GIANTS

Gruppi Italiani di Astrofisica Nucleare Teorica e Sperimentale

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Hotel Royal
Viale Vittorio Veneto, 13
81020 Caserta CE

The $^{13}C(a,n)^{16}O$ cross section measurement at LUNA

G.F. Ciani

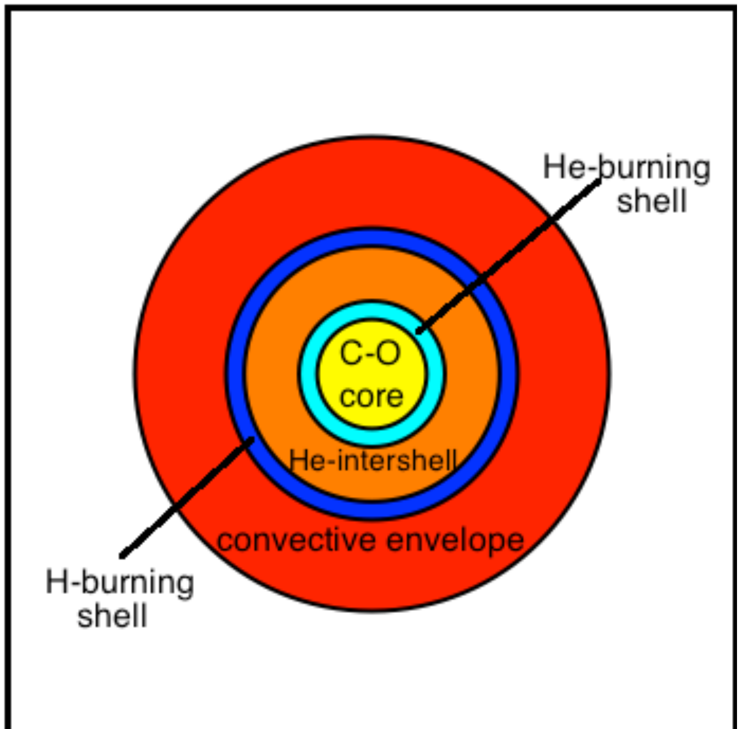
(on behalf of the LUNA collaboration)
University of Bari & INFN Ba

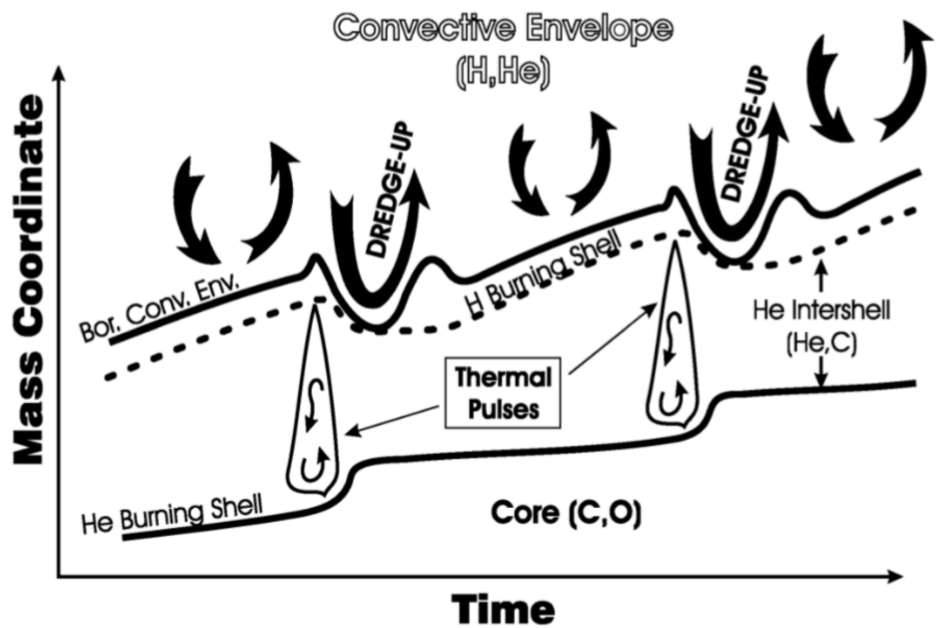
giovanni.ciani@ba.infn.it

ASTROPHYSICAL MOTIVATION

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

- $^{13}C(\alpha,n)^{16}O$ (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**





FOR THE REACTION RATE WE NEED CROSS SECTION

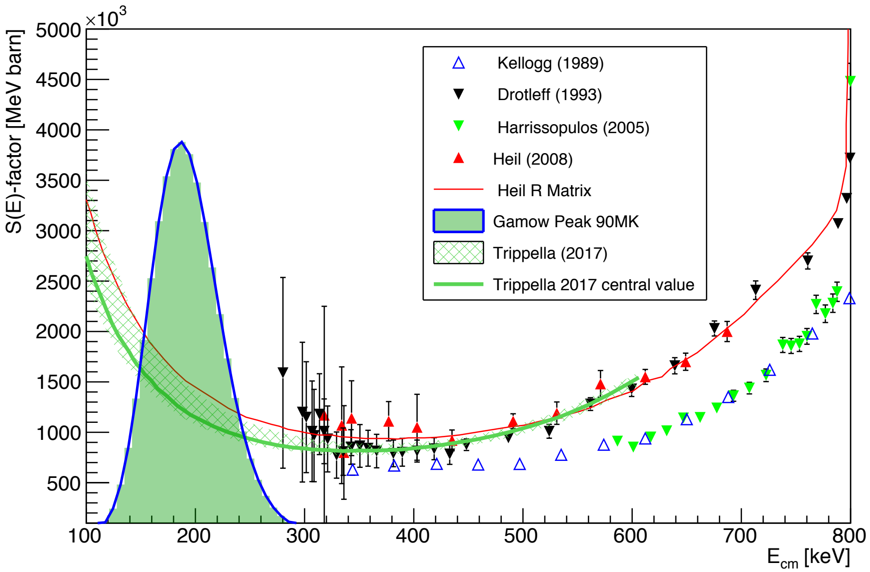
$$\langle \sigma v \rangle_{ab} = \sqrt{\frac{8}{\pi \mu}} \left(\frac{1}{k_B T} \right)^{3/2} \int_0^{+\infty} E\sigma(E) exp\left(-\frac{E}{k_B T} \right) dE$$

