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Cross section of the $^{13}C(\alpha,n)^{16}O$ reaction at low energies in the framework of LUNA collaboration

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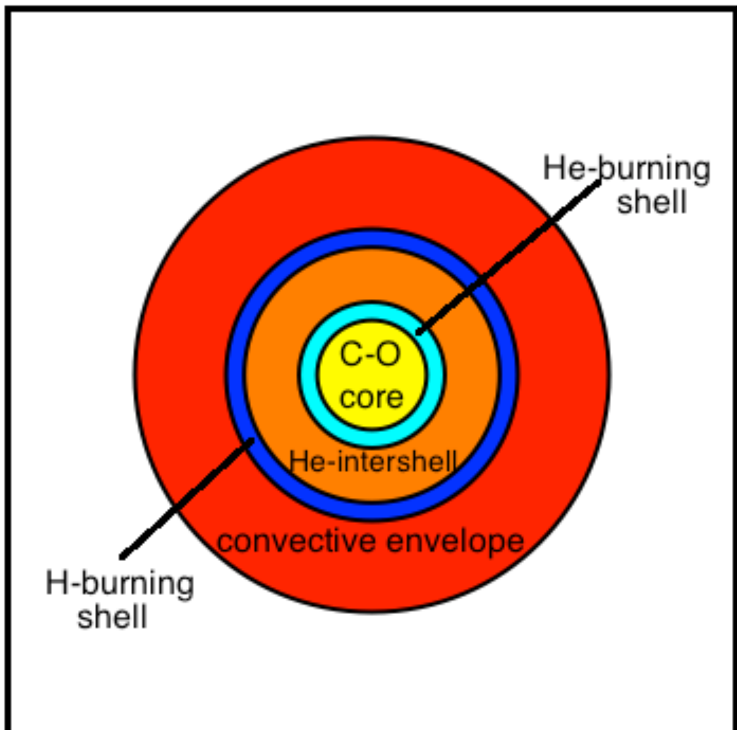
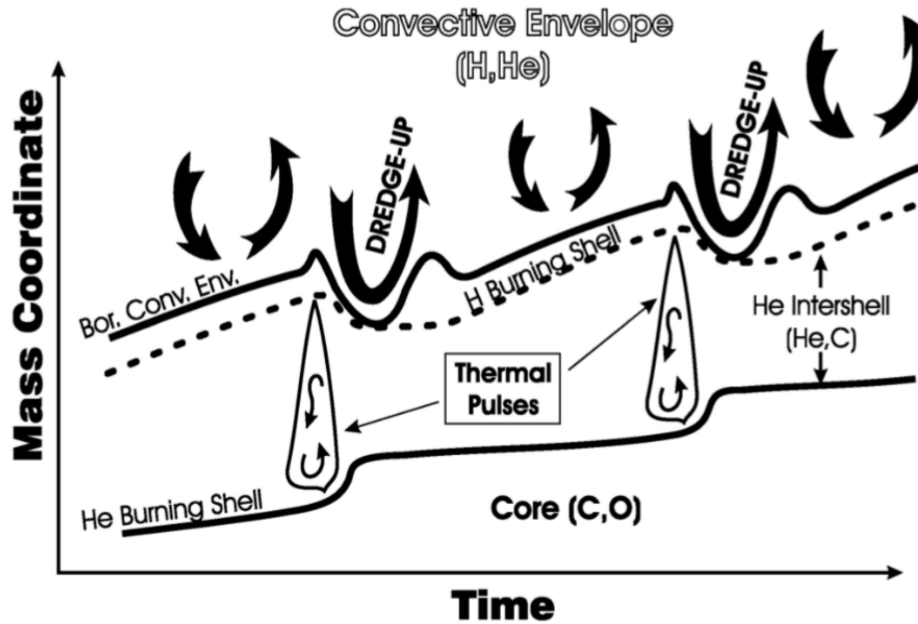
ASTROPHYSICAL MOTIVATION

$^{13}C(\alpha,n)^{16}O$ neutron source for s process

- $^{13}C(a,n)^{16}O$ (Q=2.215 MeV) is the main neutron source feeding s-process in low (1-3 $M_{\odot}$) mass TP-AGB stars, responsible for nucleosynthesis of half of nuclides heavier than iron
- Average temperature 10^8 K → Gamow window **140-250 keV**

