The ¹²C + ¹²C fusion reaction has been directly investigated down to 2.1 MeV.
- Determination of reaction rates at stellar energies relies on extrapolation of high energy data → large uncertainties.
- Extrapolation is further complicated by possible cluster configurations in ²⁴Mg.
- The direct measurements are complemented by indirect measurements, transfer techniques or other reaction methods.
- These often rely on complex theoretical frameworks and assumptions to interpret the measured data.
- Conflicts at the energies of interest.

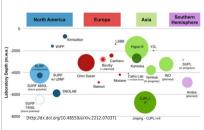
Laboratori Nazionali del Gran Sasso











- CUORE (Data Taking) - CUPID (R&D) - LEGEND-200 (Commissioning)

- Neutrinoless double beta decay:

Dark Matter: - Xenon nT (Data Taking)

- Dark Side 20k (Construction) - CRESST (Data Taking)
- Chemistry Service - CYGNUS (R&D) - Flectronic Workshop - COSINUS (Construction) - Clean Room - DAMA/LIBRA (Upgrade)

Encilities:

Mechanical Workshop

- Additive Manufacturing

Laboratory

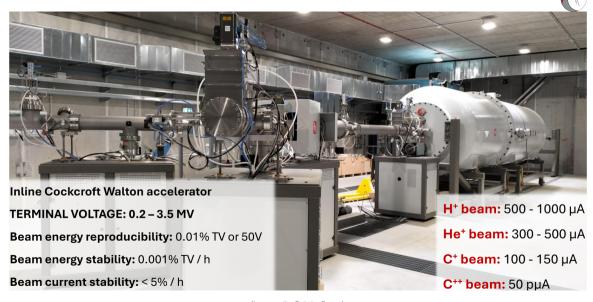
- PTOLEMY (R&D) Quantum Computing:

Neutrino Physics - SOMS (Testing)

Nuclear Astrophysics:

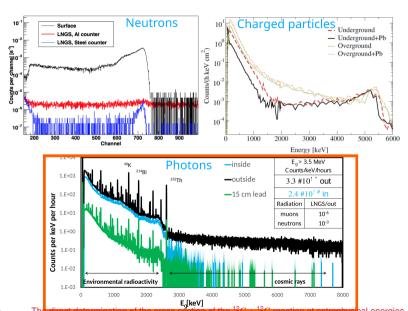
- LUNA400 (Experimental activity)
- 3.5MV Accelerator@Bellotti IBE (Experimental activity)

The Bellotti Ion Beam Facility



Background reduction at LNGS



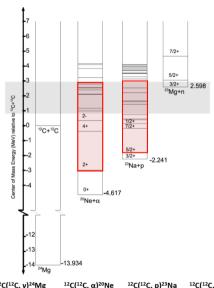


¹²C + ¹²C: experimental method



- About 50 % of the reactions leave the final nucleus in an excited state.
- Count photons emitted in the de-excitation of the final nucleus.

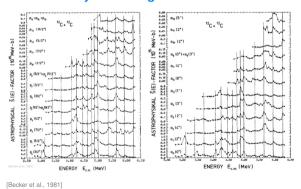
About 11 counts/day expected at the lowest energies!



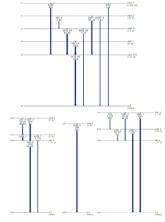
Branching ratios and gamma transitions



Particle decay branching ratios



Gamma decay branching ratios



Most intense g-rays and a particles energies fo excited states for								
	12C(12			4.617 MeV)				
Initial level		Final level		Transitions	Alpha			
E _x (MeV)	p	E _x (MeV)	J»	E _r (MeV)	ID			
0.0	0*				ao			
1.634	2'	0	0+	1.634	8,			
4.248	4'	1.634	2+	2.614	82			
4.967	2	1.634	2+	3.333	83			
5.621	3	1.634	2+	3.987	84			
5.788	11	1.634	2+	4.154 5.787	a _s			

Most intense g-rays and a particles energies for excited states for							
10	C(12C,	p) ²³ Na (Q	= 2.2	241 MeV)			
Initial level		Final level		Transition s	Alpha		
E _x (MeV)	Je	E _x (MeV)	J#	E, (MeV)	ID		
0.0	3/2"				P ₀		
0.440	5/2*	0	3/2+	0.440	p_1		
2.076	7/2*	0.440	5/2*	1.637	p_2		
2,391	1/2"	0.440	5/2"	1.951	\mathbf{p}_{3}		
2.391		0	3/2*	2.391			
2.640	1/2	0	3/2+	2.640	p_4		
2.704	9/2*	2.076	7/2*	0.627			
		0.440	5/2*	2.263	p_6		
2.982	3/2*	0.440	5/2*	2.541			
2.982		0	3/2*	2.982	p_6		