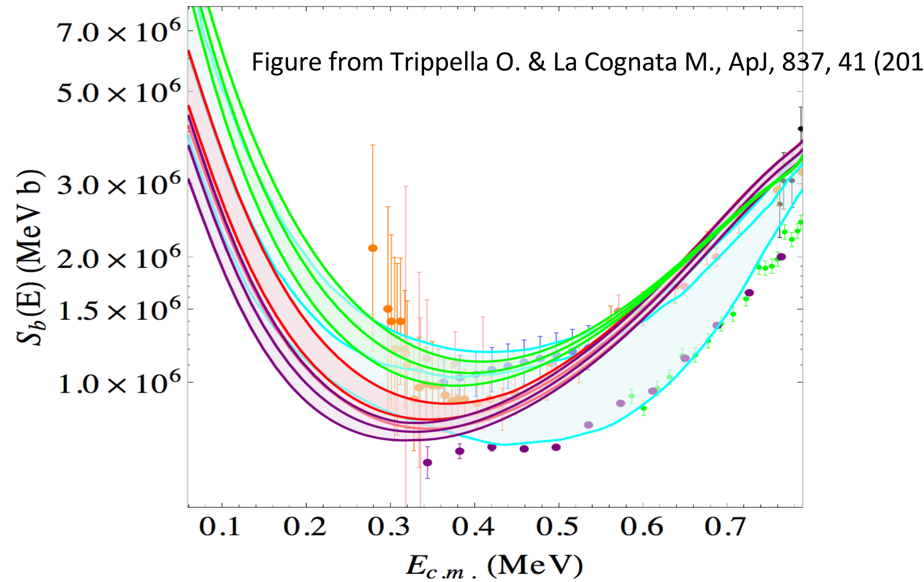
FOR THE CROSS SECTION WE NEED EXPERIMENTAL YIELD

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

STATE OF THE ART

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





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)

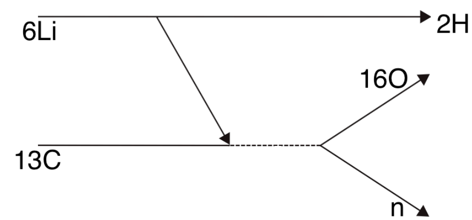
LUNA MAIN GOAL

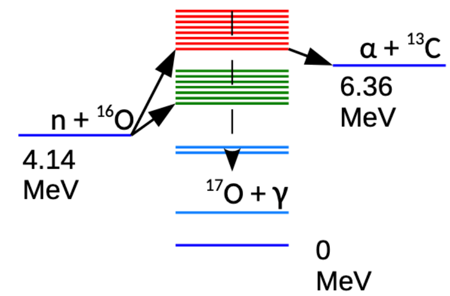
A direct meausurement of the $^{13}C(\alpha,n)^{16}O$ approaching the Gamow window with a 20% uncertainty.

INDIRECT MEASUREMENTS

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

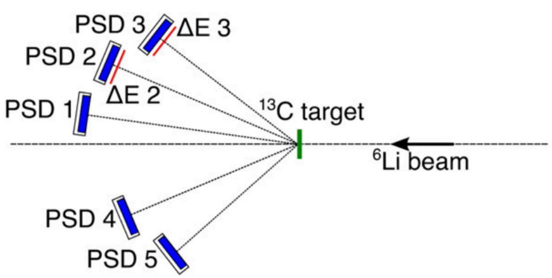
GIANTS: a complementary contribution

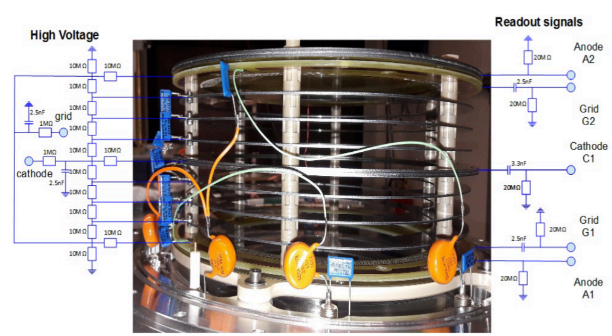




- **Trojan Horse Method** via $^{13}C(^{6}Li, n^{16}O)^{2}H$ "quasi-free" kinematic regime (E_b= 7.82 MeV)
- **Advantages**: not depentend to coulombian barrier repulsion and to electron screening effect
- **Drawback**: normalization to direct measuement

