The $^{13}C(\alpha,n)^{16}O$ reaction, results and further plans

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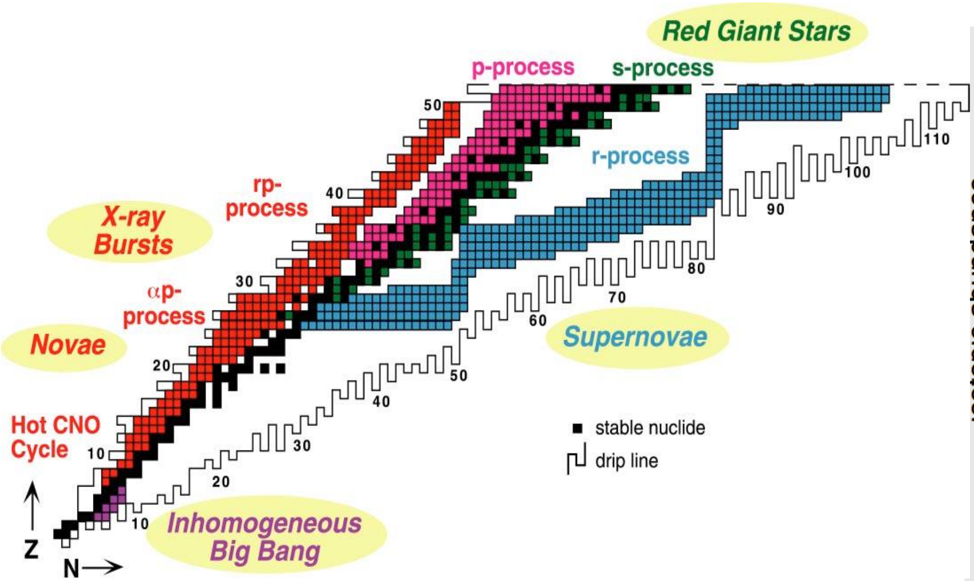
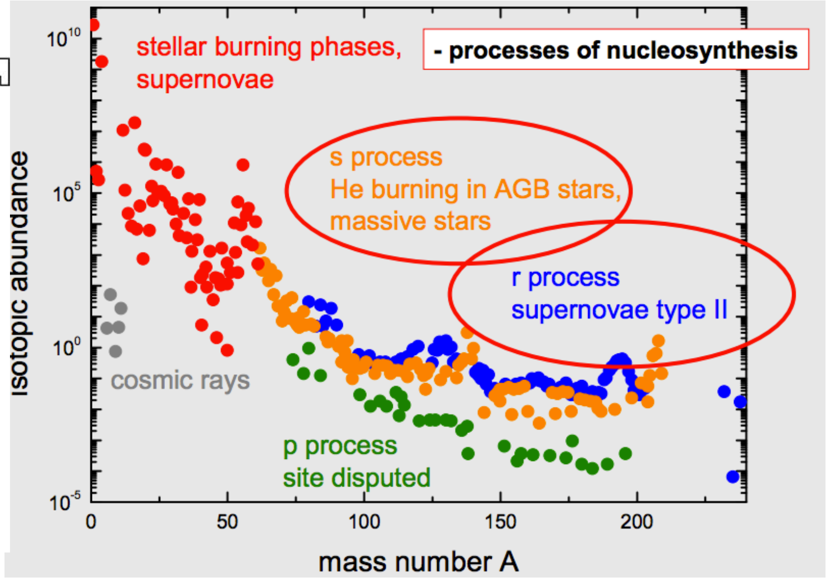
NUCLEOSYNTHESIS PROCESS:

- **Big Bang Nucleosynthesis (BBN) -> from ^{1}H to^{7}Be**
- **Stellar NS: per A≤56: nuclear fusion (PP, CNO, NeNa, He-Burning…)**
- **Ns: beyond A>56: neutron capture (*r and s process) or proton capture (p process)***
- ***Cosmic-ray spallation***



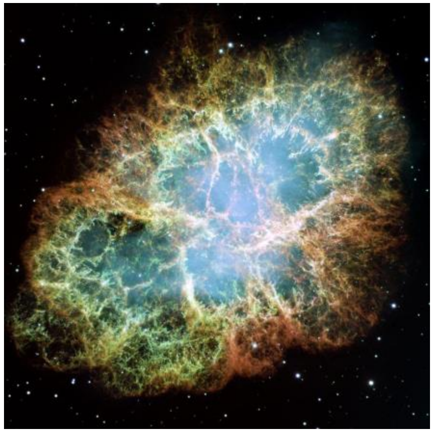


Neutron capture processes

Name(s)	N_n (cm^{-3})	Neutron source(s)	Astrophysical site(s)
Slow (*s*)	10^6–10^{11}	$^{13}C(\alpha,n)^{16}O$	AGB[b] stars
		$^{22}Ne(\alpha,n)^{25}Mg$	Massive stars[c]
Intermediate (*i*)	10^{12}–10^{15}	$^{13}C(\alpha,n)^{16}O$	Post-AGB stars[d]
			Low-*Z*[e] AGB stars
			Super-AGB stars[f]
			Accreting white dwarfs
			Massive stars[c]
Neutron (*n*) (also called neutron burst)	10^{18}–10^{20}	$^{22}Ne(\alpha,n)^{25}Mg$	He shell of CCSNe[g]
Rapid (*r*)	$>10^{20}$	—	Compact mergers[h] Special CCSNe[i]