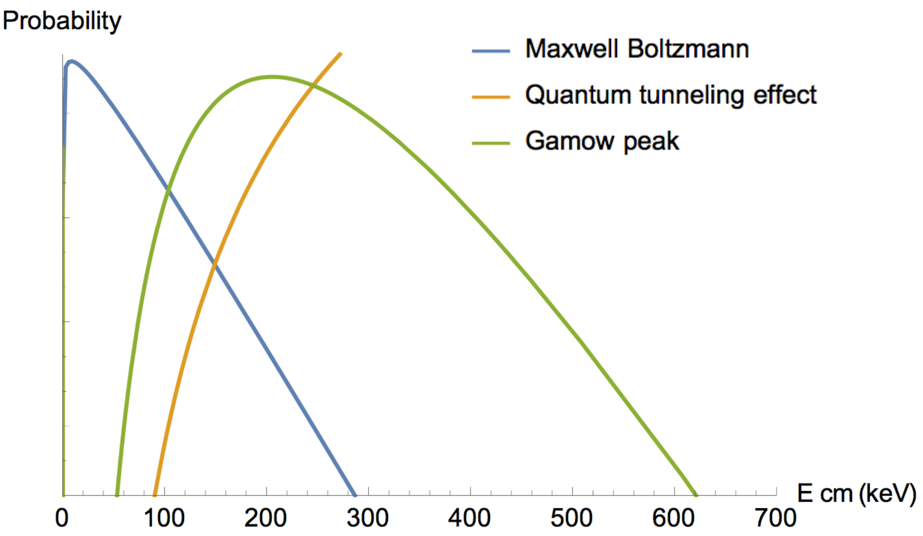


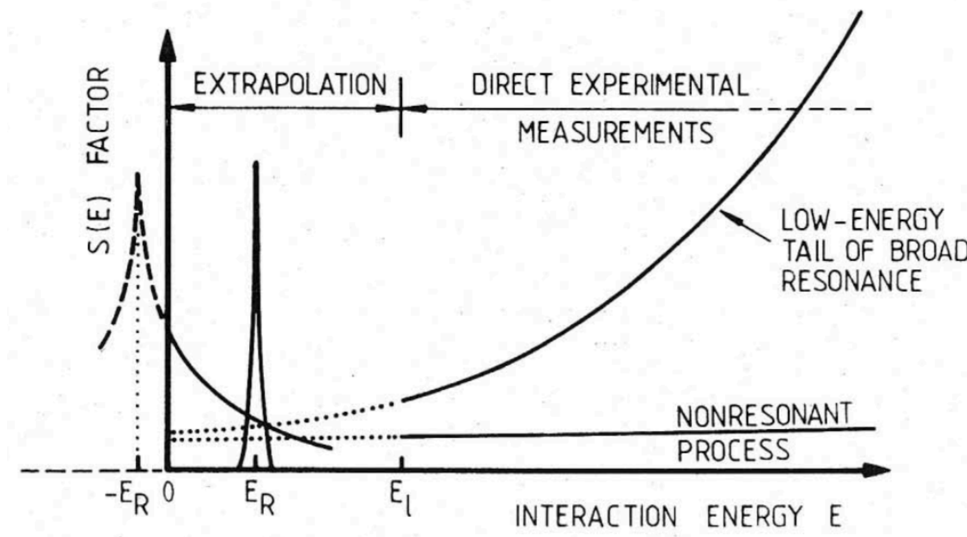


FROM THE REACTION RATE TO THE CROSS SECTION

$$\langle \sigma v \rangle_{ab} = \sqrt{\frac{8}{\pi\mu}} \left(\frac{1}{k_B T}\right)^{3/2} \int_0^{+\infty} E\sigma(E) exp\left(-\frac{E}{k_B T}\right) dE$$

$$\sigma(E) = \frac{1}{E} S(E) e^{-2\pi\eta}$$





STATE OF THE ART

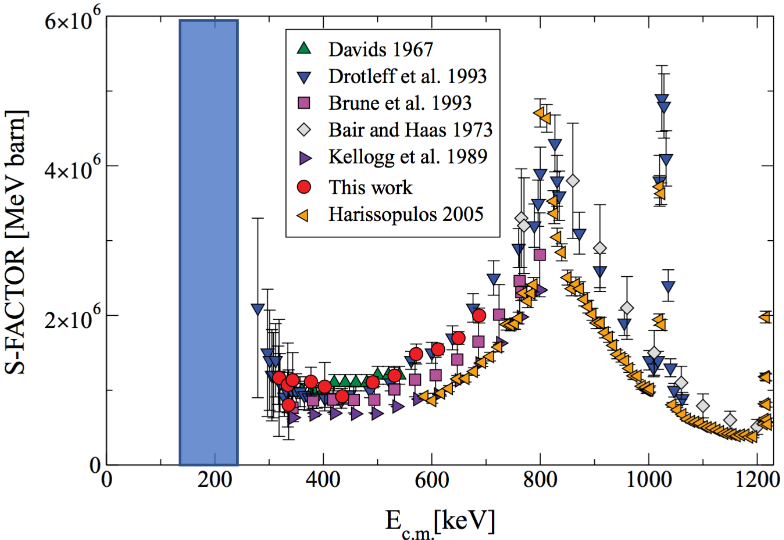


Figure from Heil et al,PRC 78, 025803 (2008)

