Direct measurement of the $^{13}C(\alpha,n)^{16}O$ reaction in the Gamow window of the s-process nucleosynthesis

LUNA

A.Formicola & G.F. Ciani
(on behalf of the LUNA collaboration)

13th International Spring Seminar on Nuclear Physics: "Perspectives and Challenges in Nuclear Structure after 70 Years of Shell Model"

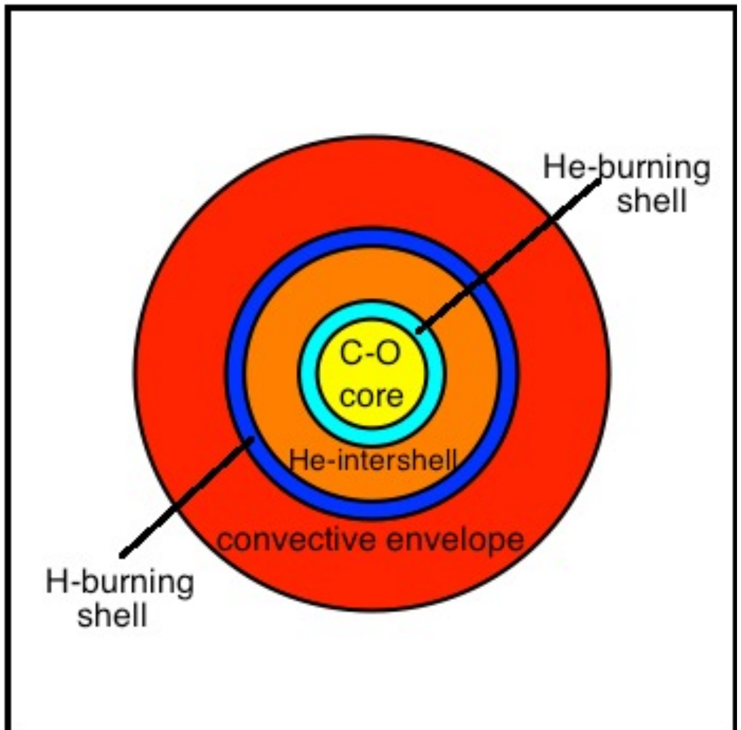
Sant'Angelo d'Ischia, May 15-20, 2022

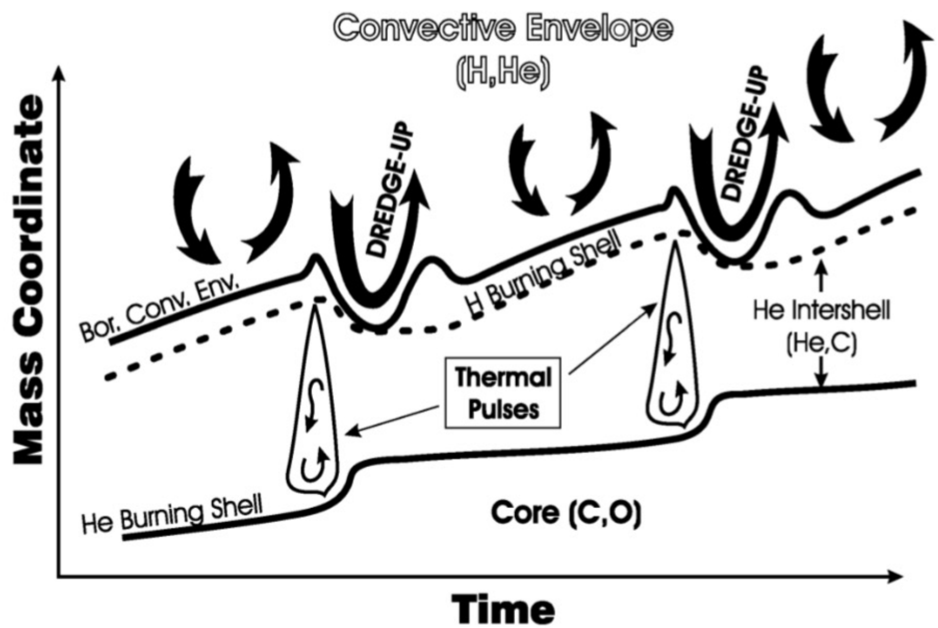
INFN ROMA
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

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**





Pioneering works

ORIGIN OF ANOMALOUS ABUNDANCES OF THE ELEMENTS IN GIANT STARS

A. G. W. CAMERON*
Iowa State College, Ames, Iowa
Received July 9, 1954; revised September 14, 1954

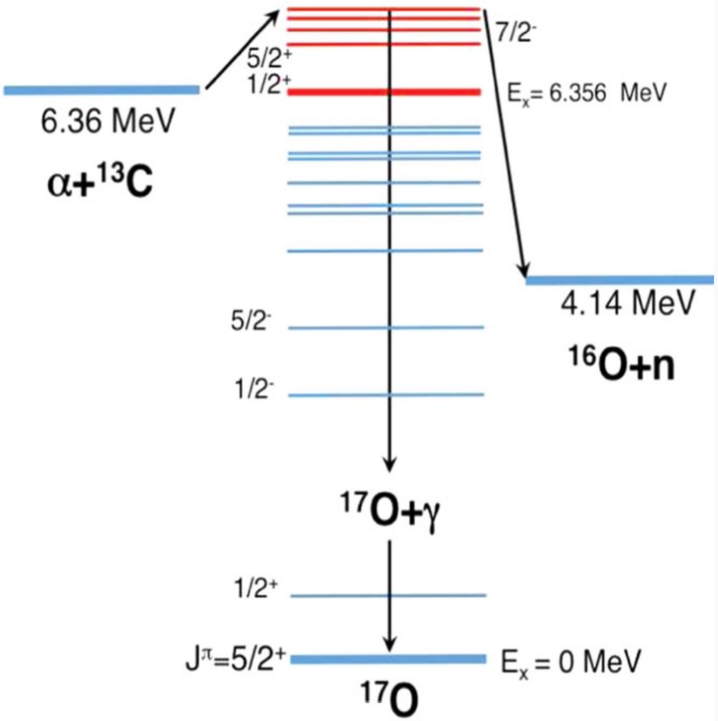
ABSTRACT

Following the exhaustion of hydrogen in the cores of certain massive stars, it appears that the cores contract and the envelopes expand, the stars becoming red giants. When the central temperature and density have increased sufficiently, thermonuclear reactions involving the helium in the core can take place with the nuclei which have taken part in the carbon cycle. The rate of the $C^{13}(\alpha, n)O^{16}$ reaction is calculated; it is found to produce neutrons rapidly at a temperature of 10^8 ° K and a density of 5×10^4 gm/cm^3. These neutrons are slowed down until they reach thermal equilibrium with their surroundings (neutron energies of about 10 kev) and are then captured by the surrounding nuclei in proportion to their cosmic abundances and neutron-capture cross-sections. The latter quantities are estimated for neutron energies of 10 kev as a function of the mass number of the capturing nucleus. The heavier nuclei each appear to capture many neutrons (about 35 neutrons at mass number 100). Nuclei with closed shells of 50, 82, and 126 neutrons have much smaller cross-sections and become concentrated by the neutron-capture processes. With the assumption of a moderate amount of mixing between core and envelope of the star, it is thus found that the distinctive features of S-type and *Ba* II–type spectra can be explained. The further evolution of the star should then lead to the production of excess carbon by the Salpeter reactions, and the spectrum should gradually turn into that of type R or N.

