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Direct measurement of the $^{12}C+^{12}C$ reaction rate

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Astrophysical motivations

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

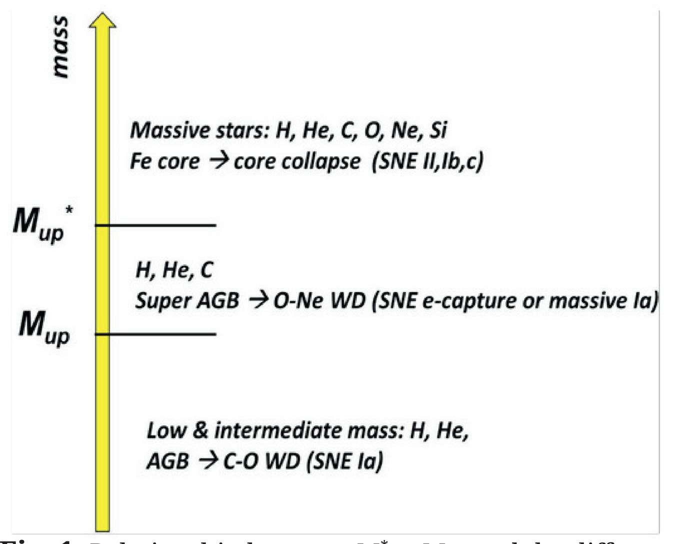

Fig. 1: Relationship between M^{*}_{up}, M_{up} and the different phases of stellar evolution [1].

The $^{12}C+^{12}C$ reaction

- Stellar C burning proceeds mainly through the $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ channels.
- About 50% of the reactions leave the final nuceus in an excited state.
- The cross-sections can be measured either detecting the emitted charged particles or the γ-rays produced by the decay of the excited states of ^{20}Ne and ^{23}Na.
- This way it is also possible to measure the level density of ^{24}Mg through the de-excitation of ^{20}Ne and ^{23}Na.

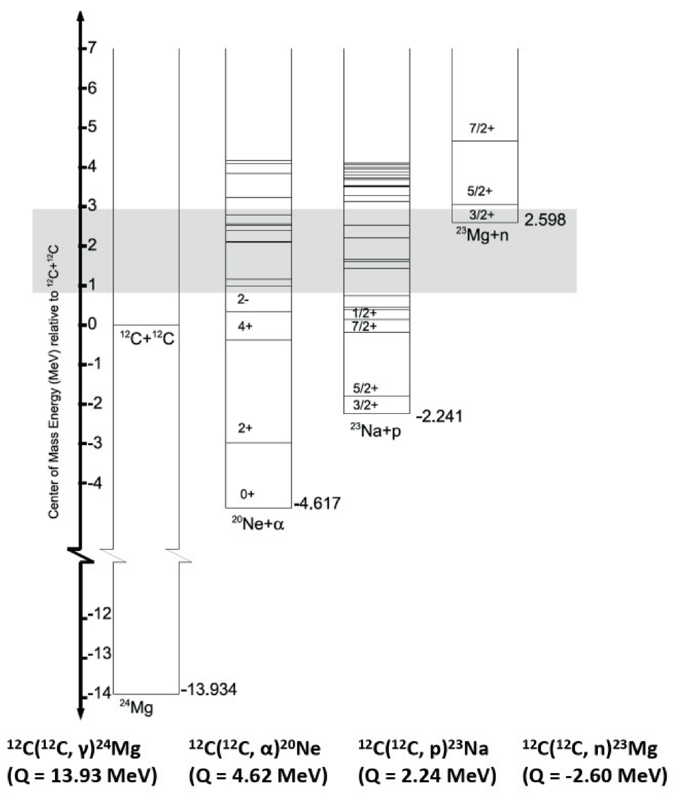

Fig. 2: Nuclear energy levels for $^{12}C+^{12}C$ fusion reaction exit channels. The shaded region represents the astrophysical relevant energy region.