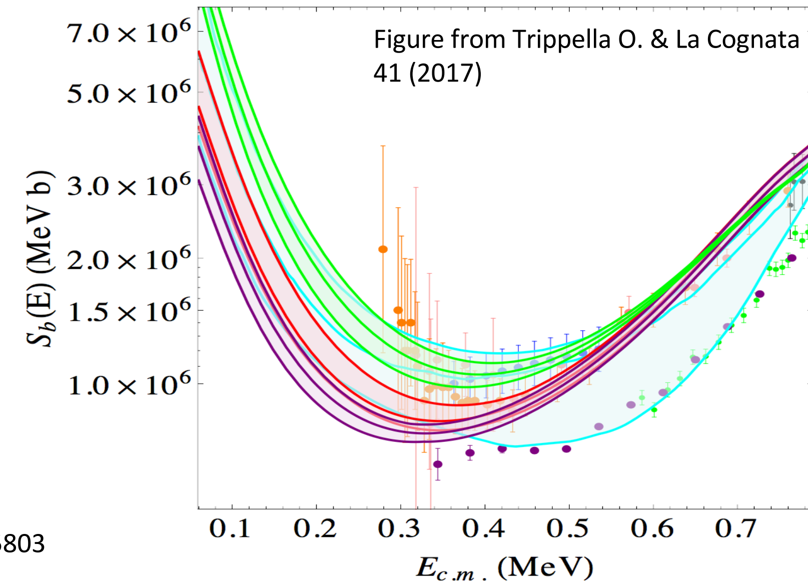


Figure from Trippella O. & La Cognata M., ApJ, 837, 41 (2017)

DIRECT MEASUREMENTS

Lowest point at E_{cm} = 280 keV by Drotleff et al.

Most recent meas + R Matrix at low energies: Heil (2008)

High systematic uncertainty from target control (degradation, C build up)

LUNA MAIN GOAL

A direct meauserement of the $^{13}C(\alpha,n)^{16}O$ approaching the Gamow window with a 10% uncertainty.

INDIRECT MEASUREMENTS

- Trippella (red band) et al.(2017) and La Cognata (green band) et al. (2013) with the THM, the R matrix is higher then Heil one at 100 keV.
- ANC: Avila (violet band) et al (2015)
- Cyan band is NACRE II compilation

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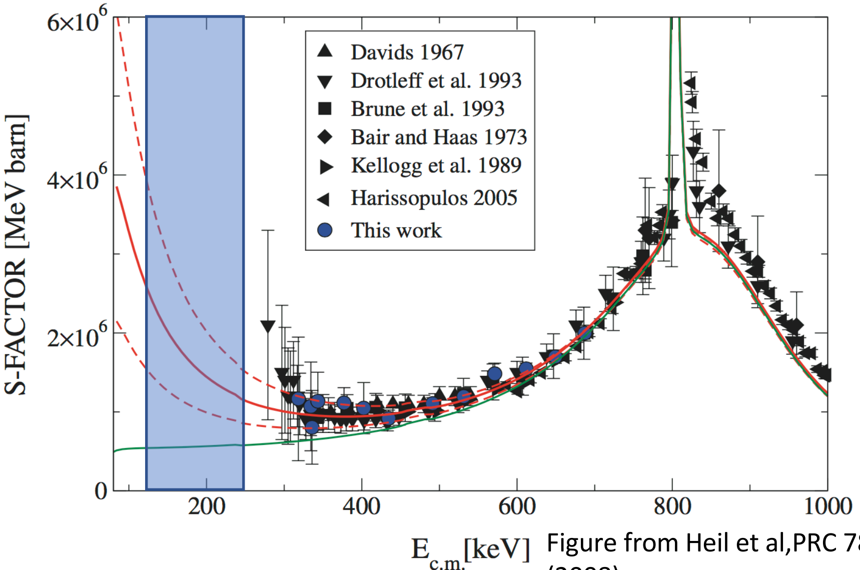