The first stellar neutron source was proposed by Greenstein (Gr54) and by Cameron (Ca54, Ca55), namely the *exothermic* reaction:

$$C^{13}(\alpha,n)O^{16}+2.20 \text{ Mev.}$$

Importance of the threshold state



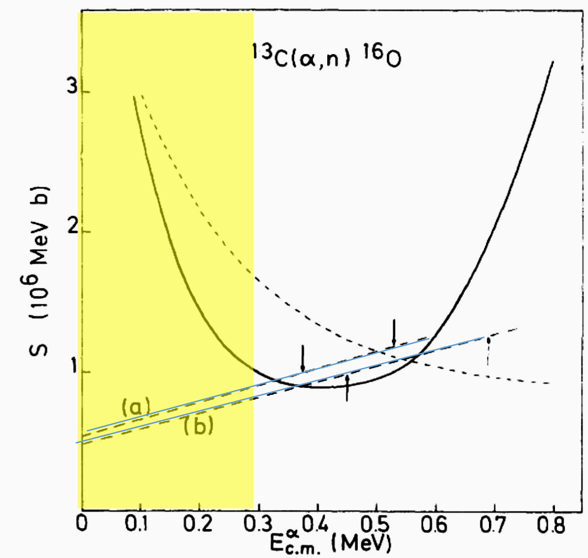
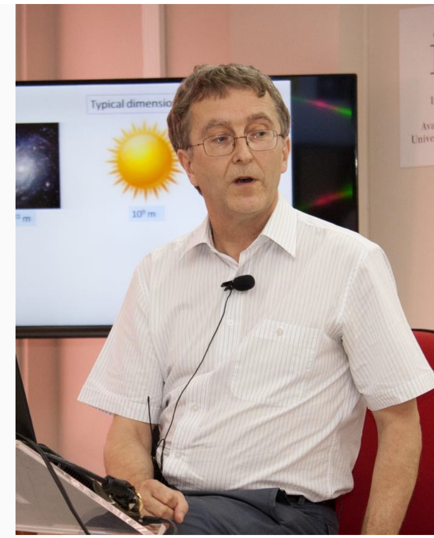


FIG. 6. $^{13}C(\alpha,n)^{16}O$ *S* factor. The dotted line represents the GCM result; the full line is obtained with the Breit-Wigner parametrization (see text); the dashed lines are the experimental data taken from Ref. 3 (a) and Ref. 4 (b). The arrows indicate the energy range where the experiments are carried out.



P. Descouvemont PRC(1987)

This case of a near-threshold cluster resonance in the $^{13}C(\alpha, n)\ ^{16}O$ reaction is an example of the impact of cluster configurations in nuclear astrophysics

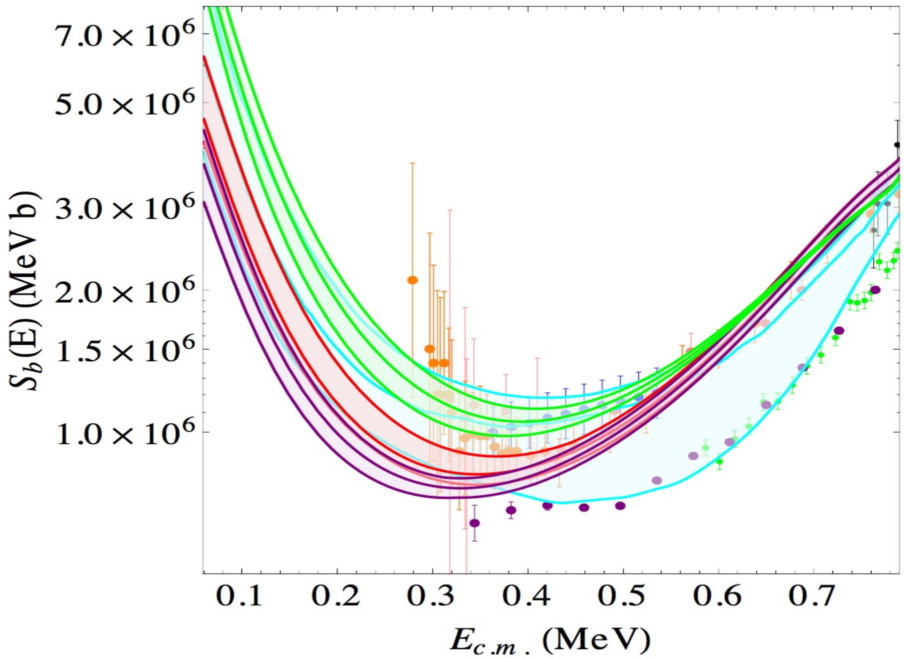
INDIRECT MEASUREMENTS

Trippella (red band) et al.(2017) and La Cognata (green band) et al. (2013) with the THM

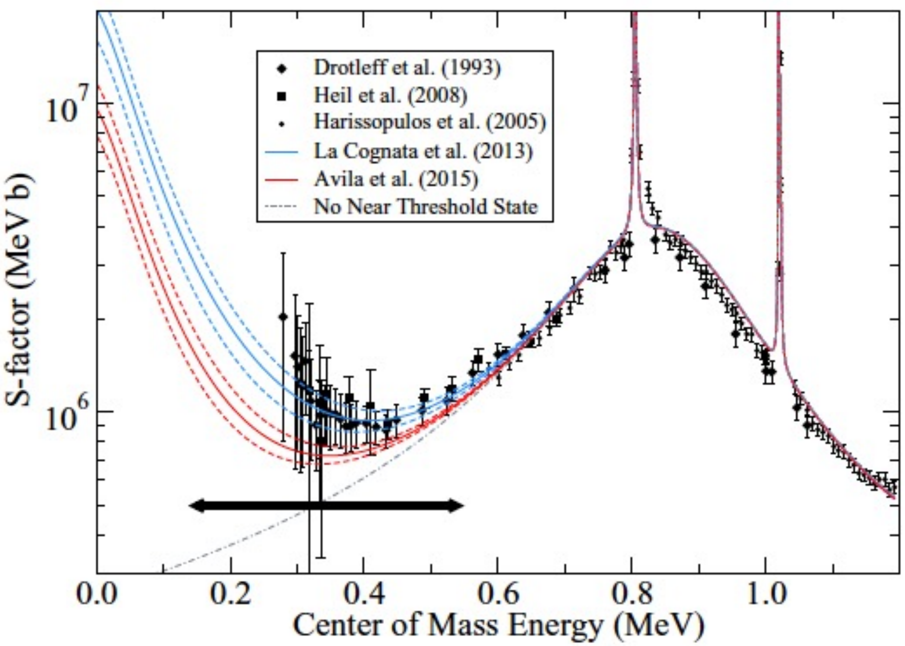
ANC: Avila (violet band) et al (2015)