M. Lugaro et al., Annu. Rev. Nucl. Part. Sci. 2023.73:315-340

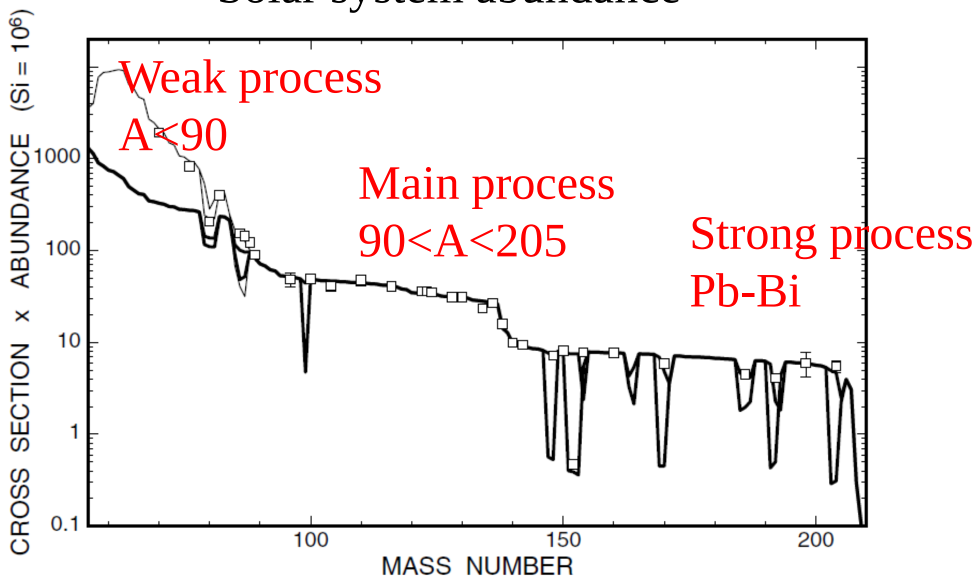
Messier 57 Nebula



The Crab Nebula

Astrophysical sites of s-process

Solar system abundance



Iliadis C 2008 Nuclear Physics of Stars (Wiley-VCH)

Main s-process: $f \approx 0.06\%, \tau_0 \approx 0.3$ mb^{-1}, $n_c \approx 10$ → Low-mass AGB stars (1-3 M/M_o) T=0.1 GK

Weak s-process: $f \approx 1.6\%, \tau_0 \approx 0.07$ mb^{-1}, $n_c \approx 3$ → Massive stars (He and C burning) T=0.3 GK

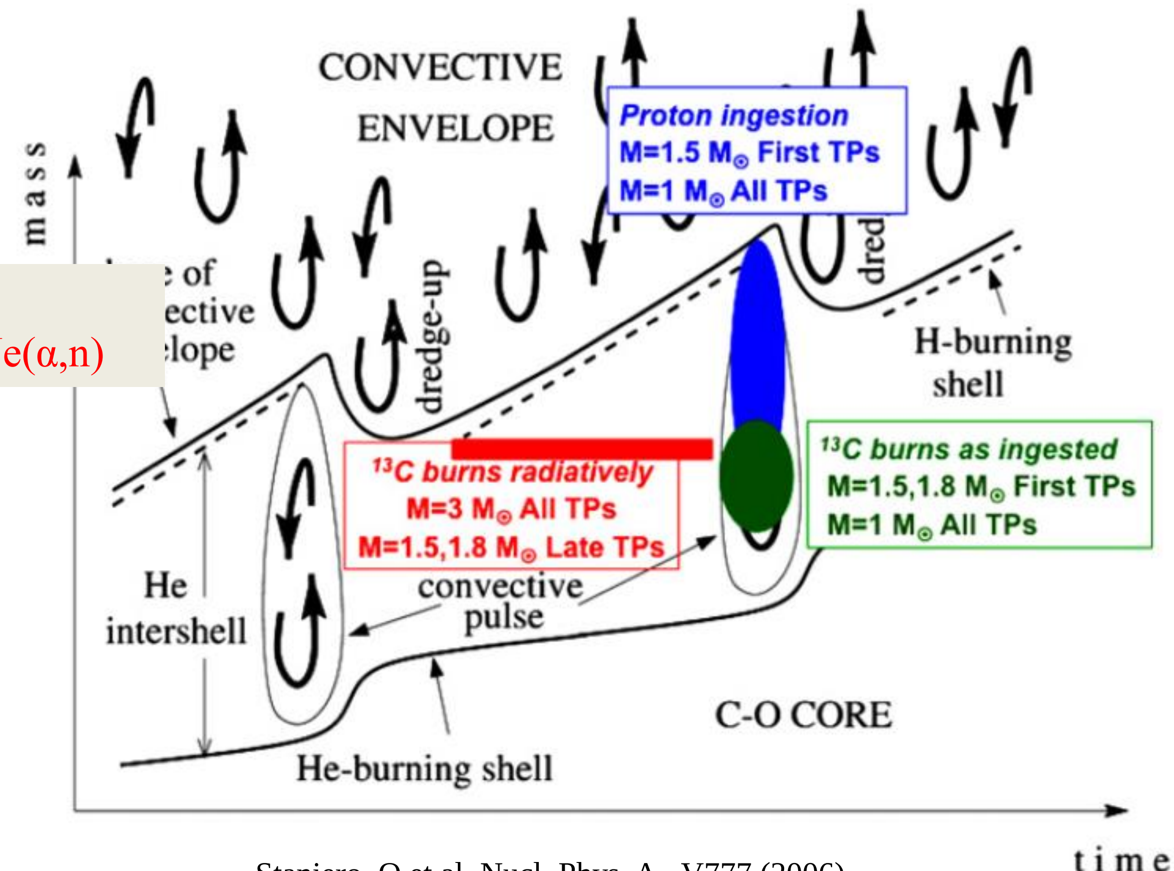
Strong s-process: $f \approx 10^{-4}\%, \tau_0 \approx 7$ mb^{-1}, $n_c \approx 140$ → low Z, Low-mass AGB stars (1-3 M/M_o)