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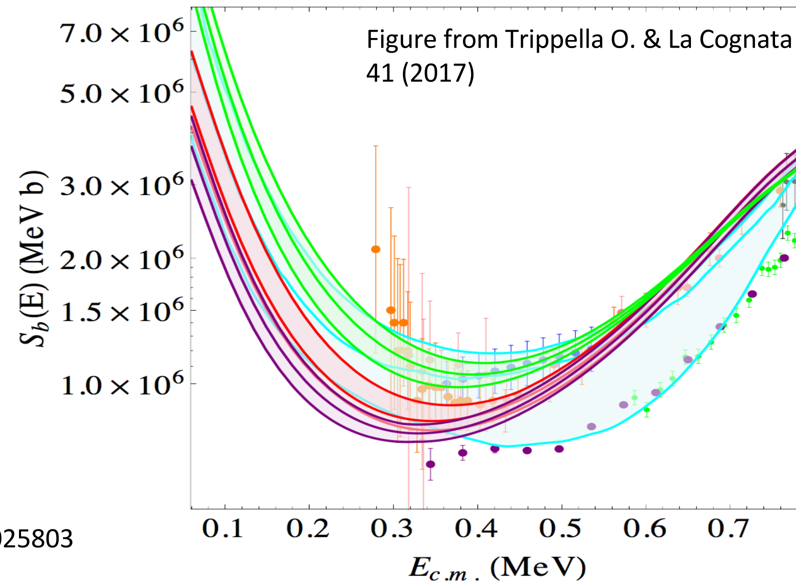

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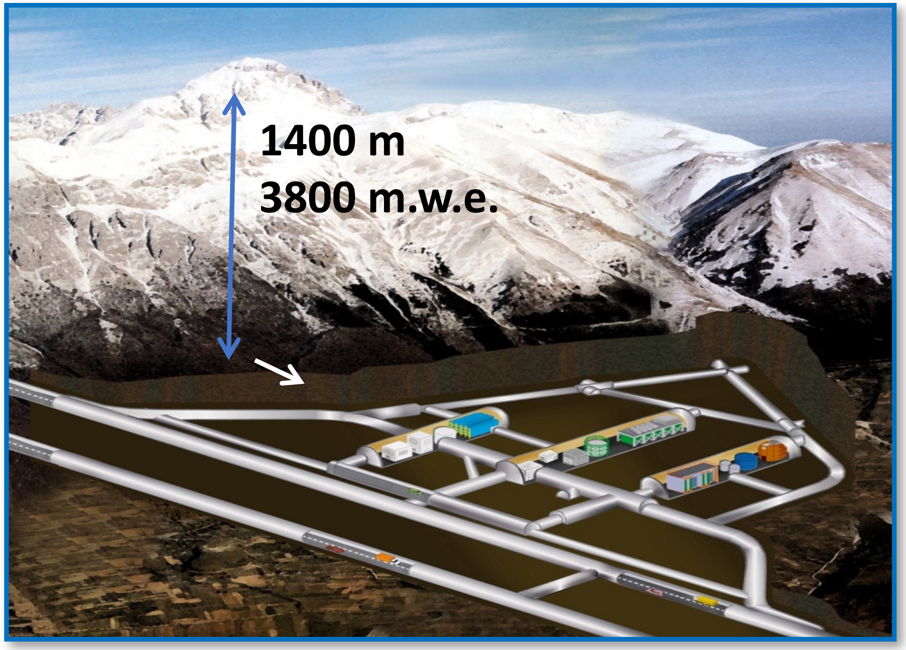
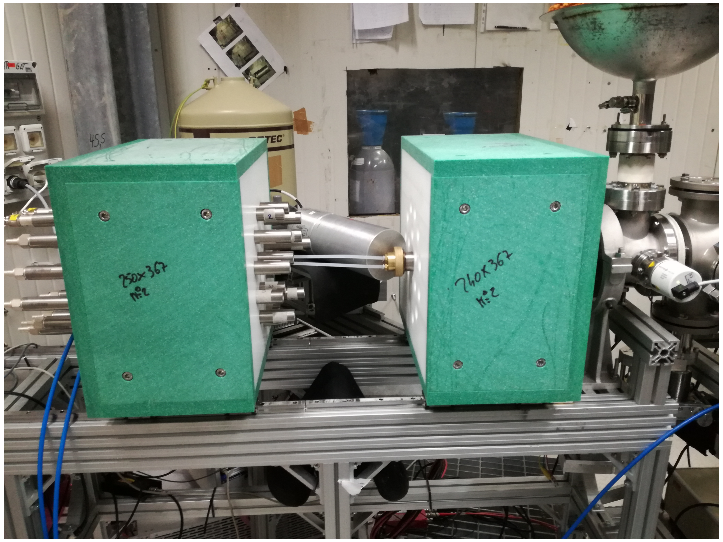
LUNA EXPERIMENTAL SETUP

- Electrostatic accelerator up to 400 kV installed at Laboratori Nazionali del Gran Sasso, Italy
- <I>= 200 μA p or α beam impinging on an evaporated 99% ^{13}C target
- First neutron detector developed by LUNA:
  - 12 ^{3}He steel counters 40 cm long .
  - 6 ^{3}He steel counters 25 cm long.
  - 120% HPGe .