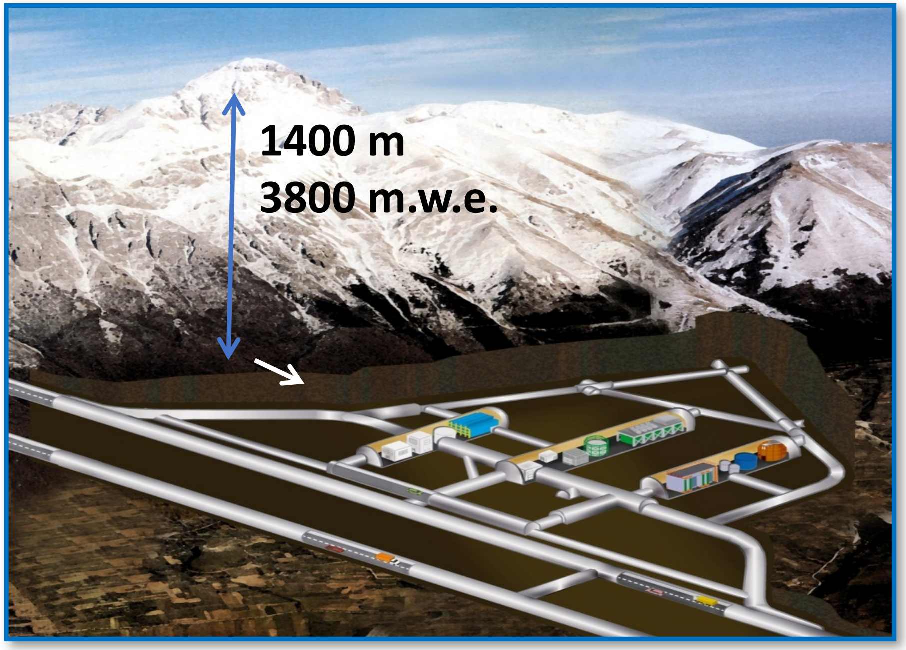
- **Inverse reaction measurement**: $^{16}O(n,\alpha)^{13}C$ + principio dettagliato
- **Advantages** : neutron beam avoids coulombian barrier effect
- **Drawback:** emitted α with energy of hundreds keV





Double Frisch Grid Ionisation Chambers (DFGIC) build at Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

LUNA EXPERIMENTAL SETUP



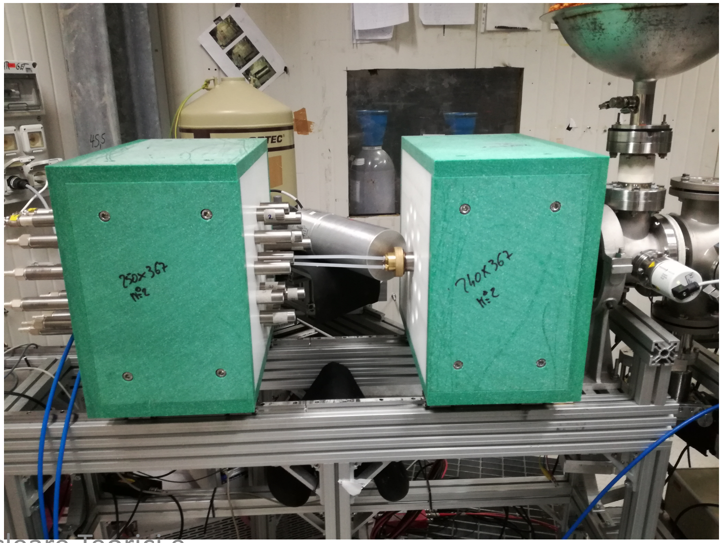
- Electrostatic accelerator up to 400 kV installed in Laboratori Nazionali del Gran Sasso, Italy

- Background reduction by:
  - 6 orders of magnitude for muons
  - 3 orders of magnitude for neutrons

- <I>= 200 μA p or α beam impinging on solid or gas 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.