State of the art

- The $^{12}C+^{12}C$ fusion reactions have been directly investigated down to 2.1 MeV.
- The determination of reaction rates rely on extrapolation of high energy data towards the stellar energy range, with large uncertainties.
- Extrapolation is further complicated by possible cluster configurations in ^{24}Mg.
- The direct measurements are complemented by indirect measurements, tranfer techniques or other reaction methods.
- These rely on complex theoretical frameworks

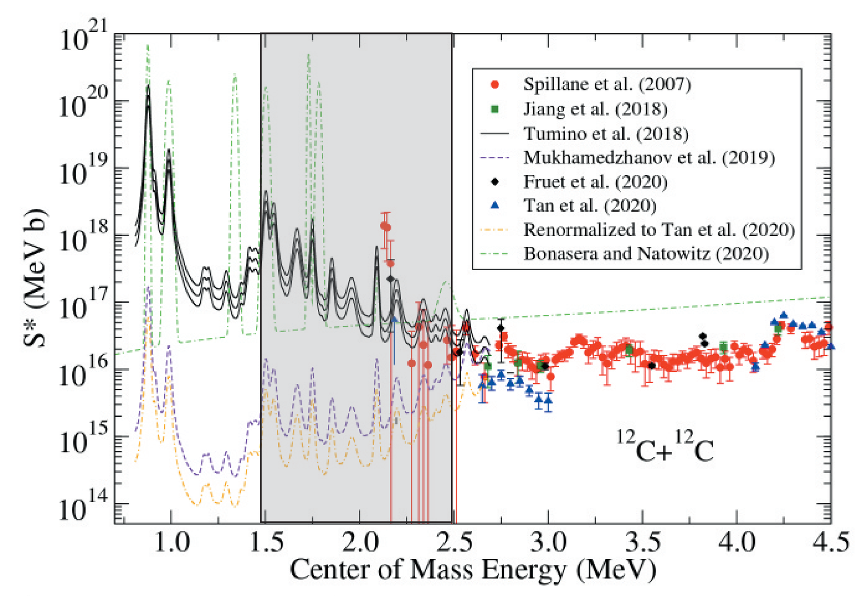

Fig. 3: Modified S-factor (S*) for the 12C+12C fusion reaction from recent experiments [2]. The shaded region represents the energy range of interest.

Detection sensitivity

Minimum daily reaction rate to reach 50% statistical uncertainty considering detection efficiency, beam current (200 pμA) and 60 days of detection time	
$^{12}C(^{12}C,p)^{23}Na$	$^{12}C(^{12}C,\alpha)^{20}Ne$
E_{γ} = 440 keV	E_{γ} = 1634 keV
11 reactions/day	3 reactions/day

- Experiment performed at LNGS (Italy), below a 1400m thick overburden of rock:
  - Cosmic ray-induced μ background reduced by 6 orders of magnitude;
  - Neutron background reduced by 3 orders of magnitude.

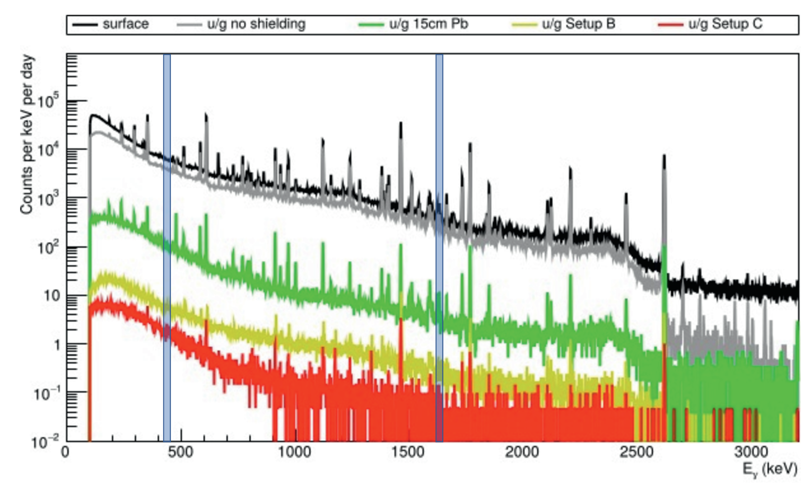

Fig.4: Comparison of γ-ray background measured with a HPGe at LNGS on surface and underground ("u/g"). Setup B is made of a 25cm Pb shielding, while in setup C the 25cm Pb shielding is placed inside a anti-radon box. The estimated natural background in 8 counts/day in the 440 keV ROI and 0.2 counts/day in the 1643 keV ROI.