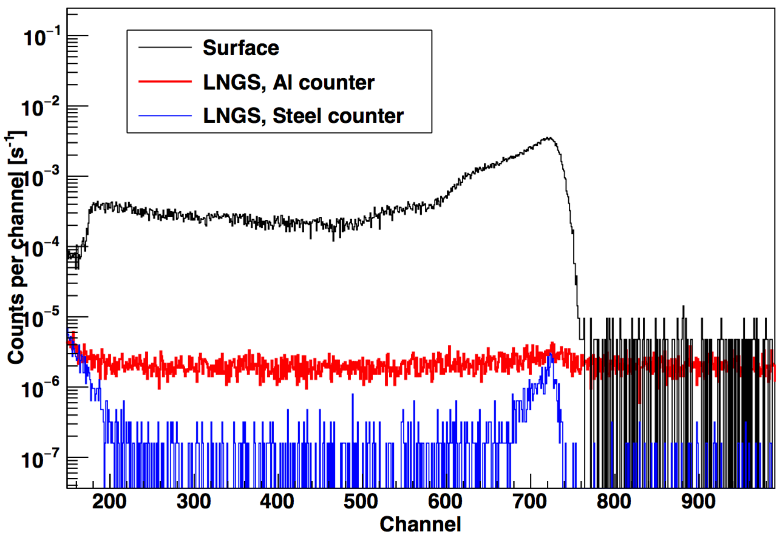
$$\frac{n_{det}}{Q} = Y(E_\alpha) = \int_{E_{\alpha-\Delta E}}^{E_\alpha} \frac{\eta(E)\,\sigma(E)}{\varepsilon(E)}\,dE$$

BACKGROUND REDUCTION

ENVIRONMENTAL: neutron flux reduction of a factor 1000 **in Underground Laboratory**

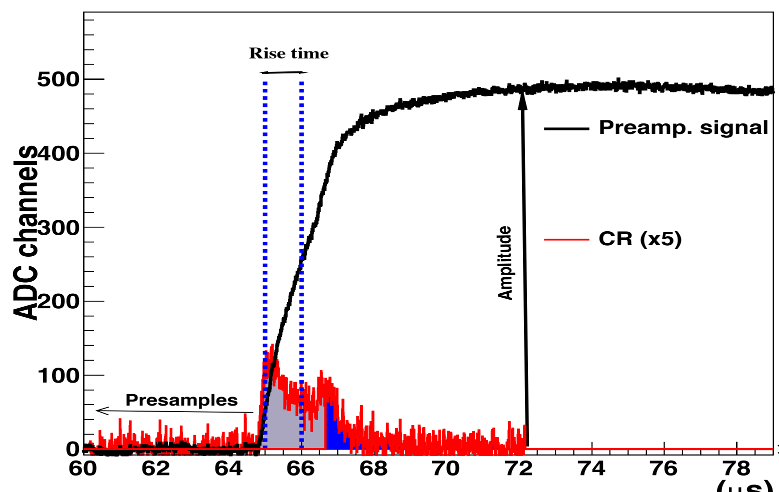
INTRINSIC: α particles source of intrinsic background from U and Th impurities in the counters' case

10 atm pressurised ^{3}He counters with a stainless steel case with low intrinsic background
Background (n+α): (2.93+-0.09) counts/h in the ROI



POST Processing PULSE SHAPE DISCRIMINATION*
(rejects 90% alpha and 10% neutrons)
Background rate (ROI) for the entire ^{3}He setup:
~ (1.05+-0.06) counts/hour

*J. Balibrea-Correa et al., NIM A 906,103-109, (2018)