• **$^{13}C(\alpha,n)^{16}O$ Neutron source** of main component of the s (slow neutron capture) process

• TP-AGB stars average T ~90-100 MK → Energy range of **Gamow Window ~140-240 keV**

•Energy balance of TP depends on reaction rate

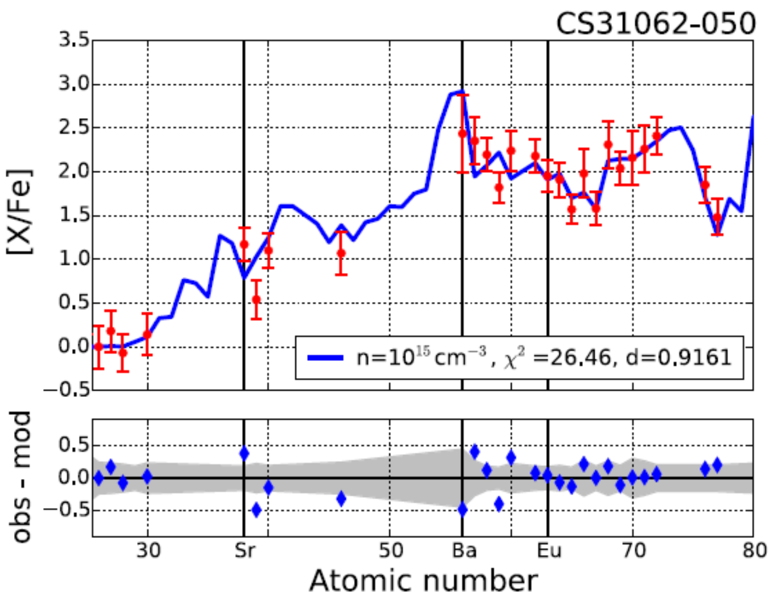
$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)$
$^{13}C(p,\gamma)^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$



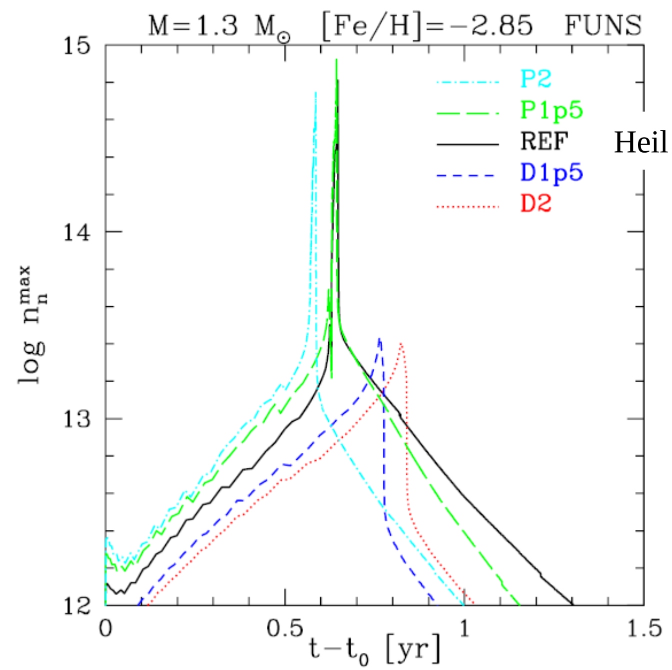
Staniero, O et al. Nucl. Phys. A., V777 (2006)
B. Guo et al., ApJ 756 (2012)

i-process: $10^{12\text{-}15}$ neutrons/cm^3

-Carbon-enhanced metal-poor (CEMP) stars (Hampel et al., ApJ 831 (2016))
-GCE models (C. Kobayashi et al., ApJ 900(2020)) suggest the need of i-process at low metalicity



Hampel et al., ApJ 831 (2016)



Heil et al. 2008

Cristallo et al., ApJ 856 (2018)

- Better understanding of s-process and its astrophysical site (reaction rate of $^{13}C+\alpha$ (and $^{22}Ne+\alpha$), neutron-capture cross-sections, β decay rates at branch points)
- More complex processes: Rotation, gravity waves, magnetic fields, diffusive mixing

Knowledge of $^{13}C(\alpha,n)^{16}O$ required:

- Astrophysical s- and i-process → **low energy regime**
- Background source (in rare events experiments) → **higher energies**
- Constrain on $^{16}O(n,\alpha)^{13}C$ reaction for e.g. nuclear reactor studies → **wide energy region**