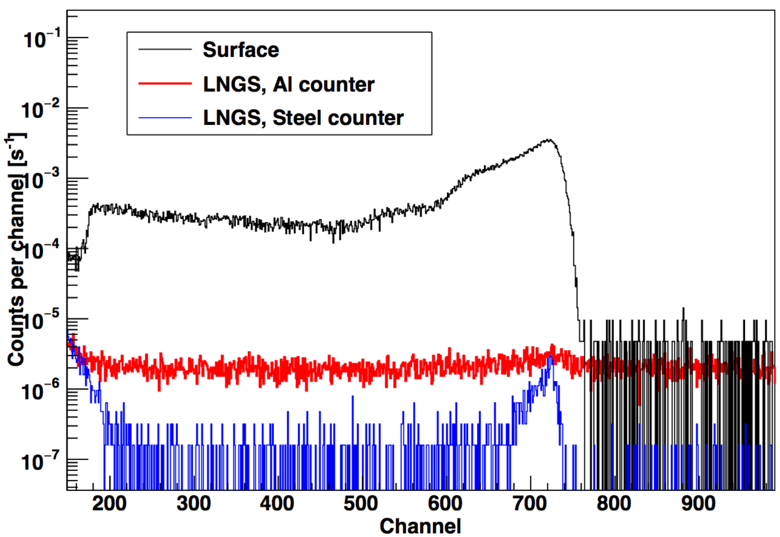


BACKGROUND REDUCTION

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

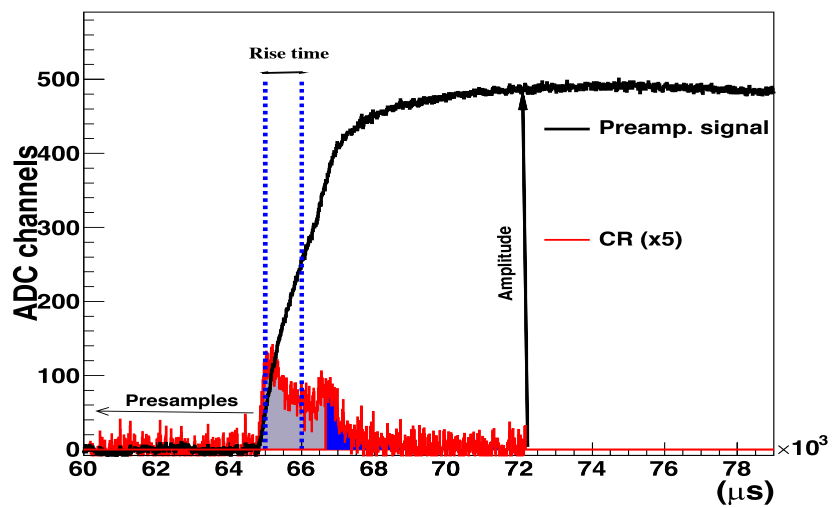
INTRINSIC: α particles source of intrinsic background from U and Th impurities in the counters' case

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

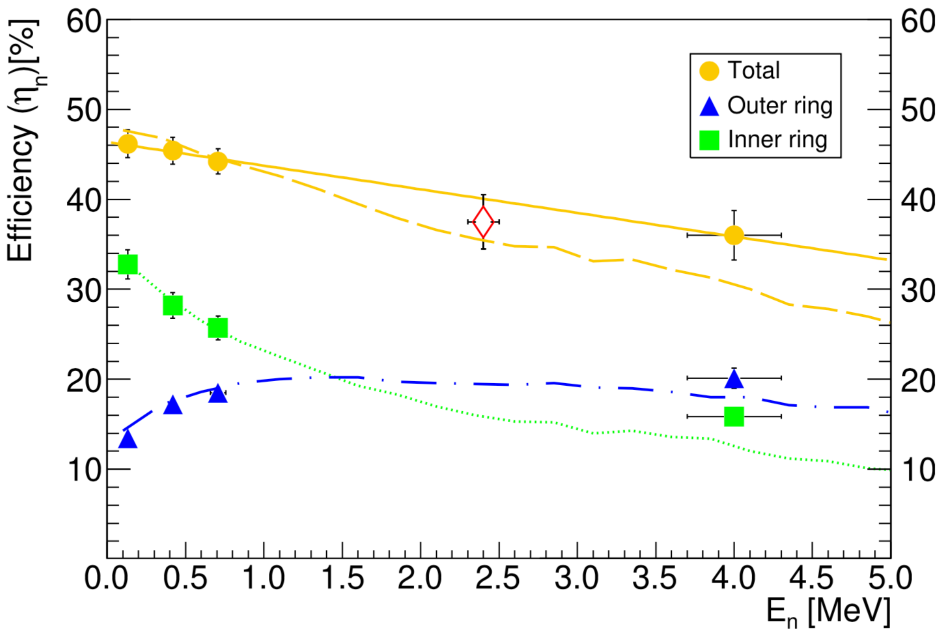
$^{51}V(p,n)^{51}Cr$

- 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: $(38 \pm 3)\%$

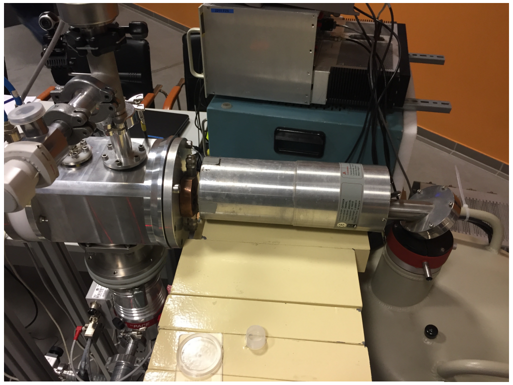


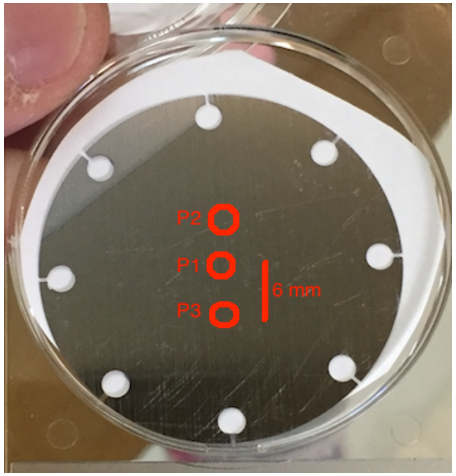
L. Csedreki et al. NIM A 994 (2021)