NEUTRON DETECTION EFFICIENCY

$^{13}C(\alpha,n)^{16}O$ → E_n=2.2-2.6 MeV emission

- Geant4 simulations validated by experimental measurements

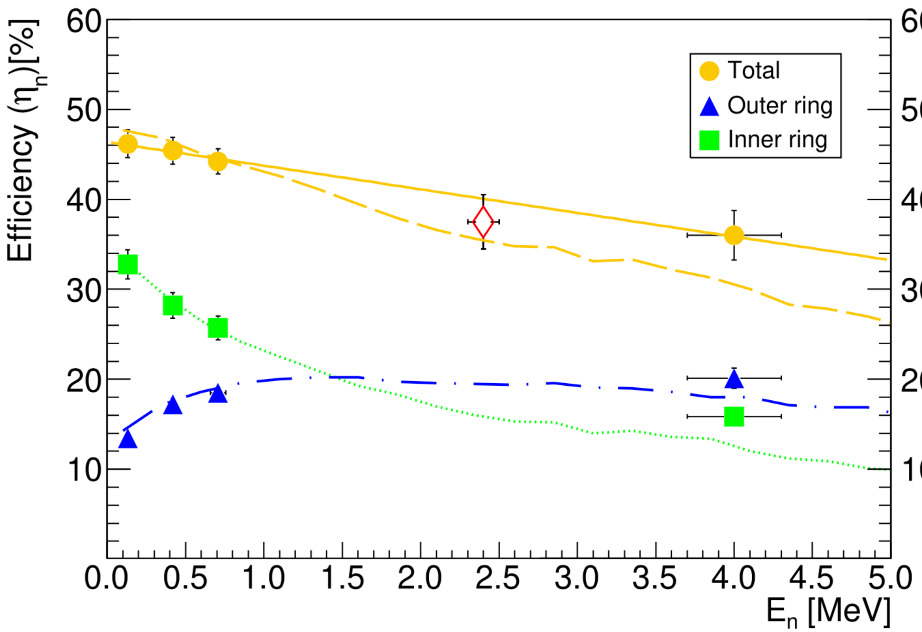
$^{51}V(p,n)^{51}Cr$

- 5 MV Van dee Graaff at Atomki, Hungary
- ^{51}Cr decay via electron capture
  ($T_{1/2}$=27.7 days and emission of Eγ=320 keV)
- $E_{p,lab}$=1.7, 2.0, 2.3 MeV
  (E_n=0.13, 0.42, 0.71 MeV)

Calibrated AmBe source

- E_n=0-12 MeV ; weighted E_n~ 4.0 MeV

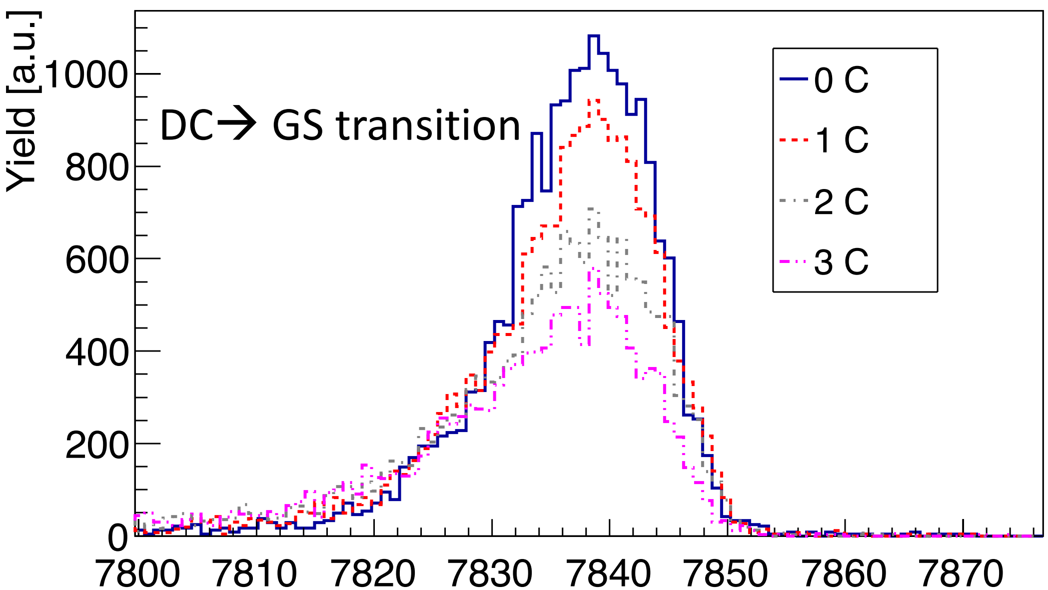
Efficiency interpolated (red diamond) in the ROI: $38 \pm 3\%$