Experimental data

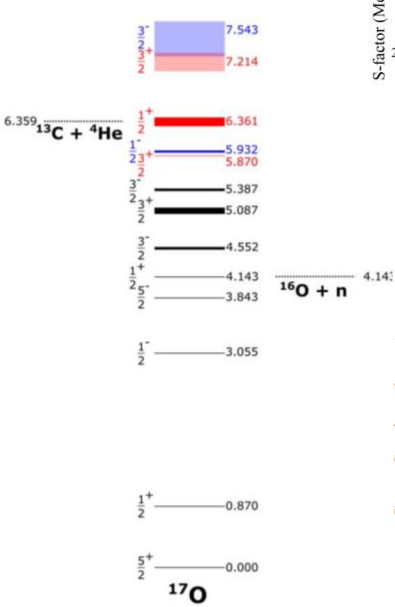
- UG experiment
- Surface experiment
- Indirect methods

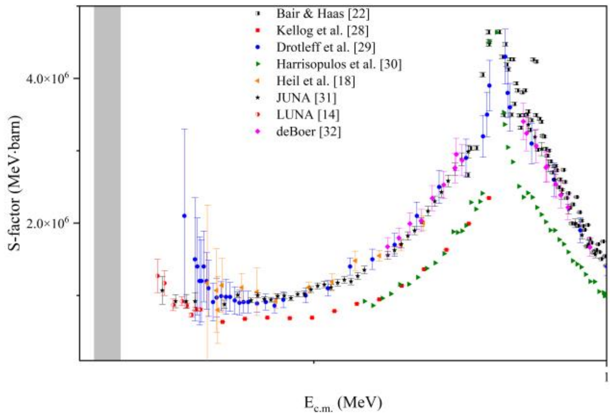
Nuclear physics input

- Several resonances
- Near Th. Res.
- spin-parity
- E_x
- Γ_{tot}, Γ_n , Γ_α

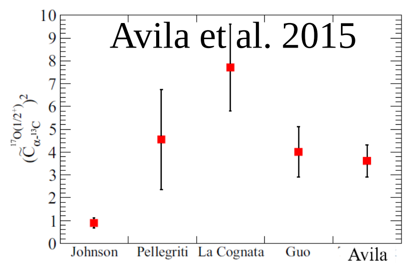
Nuclear model

e.g R-matrix

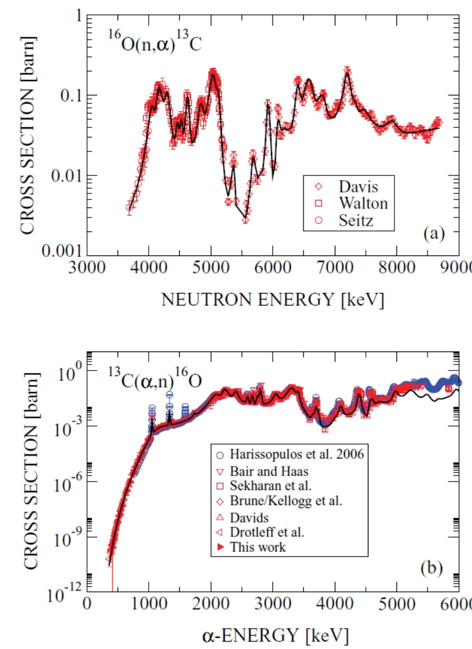




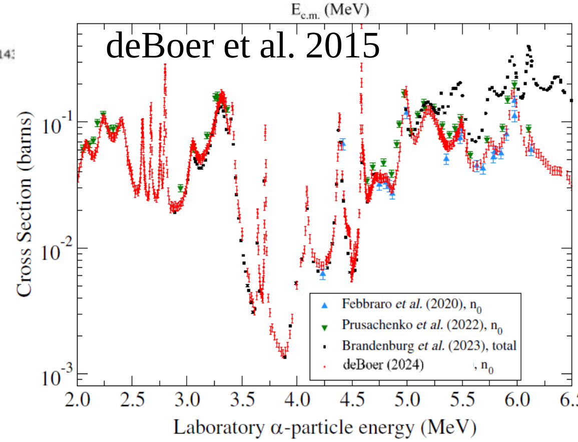
Avila et al. 2015



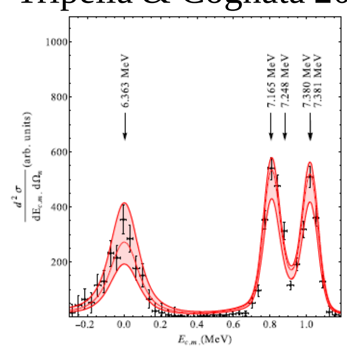
Heil et al. 2015



deBoer et al. 2015



Tripella & Cognata 2015



Experiments using direct techniques

Table 2. Selected experimental setups and parameters of direct measurements of the $^{13}C(\alpha,n)^{16}O$ reaction.