Experimental setup

- Project will use the new 3.5 MV accelerator at the Bellotti IBF:
  - high intensity C beam (200 μA for a beam of $^{12}C^{+}$ and 50 puA for $^{12}C^{++}$),
  - great energy resolution and stability.
- Detection setup made of one 150% HPGe and 16 NaI scintillators.
- NaI detectors placed in a compact arrangement around the HPGe, covering a ~3.5π angle: this guarantees high detection efficiency while preserving the excellent HPGe resolution (1.2 keV @ 1.33 MeV).
- The NaI array also works as an active veto for Compton continuum, environmental radioactivity and beam-induced background events.
- Detectors placed in a 1 cm thick copper shielding surrounded by a 25 cm thick lead shielding which will further reduce the environmental background of more than 3 orders of magnitude.

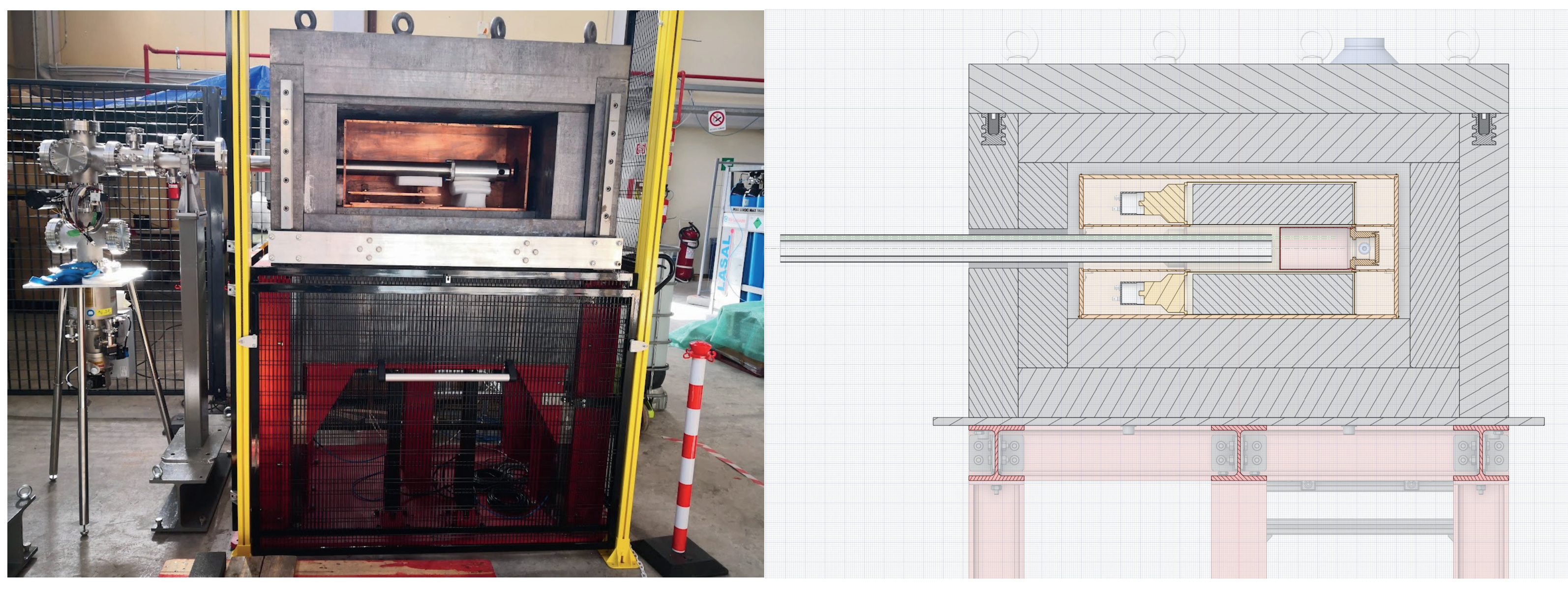

Fig. 5: *Left*: picture of the assembled lead shielding. *Right*: technical drawing of the detection array placed inside the shielding. The NaI geometry represented is not the definitive one.