L. Csedreki et al. NIM A 994 (2021)

TARGET DEGRADATION MONITORING

New method developed based on the irradiation of the 13C target with proton beam at E_p=310 keV and the acquisition of the gamma spectrum with a HPGe detector.
A gamma shape analysis of the direct capture transition to the ground state of the $^{13}C(p,g)^{14}N$ reaction was performed and from the fit of this peak we could evaluate modification in target stochiometry

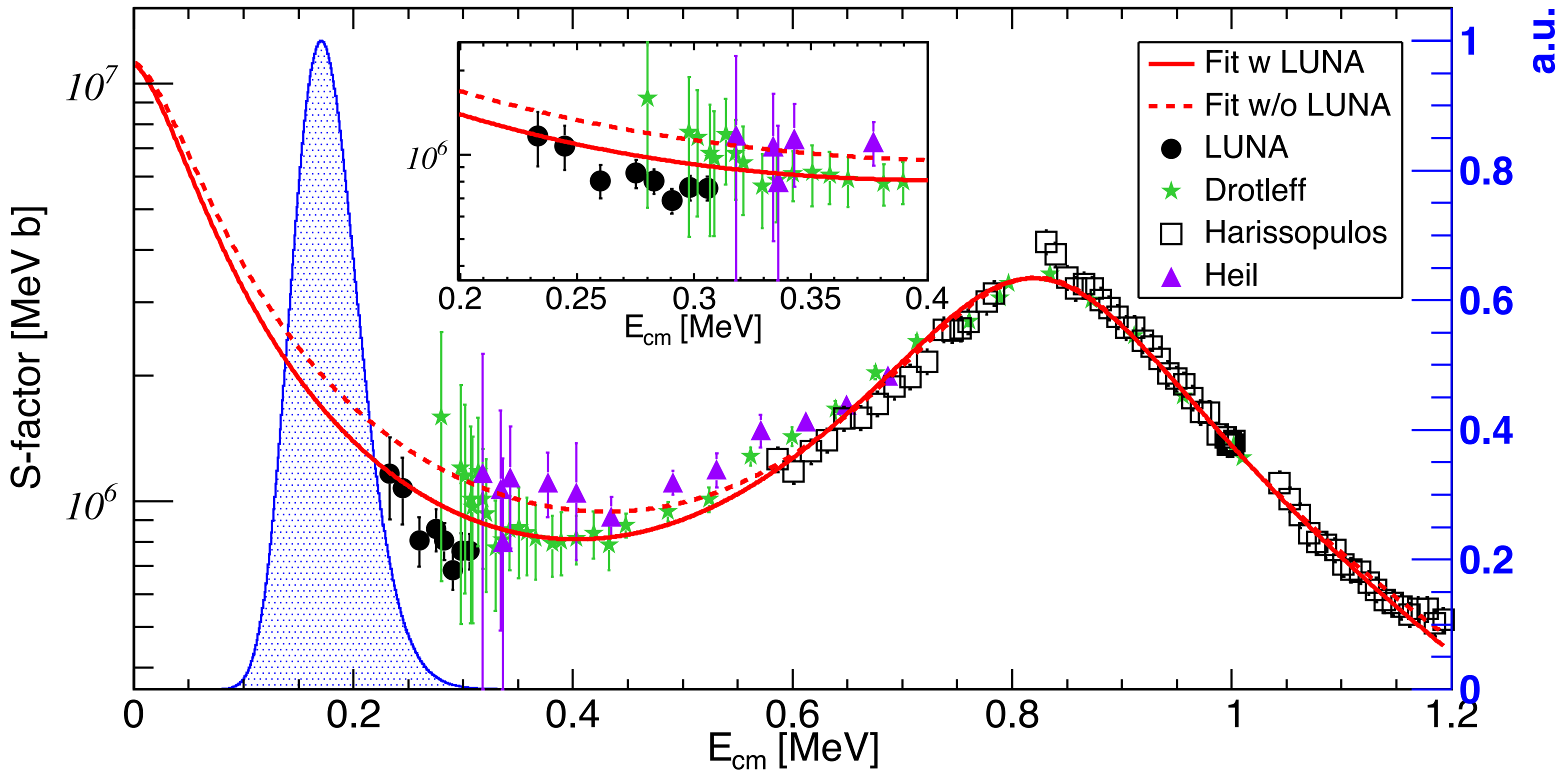


Ciani et al, Eur. Phys. J. A(2020) 56:75

beam	detector	
proton	HPGe	Ref1 (fresh target) 0.2 C
alpha	^{3}He counters	1C
proton	HPGe	Ref2 (0.2 C)
alpha	^{3}He counter	1C
proton	HPGe	Ref3 (0.2 C)
alpha	^{3}He counter	1C
proton	HPGe	Ref4 (0.2 C)