Cyan band is NACRE II compilation

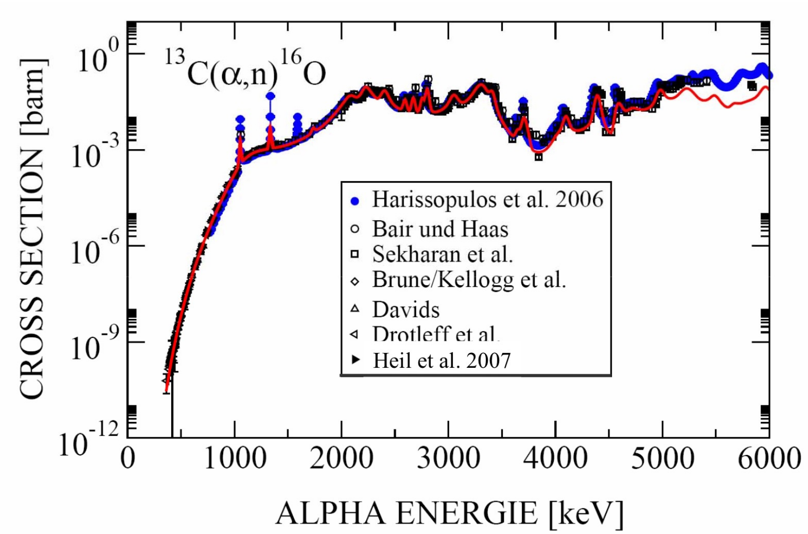
Trippella O. & La Cognata M., ApJ, 837, 41 (2017)



R.J Deboer PRC 101 837, 045802 (2020)

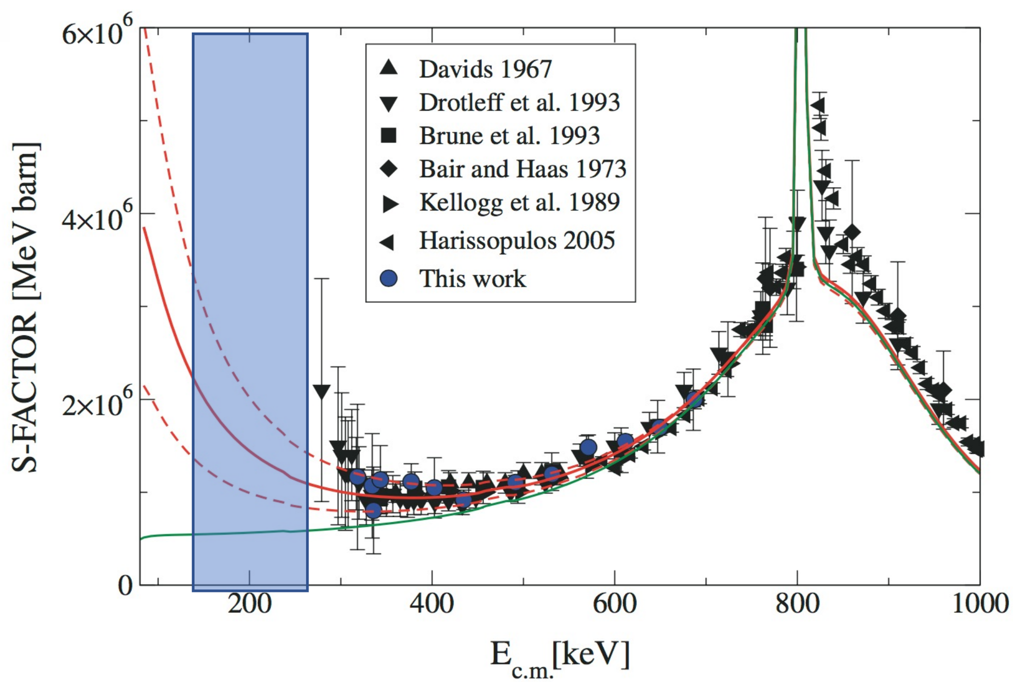


STATE OF THE ART



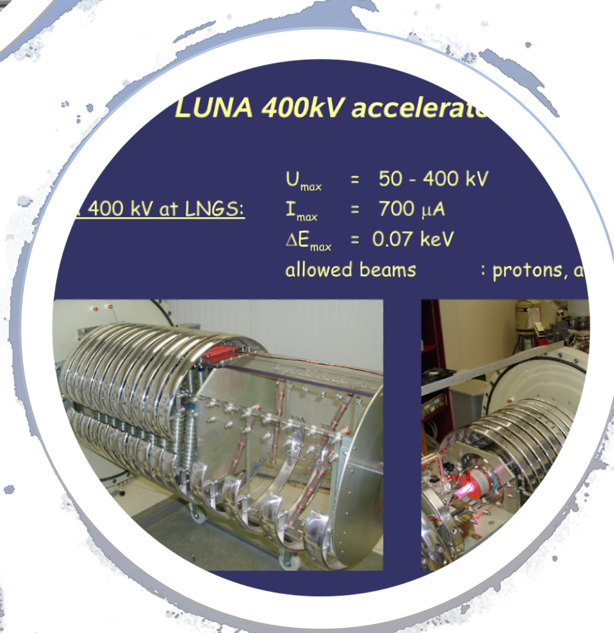
DIRECT MEASUREMENTS
Lowest point at E_{cm} = 280 keV by Drotleff et al.
Most recent meas + R Matrix at low energies: Heil (2008)
High systematic uncertainty from target control (degradation, C build up)

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



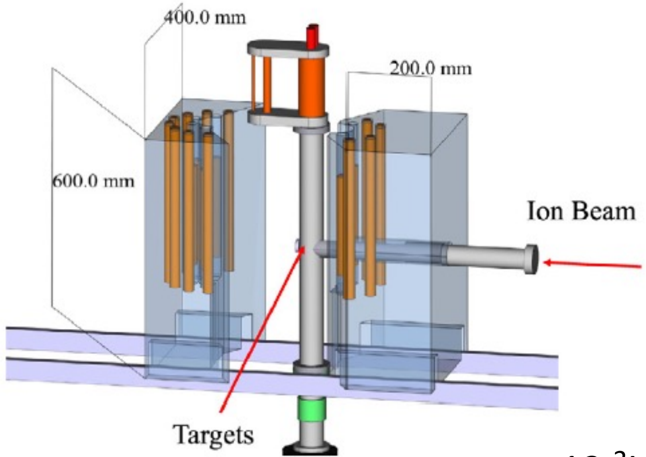
LUNA GOAL
A direct meausерement of the $^{13}C(\alpha,n)^{16}O$ (230-330keV) approaching the Gamow window with a 20% uncertainty.