Detector characterization

- Characterization of the active volume of HPGe using radioactive γ sources (Fig. 6):
  - ^{137}Cs → E_{γ} = 661 keV → sensitive to macroscopic features, single γ ,
  - ^{133}Ba → E_{γ} = 81,356,... keV → sensitive to macroscopic and microscopic features, several γ .
- Scanned front and side of the detector.
- Results will be used to fine-tune the simulations.
- Characterization of the intrinsic activity of the detectors with long background acquisitions inside and outside thick lead shielding:
  - α peak at 5.3 MeV in HPGe → ^{210}Pb contamination in soldering material (Fig. 7).

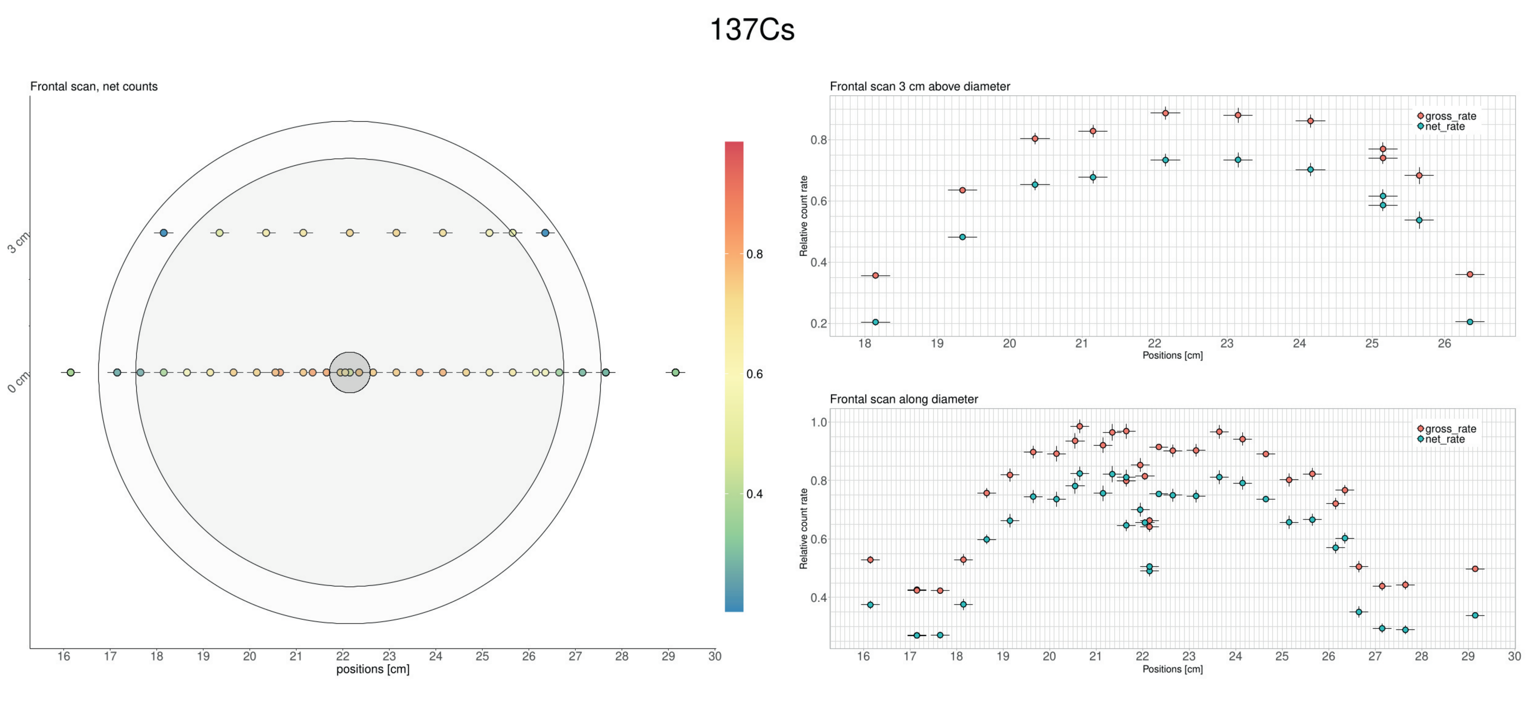

Fig. 6: *Left*: 2D projection of the background-subtracted scans. *Right*: Scan of the front face of the detector, along the diameter and 3 cm above the diameter.

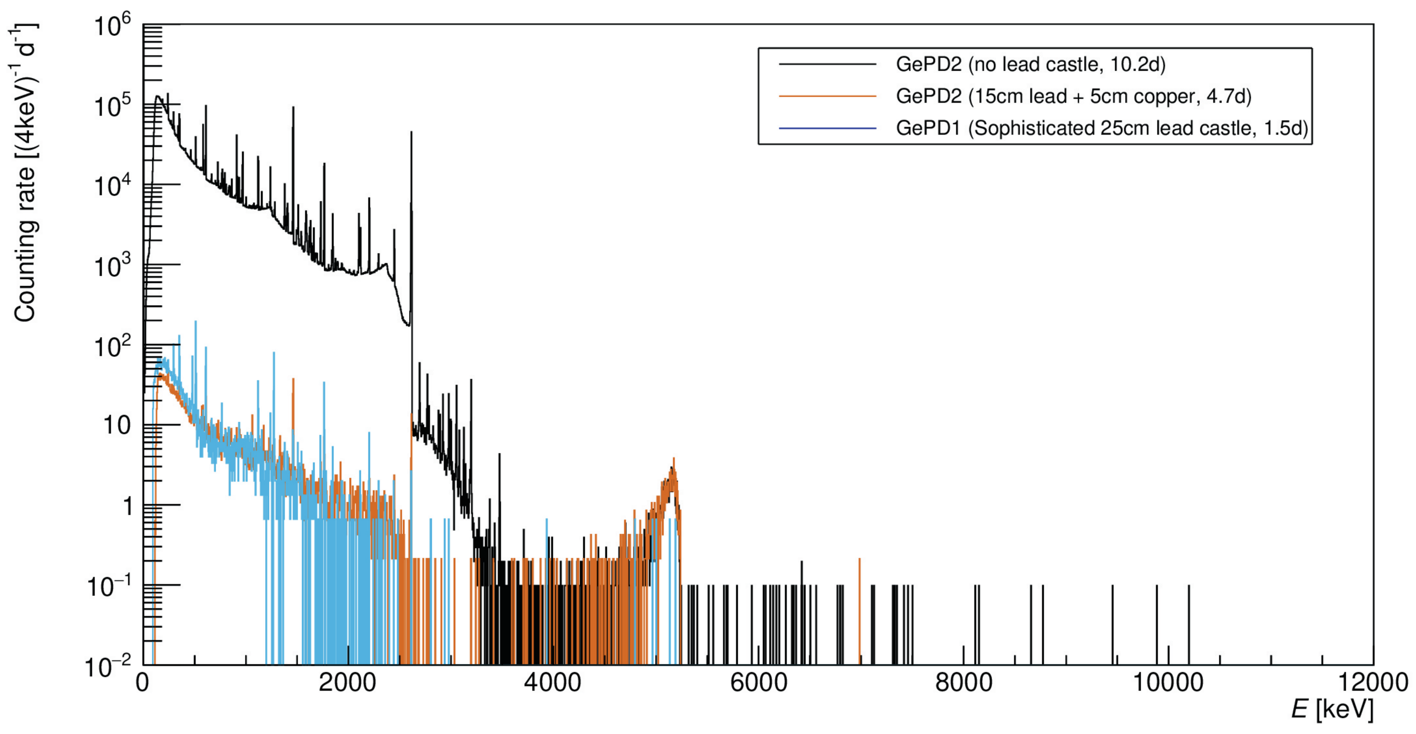

Fig. 7: Comparison of HPGe background acquisitions. GePD2 labels the detector used for the present measurement, while GePD1 is a HPGe, produced by the same manufacturer and used in a previous experiment.