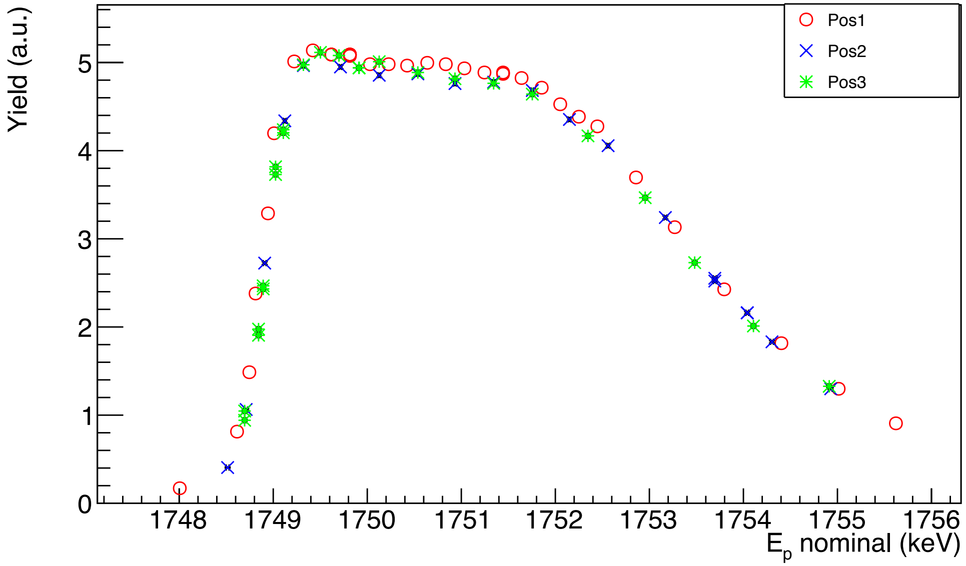
TARGET CHARACTERIZATION by $^{13}C(p,\gamma)^{14}N$

1^{st} phase at MTA Atomki

- 99% enriched ^{13}C powder evaporated on Tantalum backing using the electron gun technique
- Thickness measured at 2 MV Tandetron (<I> 500 nA) using the scan of the resonance E_{lab} = 1747.6 keV (Γ_R = 122 eV)
- Evaporation uniformity tested

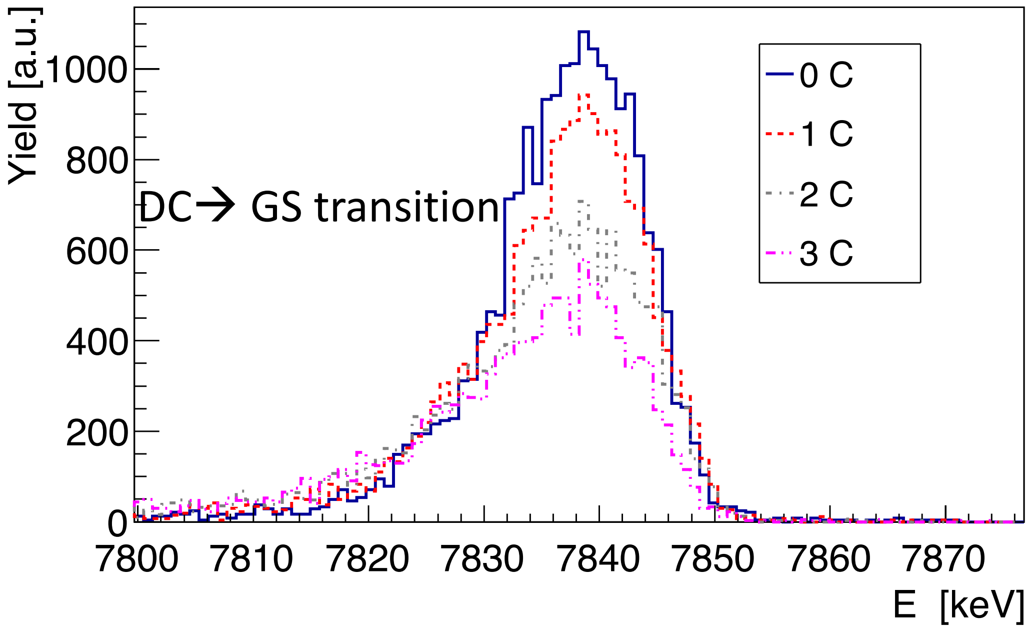






2^{nd} phase: $^{13}C(p,\gamma)^{14}N$ GAMMA SHAPE ANALYSIS at LUNA

Gamma Shape Analysis performed periodically at Ep=310 keV, alternating proton and alpha irradiation on target