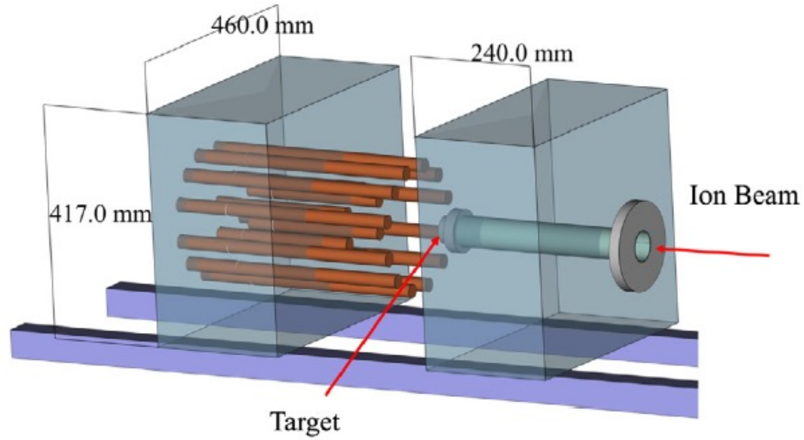
LUNA 400kV accelerator



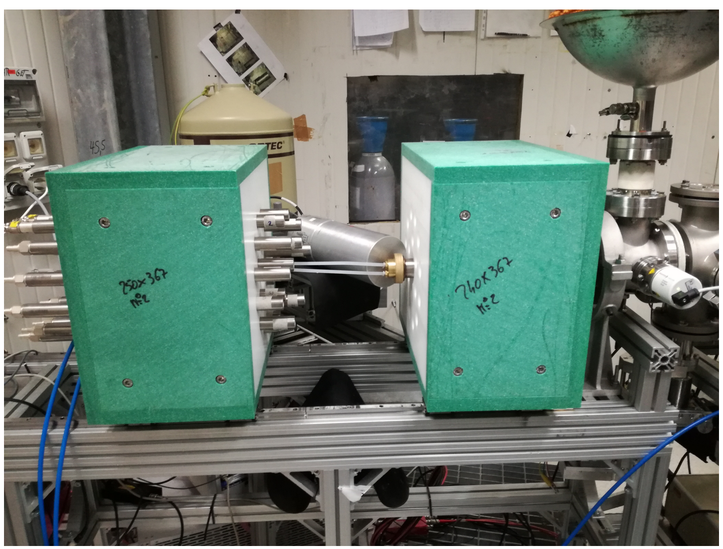
- $U_{terminal}$ = 50 – 400kV
- I_{max} = 220mA (on target)
- Allowed beams: H^+, ^4He, (^3He)

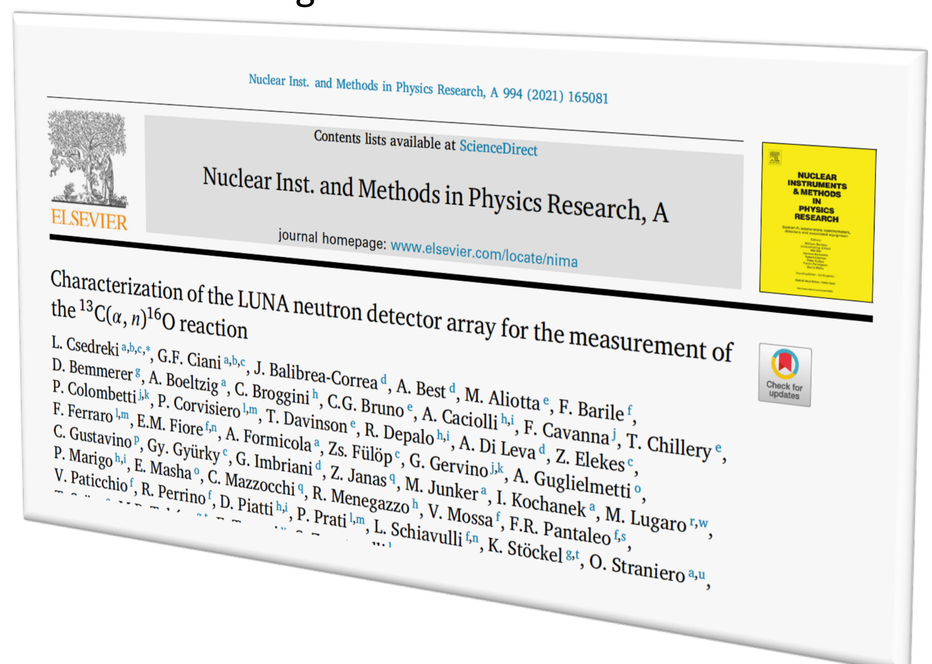
Experimental setup of the $^{13}C(\alpha,n)^{16}O$ reaction





12 ^{3}He steel counters 40 cm long .
6 ^{3}He steel counters 25 cm long




Nuclear Inst. and Methods in Physics Research, A 994 (2021) 165081

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journal homepage: www.elsevier.com/locate/nima

Characterization of the LUNA neutron detector array for the measurement of the $^{13}C(\alpha, n)^{16}O$ reaction

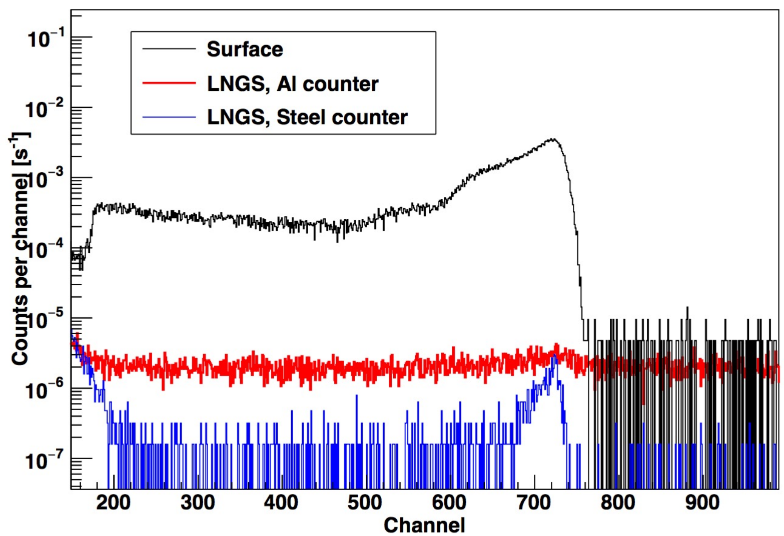
L. Csedreki[a,b,c,*], G.F. Ciani[a,b,c], J. Balibrea-Correa[d], A. Best[d], M. Aliotta[e], F. Barile[f], D. Bemmerer[g], A. Boeltzig[a], C. Broggini[h], C.G. Bruno[e], A. Caciolli[h,i], F. Cavanna[j], T. Chillery[e], P. Colombetti[j,k], P. Corvisiero[l,m], T. Davinson[e], R. Depalo[h,i], A. Di Leva[d], Z. Elekes[c], F. Ferraro[l,m], E.M. Fiore[f,n], A. Formicola[a], Zs. Fülöp[c], G. Gervino[j,k], A. Guglielmetti[o], C. Gustavino[p], Gy. Gyürky[c], G. Imbriani[d], Z. Janas[q], M. Junker[a], I. Kochanek[a], M. Lugaro[r,w], P. Marigo[h,i], E. Masha[o], C. Mazzocchi[q], R. Menegazzo[h], V. Mossa[f], F.R. Pantaleo[f,s], V. Paticchio[f], R. Perrino[f], D. Piatti[h,i], P. Prati[l,m], L. Schiavulli[f,n], K. Stöckel[g,t], O. Straniero[a,u],

BACKGROUND REDUCTION

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

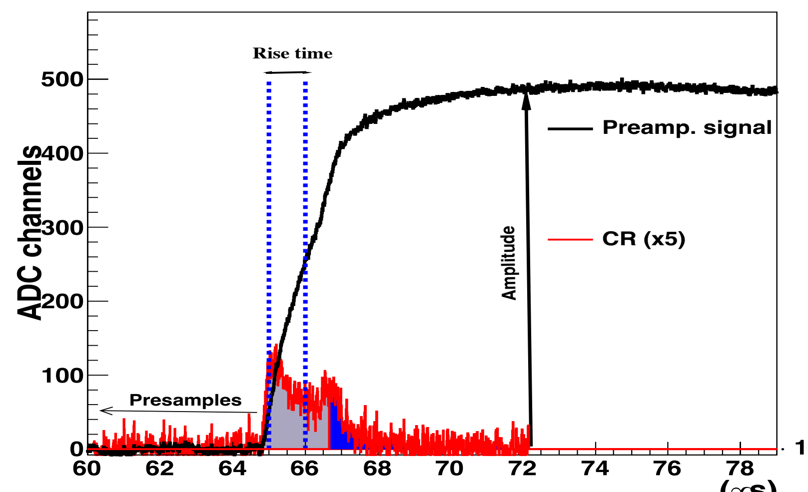
INTRINSIC: α particles source of intrinsic background from U and Th impurities in the counters' case