References	E_α (MeV)	Int. (μA)	Accelerator	Accelerator calibration	Detector	Detector calibration	Solid angle	Target	Thickness	Method	Laboratory background
Sekharan [75]	1.95–5.57		Bombay, VdG		BF_3 based counters embedded in paraffin	$^7Li(p,n)^7Be$, Ra-α-Be	4π	Electrically enriched ^{13}C (30%) onto 0.25 mm Ta			
Davids [51]	0.475–0.7	25-30	Kellogg Radiation Laboratory, Oak Ridge type RF ion source		Stilbene crystal and PSD	Not clear	0°	Thick ^{13}C target from CH_3I enriched to 54% in ^{13}C, Total 1.3 C was collected	200 $\mu g\ cm^{-2}$	$^{13}C(p,\gamma)^{14}N$ resonance, but E_r is not indicated	
Bair [22]	1–5	—	Oak Ridge NAtional Lab. 5.5 MV Van de Graaff	$^{19}F(\alpha,n)^{22}Na$, $^7Li(p,n)^{11}B$, $^{18}O(\alpha,n)^{21}Ne$	Graphite-sphere neutron detector, 8 -$^{10}BF_3$ detector	In [96] Age-diffusion Theory, recalib. with Standard Sources	4π	Infinitely thick disk of compressed carbon enriched ^{13}C and thin ^{13}C target produced by cracking enriched acetylene onto Pt backing	5 keV at 1 MeV		2–3 c/s based on [96]
Ramström [24]	0.6–1.15		Neutron Physics Laboratory, Nyköping, Sweden, 5.5 MV Van de Graaff	$E_\alpha = 1.05$ MeV was repeated, 5 keV was observed and used in corrections	20 $^{10}BF_3$ 0.7 m shielding of paraffin, Cd and concrete	PuBe, RaBe, $^{51}V(p,n)^{51}Cr$ (at 2.3 MeV) Assuming non-energy dependent detector function (18.3 ± 1.5)	4π	Methyl Iodine heated onto Ta 89% ^{13}	88 and 13 (in 0.7 and 1 MeV) $\mu g/cm^2$	Weighting and width of profile at $E_\alpha = 1.05$ MeV	
Kellogg [28]	0.4–1.2		Calltech pelletron		Neutron detector with 23% efficiency-no details		4π				0.027 c/s
Drotleff [29][a]	0.35–1.4	100	Stuttgart 4 MV Dynamitron		2 concentric cycle of 8 ^3He counter in PE plus layers of PE, Paraffin, B and Cd	^{252}Cf, E dependence was calculated with multiproup calculation	4π	99% ^{13}C on solid Cu backing			0.08 c/s
Brune [23][b]	0.45–1.05	50	Calltech pelletron		11 ^3He filled counter in PE [100]	^{252}Cf (20.2% efficiency obtained), [100] $^7Li(p,n)$ reaction eff. is constant 50 keV and 2 MeV within 5%	4π	Thin ^{13}C target (99.2%) onto Cu disk, electron beam evaporated		From known $^{13}C(\alpha,n)$ yield of non-resonance range and resonance strength (refer to [23] and [22]	0.1 c/s
Harissopulos [30]	0.8–8	100 nA	Ruhr-Universitat, Bochum, Dynamitron-Tandem Laboratory		8 ^3He counter at 16cm,8 ^3He counter at 24 cm, Embeded in PE passive shielding (Cd, PE, B-PE, B-parafin)	^{252}Cf with MCNP simulation, Above 6 MeV n1, n2 branching	4π	99% ^{13}C on Ta backing. Air cooled target 40 mm, target degrad. is partially explained. Yield test at selected energies gave 2% reproducibility. Presumably 1 target was used in this measurement.	22 $\mu g\ cm^{-2}$, 1e^{18} atom cm^{-2}	NRRA using $^{13}C(p,\gamma)^{14}N$ at E_p = 1.75 MeV	0.22 c/s
Heil [18]	0.416–0.899	50	Karlsruhe 3.7 MV van de Graaff	$^7Li(p,n)^{11}B$, E_r = 402, 814, 953 keV	42xBF_2 n/γ converter using $^{113}Cd(n,\gamma)^{114}Cd$	$^{51}V(p,n)^{51}Cr$ E_n = 135, 935, 1935 keV GEANT4 simulation	4π	^{13}C(99%) electron gun onto 5 μm Au and Cu sheet, Impurities of Cu is not discussed	7 keV at E_p = 448.5 keV	NRRA $^{13}C(p,\gamma)^{14}N$ at E_p = 448.5 keV, yield check at E_α = 800 kev, ^{12}C build up, mixing with Au	Almost BG free condition due to multiplicity
Febbraro [12]	4.2–6.4		University of Notre Dame Nuclear Science Laboratory	E_α = 1.05, 1.34, 1.59 MeV and $^{27}Al(p,\gamma)^{28}Si$ E_p = 992 keV	EJ315 and EJ301D scintillators	$^{51}V(p,n)^{51}Cr$, $^{19}F(\alpha,n)^{22}Na$	Between 0° and 90° in five-point and twelve-point (near resonances) angular steps	^{13}C ACF foils 99% evap. onto Ta (0.2 mm)	12–20 $\mu g\ cm^{-2}$	Yield at E_α = 1.05, 1.34 MeV and E_p = 1.75 MeV	
Ciani [14]	0.305–0.4	300 μA	LUNA400, INFN-LNGS		18 ^3He based counters embedded in	$^{51}V(p,n)^{51}Cr$, AmBe combined with GEANT4	4π	Enriched ^{13}C targets using electron gun evaporation onto 0.25 mm Ta backings	170 nm	NRRA $^{13}C(p,\gamma)^{14}N$ at E_p = 1.75 MeV,	0.000 85(8) c/s and 0.0003(0.3)