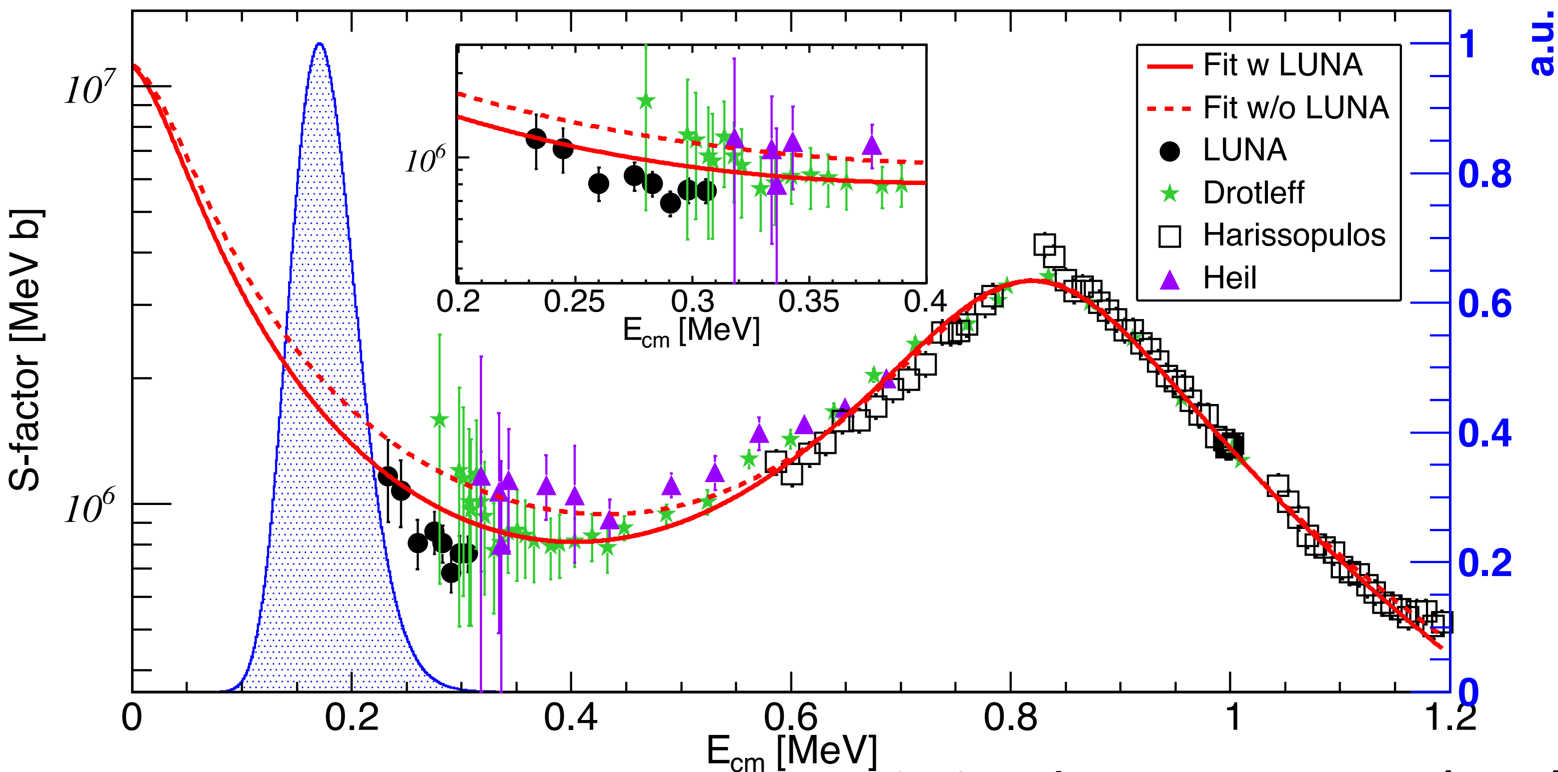


Ciani et al, Eur. Phys. J. A(2020) 56:75

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

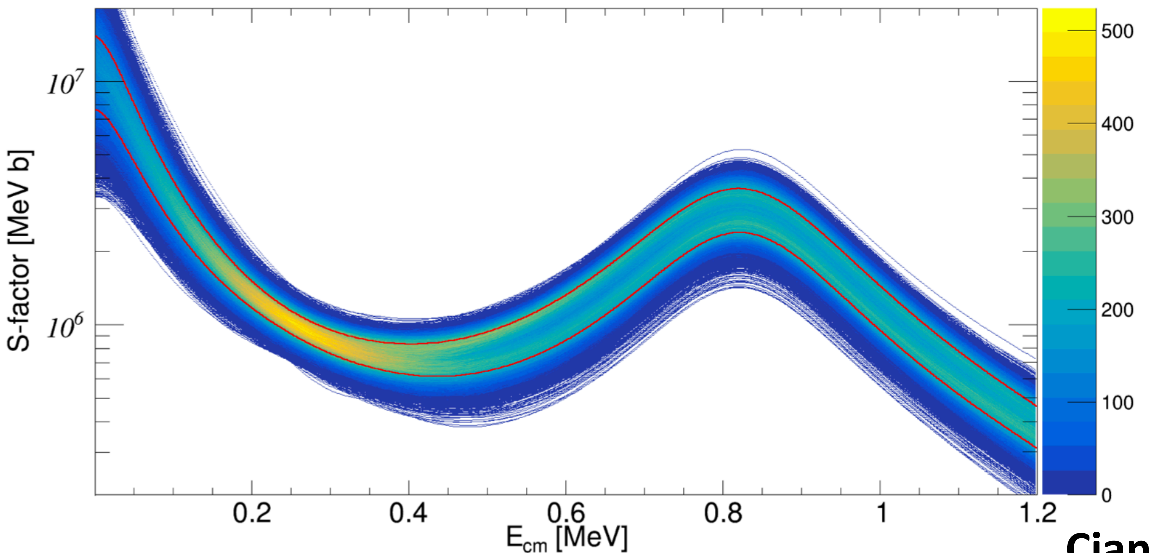
S(E) factor towards the Gamow window



Ciani et al, PRL, 127, 152701 (2021)

- 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.
- Gao et al. (published on PRL) confirm LUNA data towards Gamow peak