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

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

- Geant4 simulations validated by experimental measurements

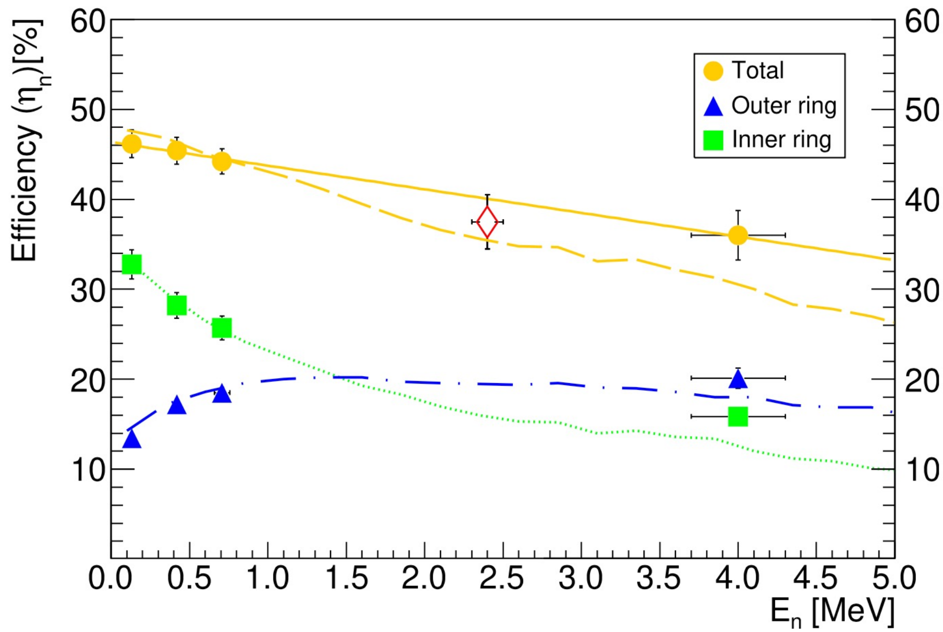
$^{51}V(p,n)^{51}Cr$

- 5 MV Van dee Graaff at Atomki, Hungary
- ^{51}Cr decay via electron capture ($T_{1/2}$=27.7 days and emission of $E\gamma$=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: $(38 \pm 3)\%$

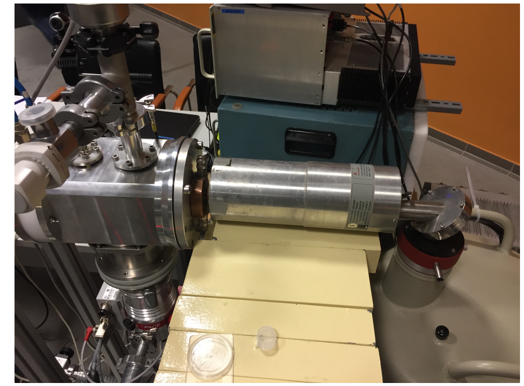


L. Csedreki et al. NIM A 994 (2021)

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)



Eur. Phys. J. A (2020) 56:75
https://doi.org/10.1140/epja/s10050-020-00077-0

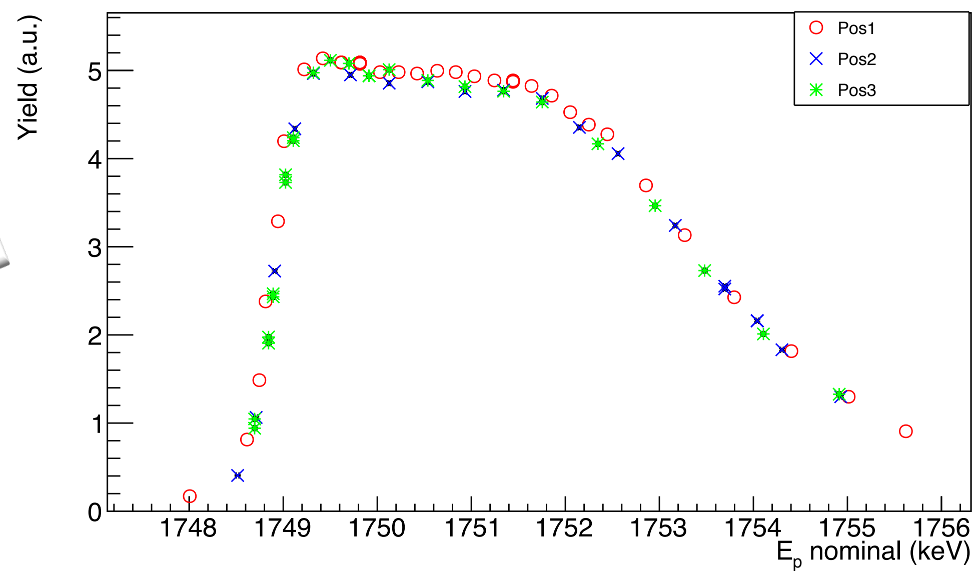
THE EUROPEAN PHYSICAL JOURNAL A

Special Article - New Tools and Techniques

A new approach to monitor ^{13}C-targets degradation in situ for $^{13}C(\alpha, n)^{16}O$ cross-section measurements at LUNA

G. F. Ciani[1,2,3,a], L. Csedreki[1,2,b], J. Balibrea-Correa[4,5], A. Best[4,5], M. Aliotta[6], F. Barile[7], D. Bemmerer[8], A. Boeltzig[1,2], C. Broggini[9], C. G. Bruno[6], A. Caciolli[9,10], F. Cavanna[11], T. Chillery[6], P. Colombetti[12,13], P. Corvisiero[11,14], T. Davinson[6], R. Depalo[9], A. Di Leva[4,5], L. Di Paolo[2], Z. Elekes[3], F. Ferraro[11,14], E. M. Fiore[7,15], A. Formicola[2], Zs. Fülöp[3], G. Gervino[12,13], A. Guglielmetti[16,17], C. Gustavino[18], Gy. Gyürky[3], G. Imbriani[4,5], M. Junker[2], I. Kochanek[2], M. Lugaro[19], P. Marigo[9,10], E. Masha[16,17], R. Menegazzo[9], V. Mossa[7], F. R. Pantaleo[7,20], V. Paticchio[7], R. Perrino[7,24], D. Piatti[9,10], P. Prati[11,14], L. Schiavulli[7,15], K. Stöckel[8,21], O. Straniero[2,22], T. Szücs[8], M. P. Takács[8,21,25], F. Terrasi[23], D. Trezzi[16,17], S. Zavatarelli[11]