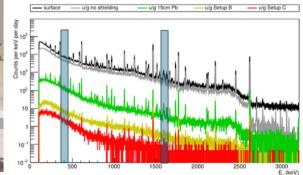
[Image credits: Federico Ferraro]

Shielding





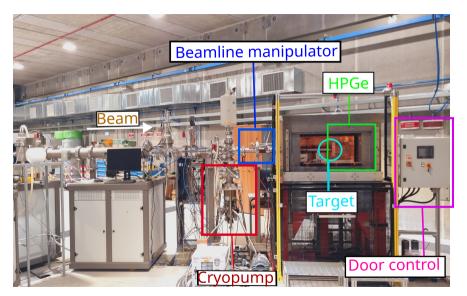
- Massive shielding built to reduce the environmental background of more than 2 orders of magnitude:
 - 2 cm + 5 cm copper shielding.
 - 25 cm lead shielding.



[Picture credits: Matthias Junker]

Beamline



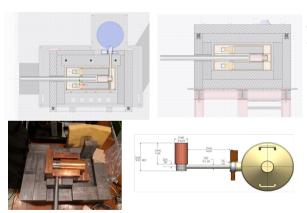


[Picture credits: Matthias Junker]

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Detector array





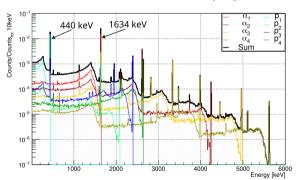
Detection setup made of several Nal scintillation detector and a 150% HpGe detector in close geometry.

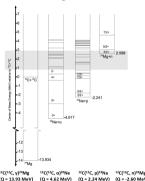
- Nal detectors placed in a compact arrangement around the HpGe covering a ~ 3.5π angle:
 - high detection efficiency,
 - preserve HpGe high resolution (1.1 keV @ 660 keV).
- The Nal array works as an active veto for Compton, environmental and beam-induced background events.
- Nal in production, ready by autumn 2025.

Geant4 simulations



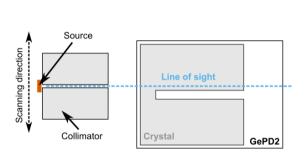
- Accurate model of the HpGe implemented → based on technical drawing.
- Simulated $^{12}C + ^{12}C \gamma$ based on Becker et al., 1981 branching ratios.
- · Critical for determination of setup's geometrical efficiency and branching ratio measurement.





HPGe characterization





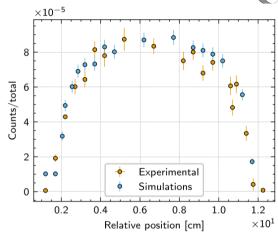


Figure 9. Lateral scan of the GePD2 detector along the bore hole axis using a collimated ¹³⁷Cs source (see inset). Experimental data (orange) are compared to results from simulations (blue). An offset of 0.5 cm was applied in order to account for misplacement of the collimator.

HPGe background



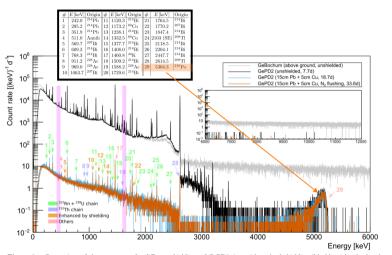


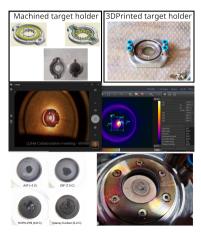
Figure 2. Comparison of the count rates for different shieldings of GePD2, i.e. without lead shielding (black), with a lead and copper shielding (blue) and an additional nitrogen flushing (orange). As a comparison, the count rate of the unshielded GeBochum above ground is shown in grey. The most prominent peak structures are labeled and color-coded according to their origin and listed in Table 1. The high energetic region from 6 MeV to 12 MeV is shown as an inset for the same spectra.