FROM S(E)-FACTOR TO REACTION RATE



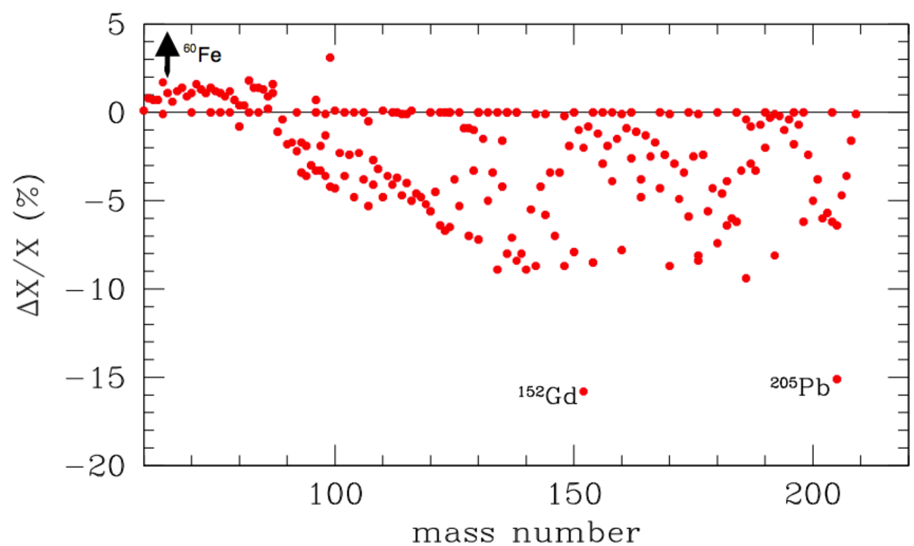
Three reaction rates evaluated

- NO LUNA (about +2σ)
- LUNA
- LOW LUNA (about -2σ)

Ciani et al, PRL, 127, 152701 (2021)

Stellar condition in the FRUITY code:
$M=2M_\odot$
metallicity Z= 0.02 and Y= 0.27

Calculated percentage variation LOW LUNA/NO LUNA data



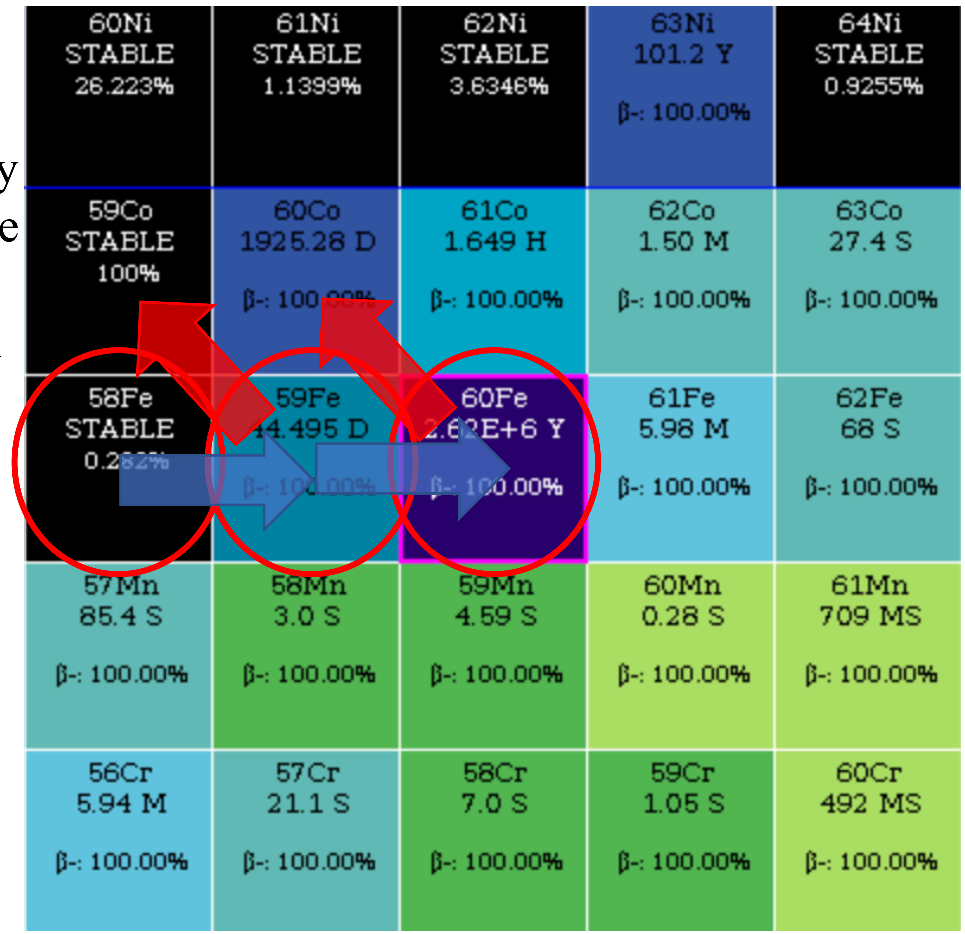
Reduction stronger for A>130.
In general variation smaller than 10% with few exeptions

VARIATION OF ^{60}Fe

The ^{60}Fe is produced when the neutron density is high enough to allow neutron captures at the ^{59}Fe branching point (half-life 44.5d). Therefore, its final abundance is enhanced in case of the activation of the second (convective) neutron burst.