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



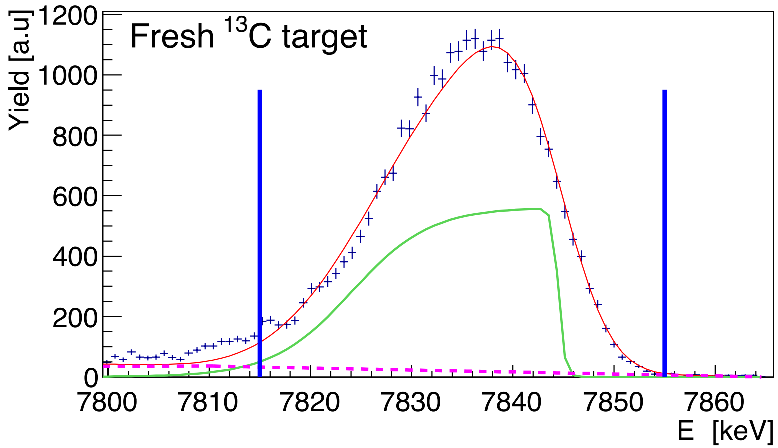
2nd phase: $^{13}C(p,\gamma)^{14}N$ GAMMA SHAPE ANALYSIS at LUNA

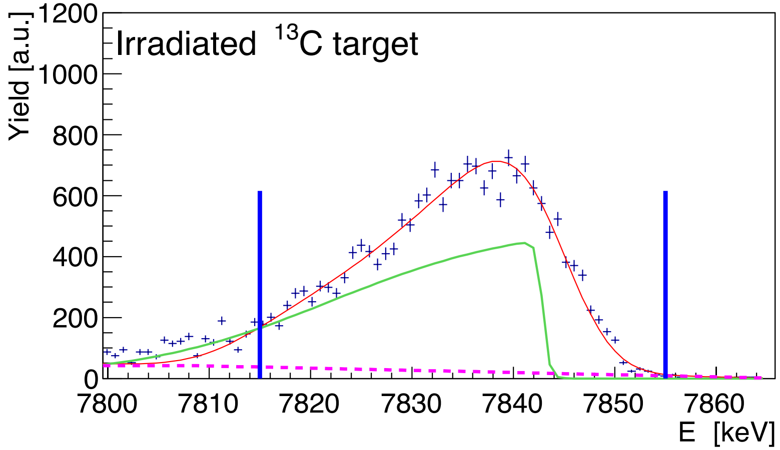
- No resonance in the energy range for online an target degradation study
- Yield mimic the cross section and stopping power dependence vs the proton energy in the γ-spectrum

$$dY(E_\gamma, E_\gamma + dE) \propto \frac{\sigma(E_p)\boldsymbol{W}(\boldsymbol{E_p})f(E_p - E')res(E_\gamma)}{\epsilon_{eff}(E_p)} dE_p, \quad \text{with } E_\gamma = Q + \frac{M_T}{M_T + M_p} E_p$$

$$\varepsilon_{eff}(Ep) = \varepsilon_A(E_p) + \sum_I \frac{N_I}{N_A} \varepsilon_I(E_p)$$