[Gesue' et al., accepted @JPG]

Graphite Targets: Felsenkeller Laboratory and LNGS



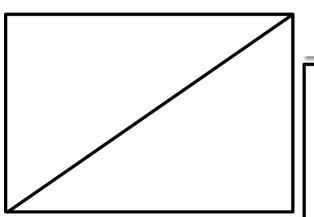
- Target characterization campaign at Felsenkeller Laboratory in 2024.
- Target characterization campaign at LNGS in December 2024 → first ¹²C beam on target @LNGS.



- LNGS workshop: developed 3D printing technology to produce target holders.
- 4 different graphite targets tested.
- Approximately 1 mm thick, density 0.178 g/cm2.
- Backing: 1.5mm Cu with a few um Ta layer on it.
- HPGe + Nal @0 deg in 5 cm lead shielding.
- E_{cm} 2850 keV 2900 keV in steps of 25-50 keV.
- Beam current 100 uA.
- Thermocamera + optical camera: ~ 1600° C on surface. Nothing melted → water cooling works!
- ZXF and AXF targets able to withstand 7C unharmed.
- Glassy Carbon and HOPG → significant damage

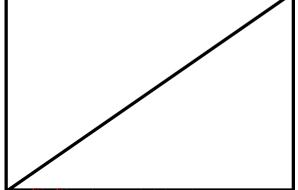
Graphite Targets: December 2024





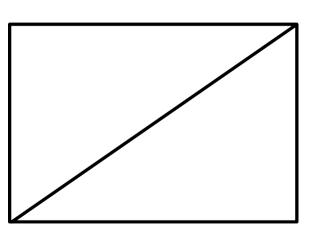
Beam Induced Background

- ${}^{1}\text{H}({}^{12}\text{C}, \gamma){}^{13}\text{N}~E_{\gamma} = 2368 \text{keV}$
- ${}^{2}\text{H}({}^{12}\text{C}, p\gamma){}^{13}\text{C}~E_{\gamma} = 3090 \text{keV}$
- Decreased by heating up the target.



Geant4 simulations: comparison with December 2024 data

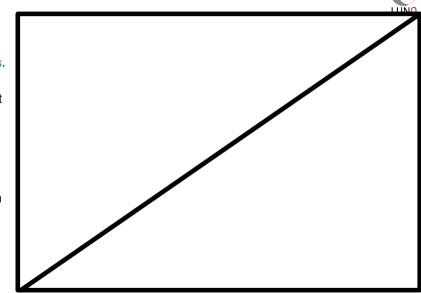




- Simulation not to scale.
- More peaks identified thanks to simulation.
- Great achievement at such low beam energies.
- Bright hopes for measurement with full setup.

First experimental campaign: May - July 2025

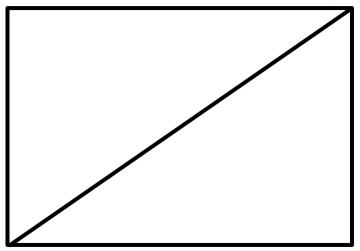
- - Heating up the target appears is a reliable way to get rid of contaminants.
 - Simple irradiation with beam is not sufficient/fast enough.
 - Kept the target ZXF 0.95 mm at 200°C in vacuum for three days: reduction of the amount of contaminants of about an order of magnitude.
 - Longer "baking times" don't seem to have a larger effect on the ¹H and ²H removal.



First experimental campaign: May - July 2025



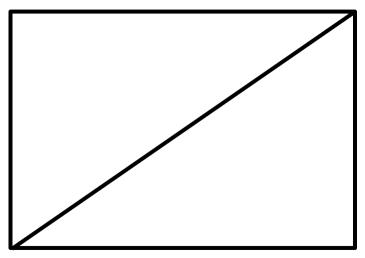
- Acquired data between ~ 3.5 MeV and ~ 2.1 MeV.
- About 40 C on 4 ZXF target, ~ 1 mm thick.
- Lower statistical uncertainties than literature data at all energies.



First experimental campaign: May - July 2025



- Acquired data between ~ 3.5 MeV and ~ 2.1 MeV.
- About 40 C on 4 ZXF target, ~ 1 mm thick.
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Conclusions and outlook



- Paper on detectors characterization accepted on JPG: 10.1088/1361-6471/ade0dc.
- More in-depth analysis of December 2024 data ongoing.
- Setup fully mounted and operational.
- First campaign with complete setup concluded.
- Lowest energy reached: 2.1 MeV.
- Nal array charcterization ongoing.
- Second campaign first quarter 2026.
- Promising first results:
 - well defined procedure to remove most of the contaminants from target;
 - several transitions recognized thanks to simulation and analysis routine.

Special thanks to the LNGS Accelerator Service.