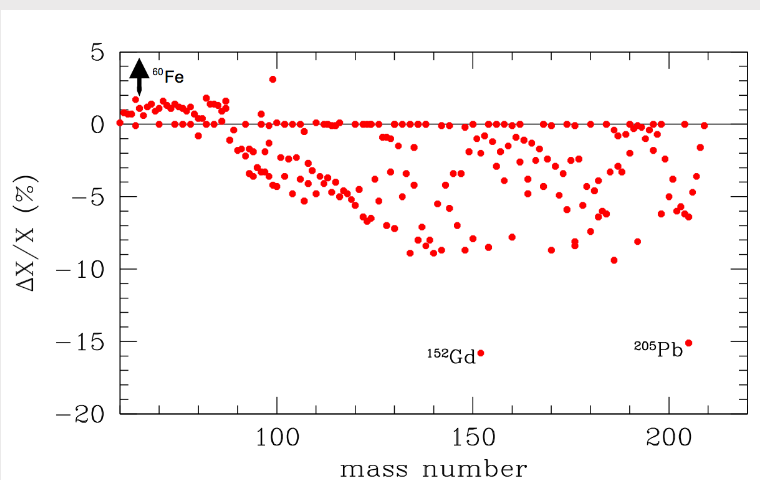
Main radiative neutron event : low flux, high exposure (80-100 MK)

Second convective neutron burst: high flux, low exposure (200 MK)

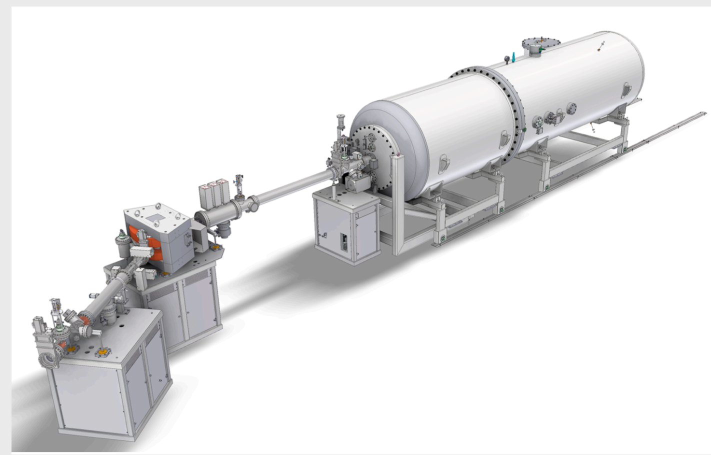


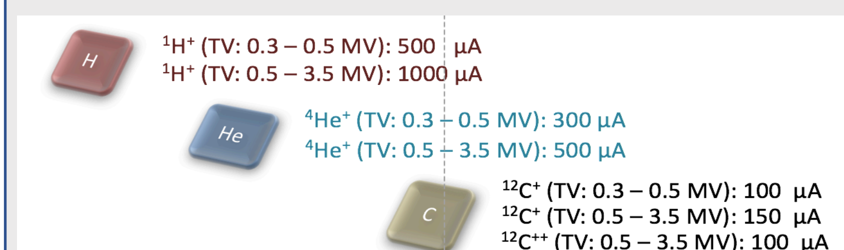
CONCLUSIONS AND OUTLOOK

- Direct measurement performed at unprecedented low energy **approaching the Gamow window** and with overall uncertainty at each point <20%
- The new LUNA dataset allows to evaluate a more constrained $^{13}C(\alpha,n)^{16}O$ reaction rate at T ~ 90 MK
- 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





THE LUNA COLLABORATION

A. Compagnucci*, M. Junker | **Laboratori Nazionali del Gran Sasso, INFN, ASSERGI, Italy/*GSSI, L'AQUILA, Italy**
F. Barile, G.F. Ciani, D. Di Bari, V. Paticchio, L. Schiavulli | **Università degli Studi di Bari and INFN, BARI, Italy**
M. Lugaro | **Konkoly Observatory, Hungarian Academy of Sciences, BUDAPEST, Hungary**
L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs |**Institute of Nuclear Research (ATOMKI), DEBRECEN, Hungary**
D. Bemmerer, A. Boeltzig, E. Masha| **Helmholtz-Zentrum Dresden-Rossendorf, DRESDEN, Germany**
M. Aliotta, C.G. Bruno, T. Chillery, T. Davinson, SIDHU Ragandeep Singh | **University of Edinburgh, EDINBURGH, UK**
P. Corvisiero, P. Prati, S. Zavatarelli |**Università degli Studi di Genova and INFN, GENOVA, Italy**
R. Perrino | **INFN Lecce, LECCE, Italy**
R. Depalo, F. Ferraro, A. Guglielmetti |**Università degli Studi di Milano and INFN, MILANO, Italy**
A. Chamseddine, A. Best, A. Di Leva, G. Imbriani, D. Rapagnani |**Università degli Studi di Napoli and INFN, NAPOLI, Italy**
C. Broggini, A. Caciolli, P. Marigo, R. Menegazzo, D. Piatti, J. Skowronski |**Università degli Studi di Padova and INFN, PADOVA, Italy**
V. Rigato, M. Campostrini | **Laboratori Nazionali di Legnaro, Italy**
A. Formicola , C. Gustavino | **INFN Roma, ROMA, Italy**
O. Straniero | **Osservatorio Astronomico di Collurania, TERAMO and INFN LNGS, Italy**
F. Cavanna, P. Colombetti, G. Gervino | **Università di Torino and INFN, TORINO, Italy**