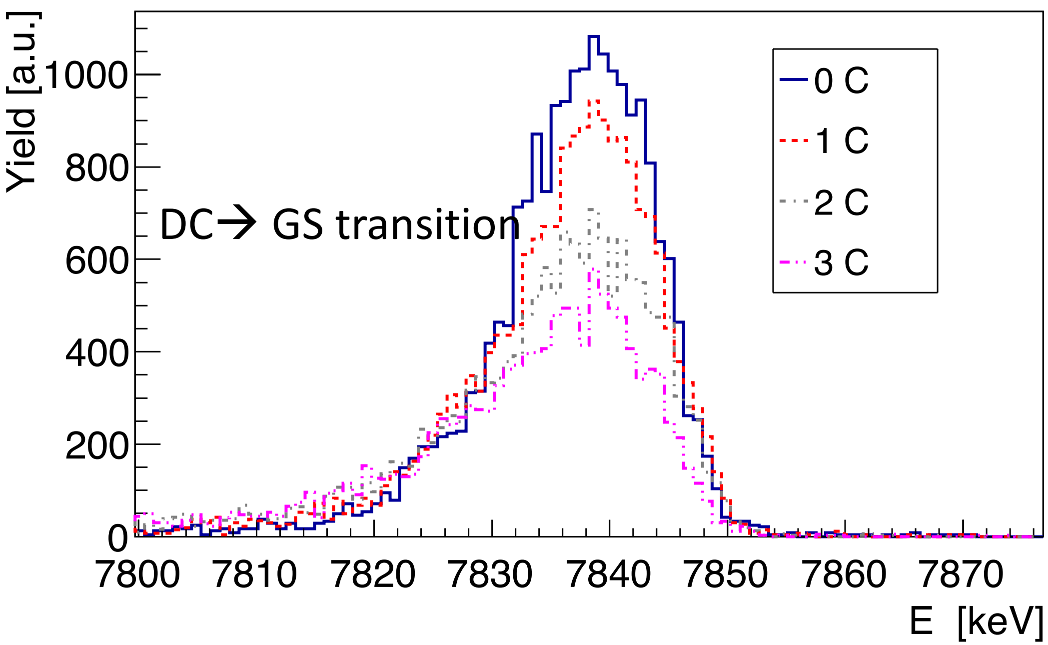
DC→ GS transition





Yield reduction as consequence of target stoichioemtry modification

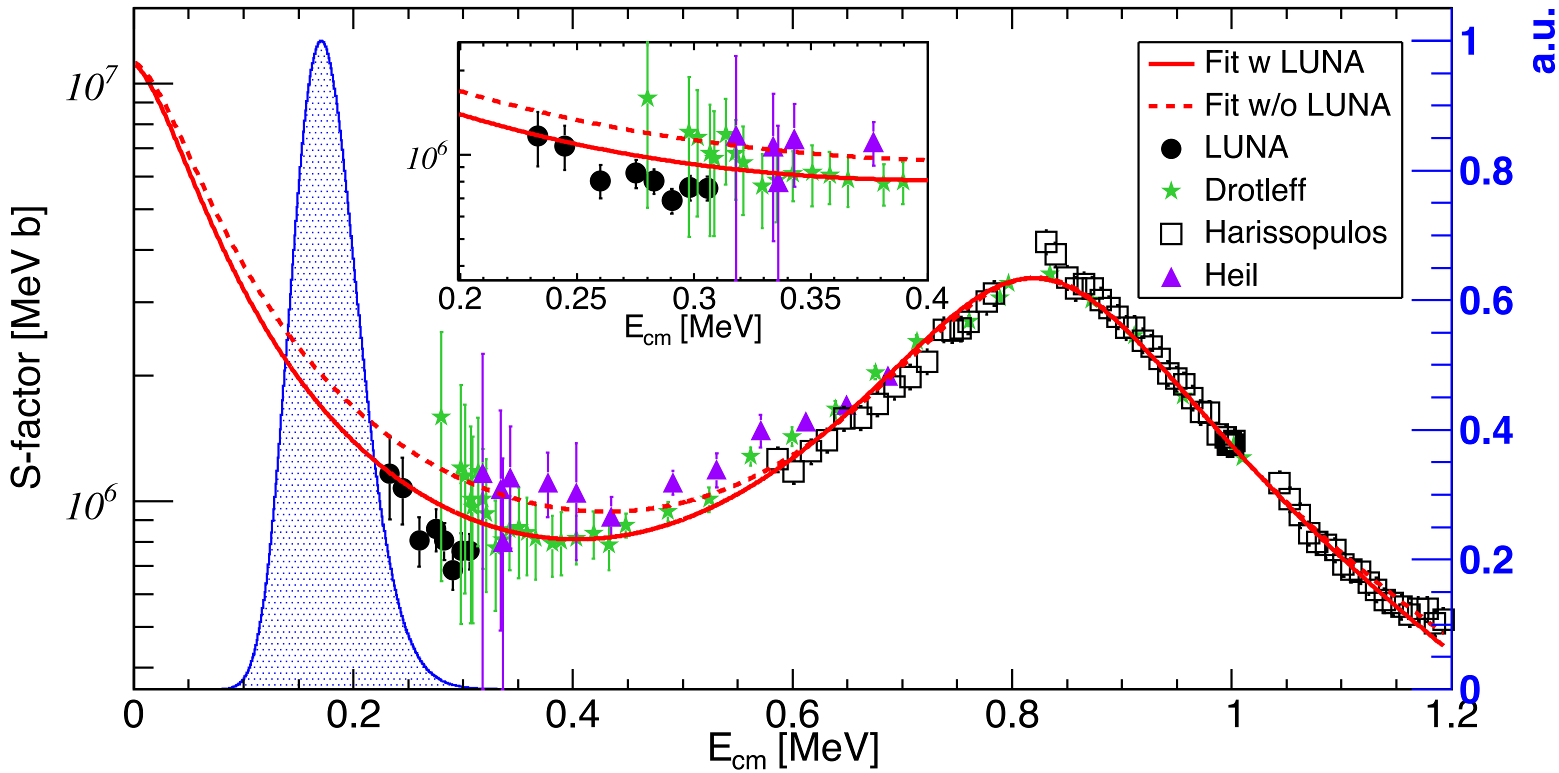
Gamma Shape Analysis performed periodically at Ep=310 keV



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)

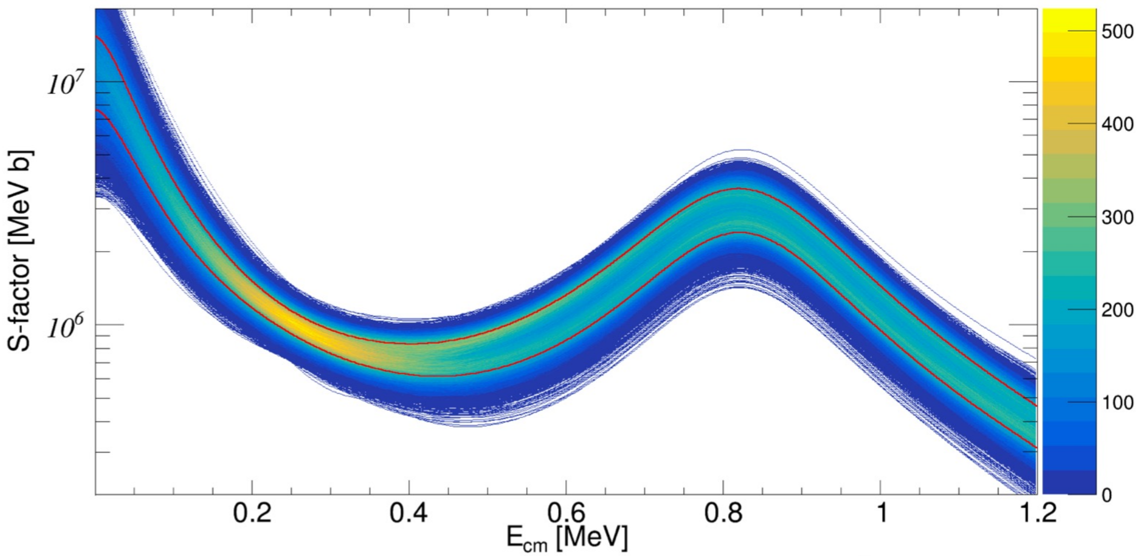
$$\frac{n_{det}}{Q} = Y(E_\alpha) = \int_{E_{\alpha-\Delta E}}^{E_\alpha} \frac{\eta\,(E)\,\sigma(E)}{\varepsilon(E)}\,dE$$

S(E) factor towards the Gamow window



- 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 to about 10%

FROM S(E)-FACTOR TO REACTION RATE



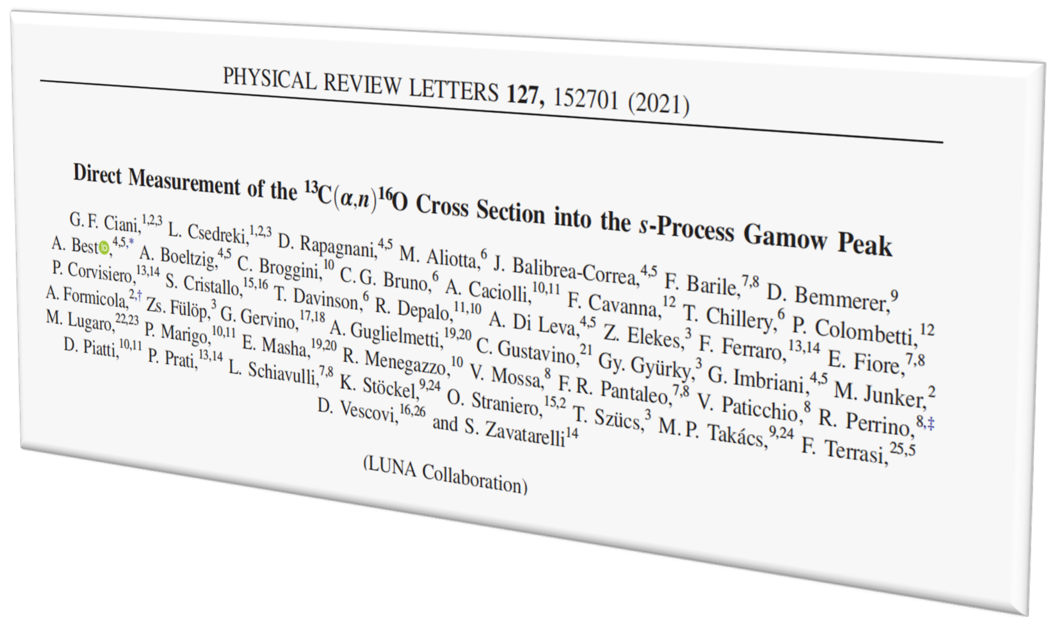
Three reaction rates evaluated

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

M=2M$_\odot$
metallicity Z= 0.02 and Y= Y= 0.27

Calculated percentage variation
LOW LUNA/NO LUNA data

Reduction of the surface abundances is stronger for A>130.
In general variation smaller than 10% with few exeptions



PHYSICAL REVIEW LETTERS **127,** 152701 (2021)

Direct Measurement of the $^{13}C(\alpha,n)^{16}O$ Cross Section into the *s*-Process Gamow Peak