					PE with BPE shielding, PSD applied					yield check at E_α = 380 keV	c/s with PSD[c]
Gao [31]	0.31–2.5	up to 2.5 meA	CJPL and 3 MV Tandetron at Sichuan University	$^{12}C(p,\gamma)^{13}N$, $^{27}Al(p,\gamma)^{28}Si$, $^{11}B(p,\gamma)^{12}C$, $^{14}N(p,\gamma)^{15}O$	24 ^{3}He filled proportional counters [57]	$^{51}V(p,n)^{51}Cr$ E_p = 1.7–2.6 MeV, GEANT4	4π	2 mm thick ^{13}C enriched graphite, 97%		Repeated yield measurements	0.0013(5.5) c/s[c]
Brandenburg [50]	2.9–8.0		Edwards Accelerator Laboratory at Ohio University		^{3}He and BF_3 neutron-sensitive proportional counters [101]	^{252}Cf, $^{51}V(p,n)^{51}Cr$, $^{13}C(\alpha,n)^{16}O$ combined with MCNP	4π	^{13}C ACF foils 99% evap. onto Cu	$(1.12 \pm 0.05) \times 1e^{18}$ atoms cm^{-2}	α-elastic scattering, α energy-loss measurements, and scan of the 1.05 MeV $^{13}C(\alpha,n)$ resonance	
deBoer [32]	0.8–6.5	10eμA	University of Notre Dame Nuclear Science Laboratory	Resonances in $^{13}C(\alpha,n)^{16}O$	ODeSA, nine deuterated scintillators [73]	$^{9}Be(d,n)^{10}B$ combined with MCNP simulation	Between 0° and 157.5°	Similar than [14]	10.3(6) and ~5 μg cm^{-2}	NRRA $^{13}C(\alpha,n)^{16}O$ at E_p = 1.05 MeV	

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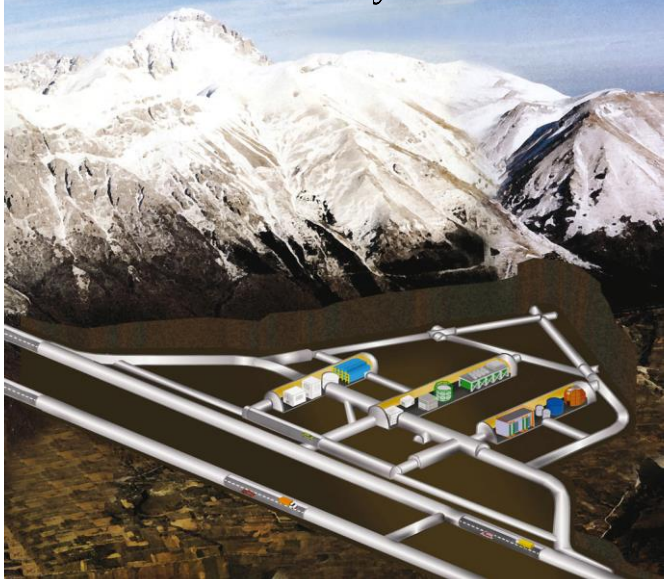
Experimental data using direct methods of $^{13}C(\alpha,n)^{16}O$

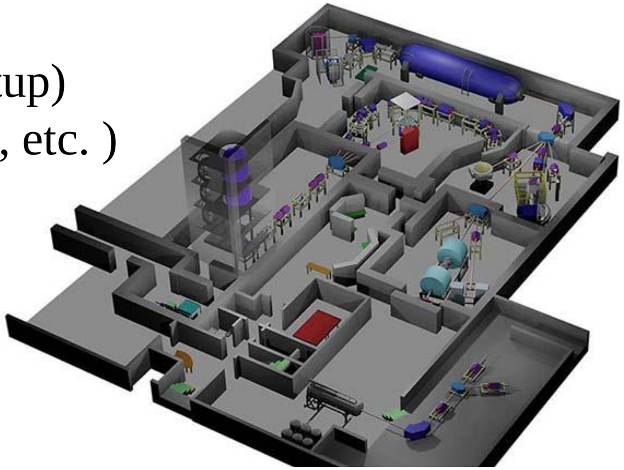
- 14 (almost) independent measurements
- >5000 data points
- Total and differencial cross-section data
- $E_{c.m.}$=230-6200 keV
- θ= 0-157.5°

Experimental backgrounds

- Environmental background (Laboratory, experimental setup)
- Beam induced background (target impurities, collimators, etc.)

National Laboratory of Gran Sasso



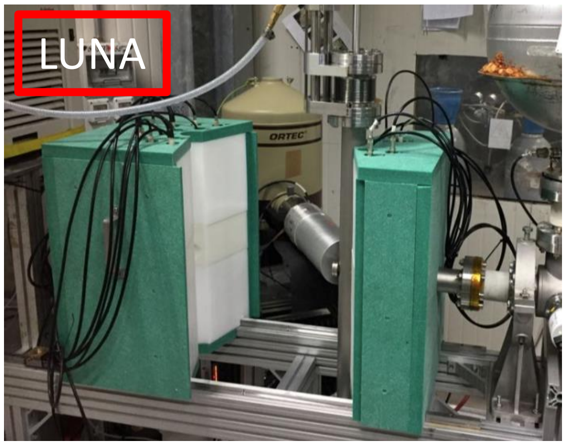


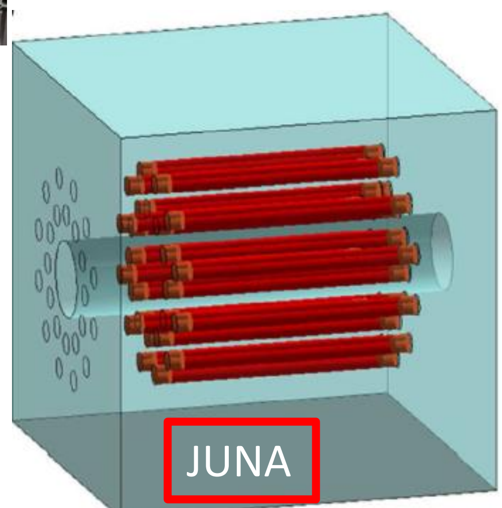
Notre Dame's Nuclear Science Laboratory (NSL)