Geant4 simulations

- Accurate model of HPGe based on technical drawings.
- NaI array ready to be implemented.
- Doppler effect contribution implementation: advanced WIP.
- Simulated $^{12}C+^{12}C$ expected γ-ray spectrum based on branching ratios reported in [3].
- Simulations will be critical for determination of setup's geometrical efficiency and branching ratio measurement.

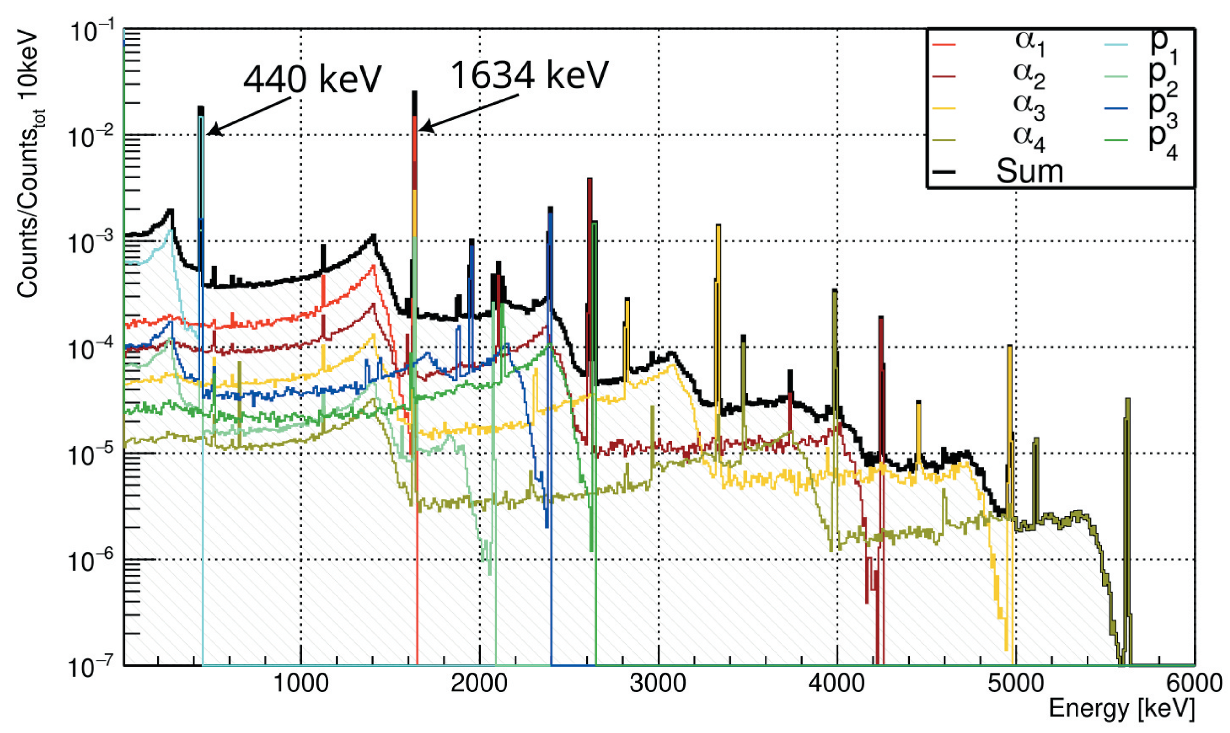

Fig. 8: Geant4 simulation of the expected γ-ray spectrum based on the decay branching ratios reported in [3]. Only HPGe considered.

References

- [1] Straniero et al. 2016 J. Phys.: Conf. Ser. 665 012008
- [2] Aliotta et al. 2022 J. Phys. G: Nucl. Part. Phys. 49 010501
- [3] Becker et al. 1981 Z. Physik. A 303.4