G. F. Ciani,[1,2,3] L. Csedreki,[1,2,3] D. Rapagnani,[4,5] M. Aliotta,[6] J. Balibrea-Correa,[4,5] F. Barile,[7,8] D. Bemmerer,[9] A. Best,[4,5,*] A. Boeltzig,[4,5] C. Broggini,[10] C. G. Bruno,[6] A. Caciolli,[10,11] F. Cavanna,[12] T. Chillery,[6] P. Colombetti,[12] P. Corvisiero,[13,14] S. Cristallo,[15,16] T. Davinson,[6] R. Depalo,[11,10] A. Di Leva,[4,5] Z. Elekes,[3] F. Ferraro,[13,14] E. Fiore,[7,8] A. Formicola,[2,†] Zs. Fülöp,[3] G. Gervino,[17,18] A. Guglielmetti,[19,20] C. Gustavino,[21] Gy. Gyürky,[3] G. Imbriani,[4,5] M. Junker,[2] M. Lugaro,[22,23] P. Marigo,[10,11] E. Masha,[19,20] R. Menegazzo,[10] V. Mossa,[8] F. R. Pantaleo,[7,8] V. Paticchio,[8] R. Perrino,[8,‡] D. Piatti,[10,11] P. Prati,[13,14] L. Schiavulli,[7,8] K. Stöckel,[9,24] O. Straniero,[15,2] T. Szücs,[3] M. P. Takács,[9,24] F. Terrasi,[25,5] D. Vescovi,[16,26] and S. Zavatarelli[14]

(LUNA Collaboration)

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.

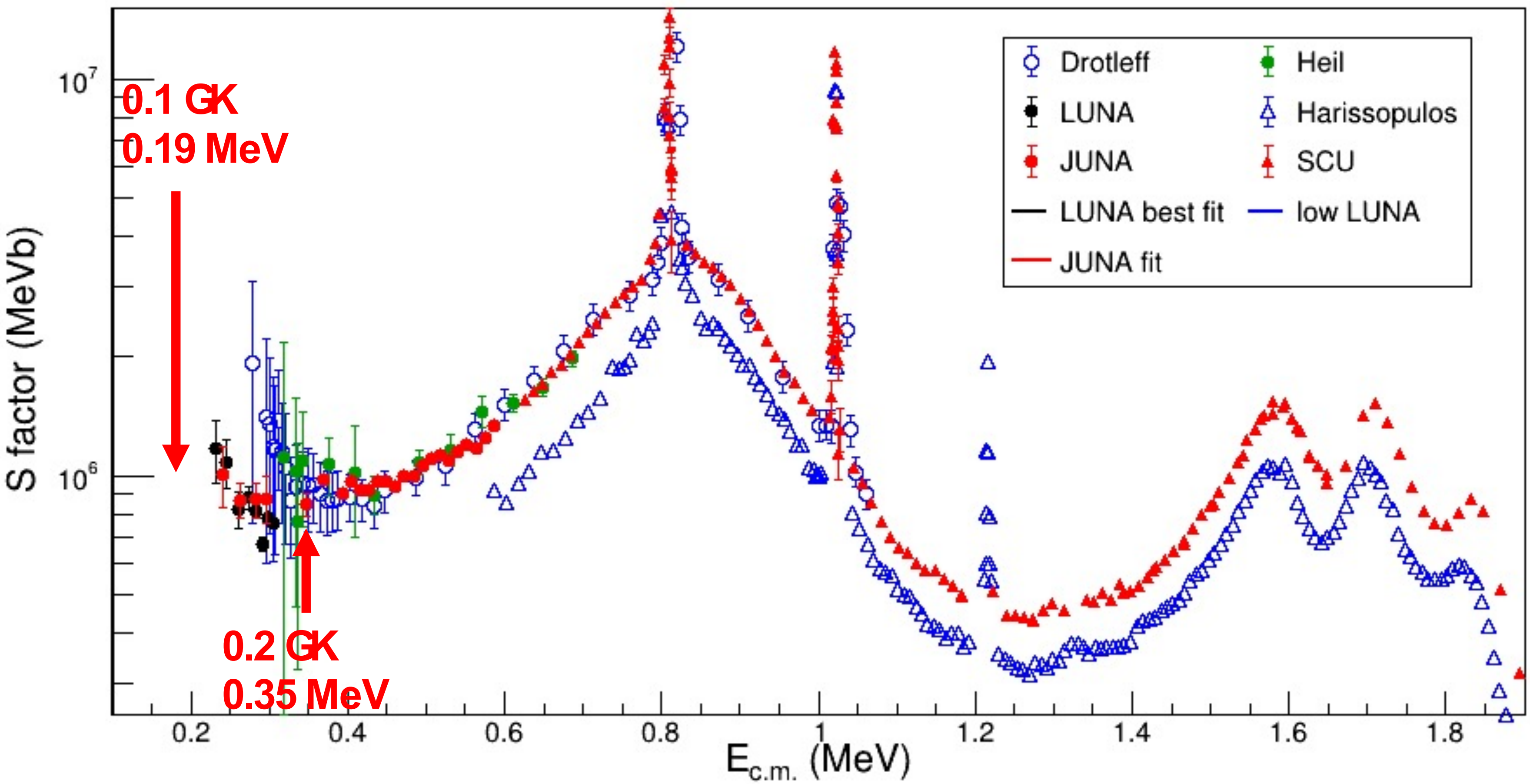
Main radiative neutron event : low flux, high exposure (80-100 MK)

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

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

S-factor of $^{13}C(a,n)^{16}O$

Courtesy by Xiaodong Tang. JUNA Collaboration



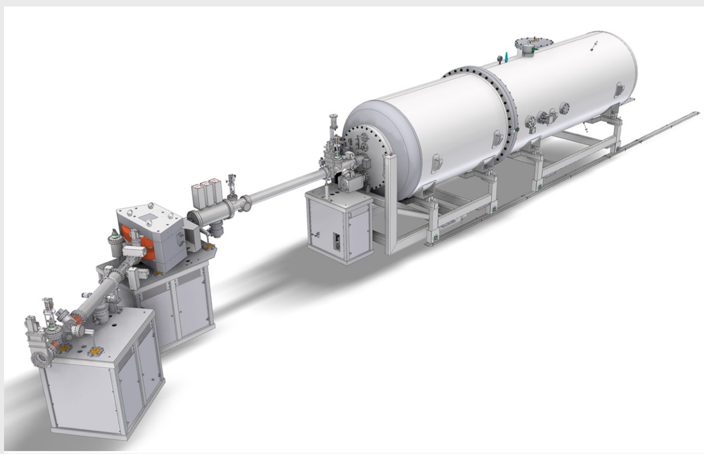
- Cover almost the entire Gamow window for i-processs (0.2-0.3 GK)
- Extrapolation needed for s-process (0.1 GK)

Deep Underground Laboratories World-wide

Image courtesy of Susana Cebrián

OUTLOOK

With the installation (2021-2022) of the LNGS facility V (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



H
$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 μA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 μA

He
$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

C
$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 μA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 μA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

THE LUNA COLLABORATION

A. Compagnucci*, M. Junker | **Laboratori Nazionali del Gran Sasso, INFN, ASSERGI, Italy/*GSSI, L'AQUILA, Italy**
F. Barile,G.F. Ciani, V. Mossa, 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, K. Stöckel, | **Helmholtz-Zentrum Dresden-Rossendorf, DRESDEN, Germany**
M. Aliotta, C.G. Bruno, T. Chillery, T. Davinson | **University of Edinburgh, EDINBURGH, United Kingdom**
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, E. Masha |**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**