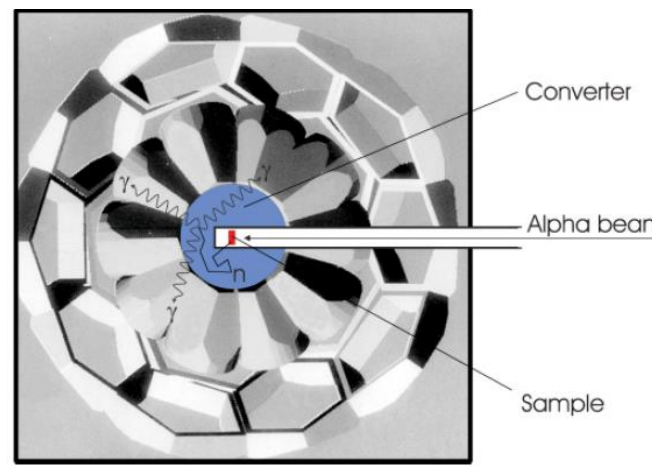
China Jinping Underground Laboratory (CJPL)

Detectors

- Detector types (proportional counters, scintillators)
- Neutron detection efficiency (~30%), angular resolution

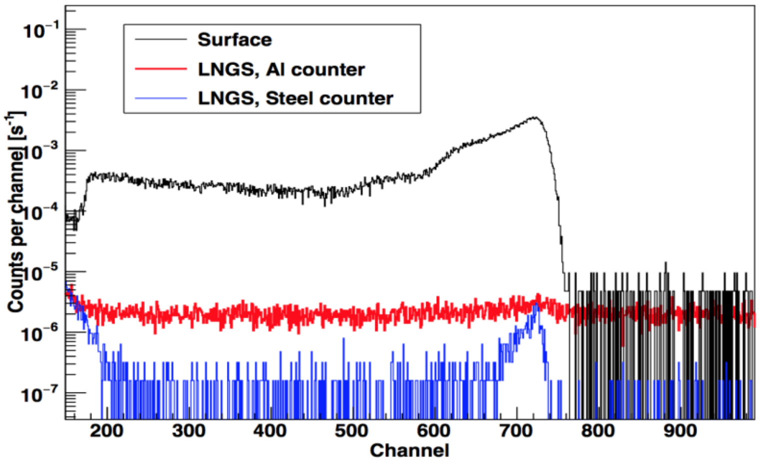






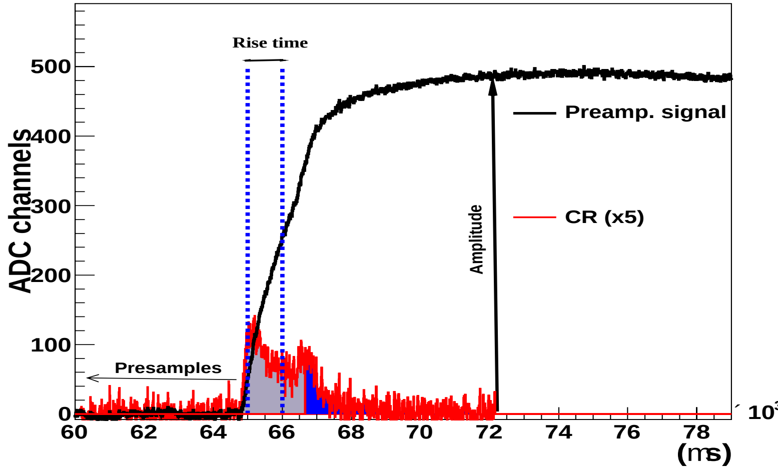
Heil et al., 2008

- Effective selection of materials (Stainless steel, PE, BPE)
- Active background suppression (PSD)
- Underground environment
- High intensity alpha beam (couple of 100 μA, even mA)



References	Intensity (μA)	Bg. c/s
Drotleff et al. 1993	100	0.08
Ciani et al. 2021	300	0.0003
Gao et al. 2022	2500	0.0013

Pulse Shape Discrimination (PSD)



Future experiments

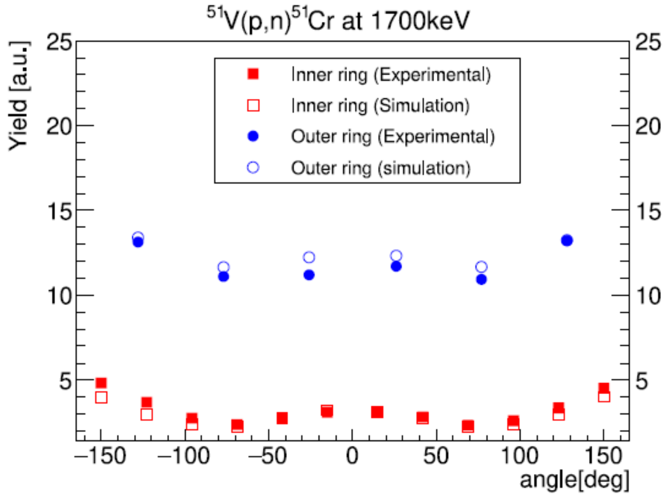
- Beam parameters: wobbling, focus
- More passive shielding
- Improved PSD
- Scintilators for fast neutron det.