Yield reduction in peak as a function of accumulated charge assumed as consequence of modification of target stoichiometry

S(E) factor towards the Gamow window



Ciani et al, PRL (2021), in production

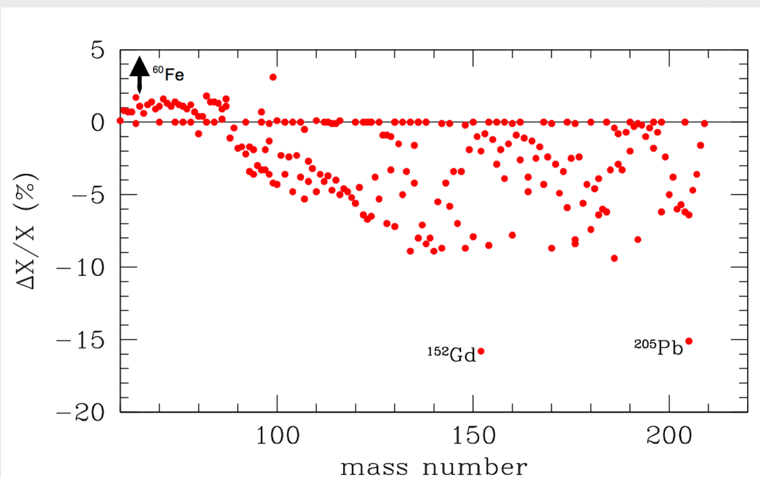
- Data taking in 4 campaigns of 3 months each in about 2 years (more than 100 targets used)
- Statistical uncertainty lower than 10% for the whole dataset (E_{cm} 230-305 keV)
- Lowest energy data ever achieved and at the Gamow window edge of low mass AGB.
- Reaction rate uncertainty reduced from 20% to about 10%

CONCLUSIONS AND OUTLOOK

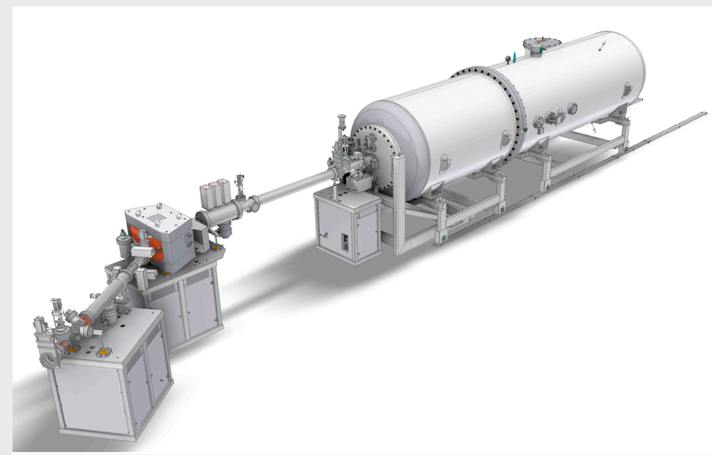
- Direct measurement performed at unprecedented low energy keeping the overall uncertainty at each point <20%, **approaching the Gamow window**

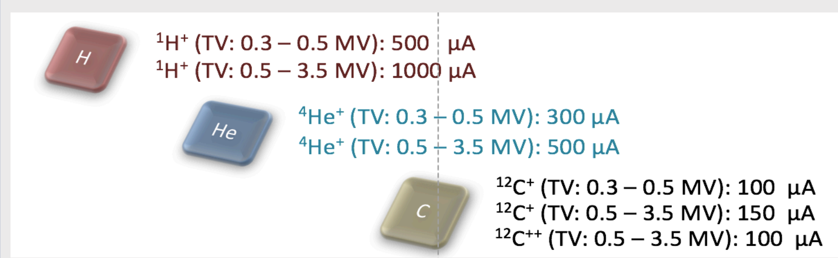
- The present work reports a much improved calculation of the $^{13}C(\alpha,n)^{16}O$ reaction rate at T ~ 90 MK, for the first time based on direct data near the Gamow window.

- We find that the new low-energy cross-section measurements imply sizeable variations of the ^{60}Fe, ^{152}Gd and ^{205}Pb yields



With the installation (2021-2022) of the LUNA facility at LNGS MV (TV max=3.5 MV) a new measurement of the $^{13}C(\alpha,n)^{16}O$ at higher energies will allow to have a unique dataset in a wide energy range





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