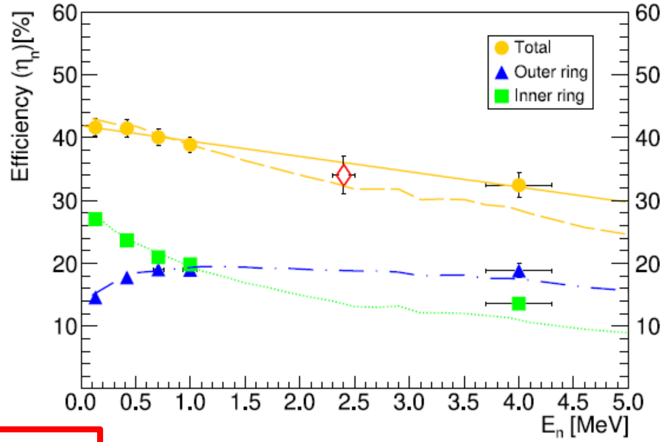
Detector calibration and simulation of detector response

$^{13}C(\alpha,n)^{16}O$: Q=2.215 MeV

$E_{c.m.}$=0.2-2 MeV ⟶ E_n=2.4-4.5 MeV

- Radioactive sources (AmBe, PuBe, ^{252}Cf)
- Nuclear reactions (^{7}Li+p, ^{51}V+p)
- Detector response matrix (^{27}Al, ^{9}Be+d)
- E. dependent sys. unc. ~10%





Challenges simulating thermal neutron scattering:

- inaccuracies in representing thermal motion
- inconsistencies in angular scattering distributions
- limitations in the thermal scattering libraries

To be improved:

- Banchmarking Geant4 simulation
- Experimental angular distribution data
- Quasi monoenergetic neutron source towards E_n>1 MeV

Target effect

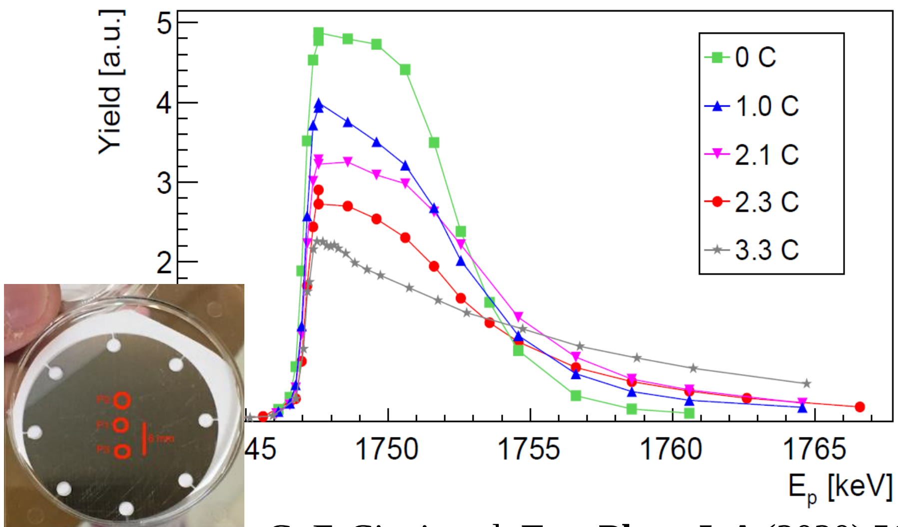
Thin target approach

- Homogeneity of evaporated layer
- Impurities
- Strong diffusion effect induced by ^{4}He beam
- Carbon build up easily controlled
- Lot of targets!

Thick target approach

- Differentiating thick target yield
- Carbon build up problem
- Helium implantation 10^{20} particle (20C)
- Cooling
- Few targets!

^{13}C(p,γ)^{14}N DC→GS at E_p~1750 keV



G. F. Ciani et al**. Eur. Phys. J. A** (2020) 56:75

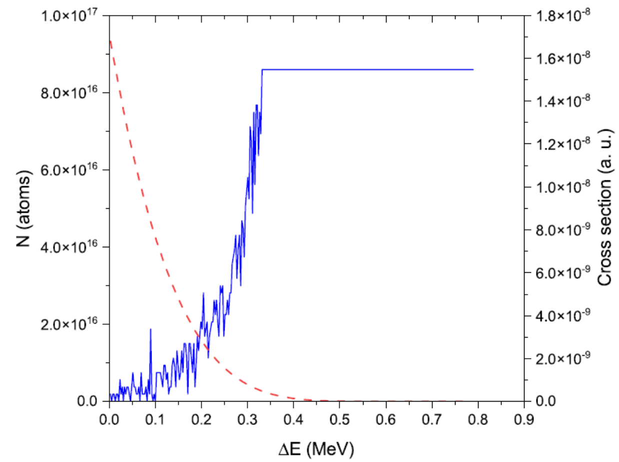
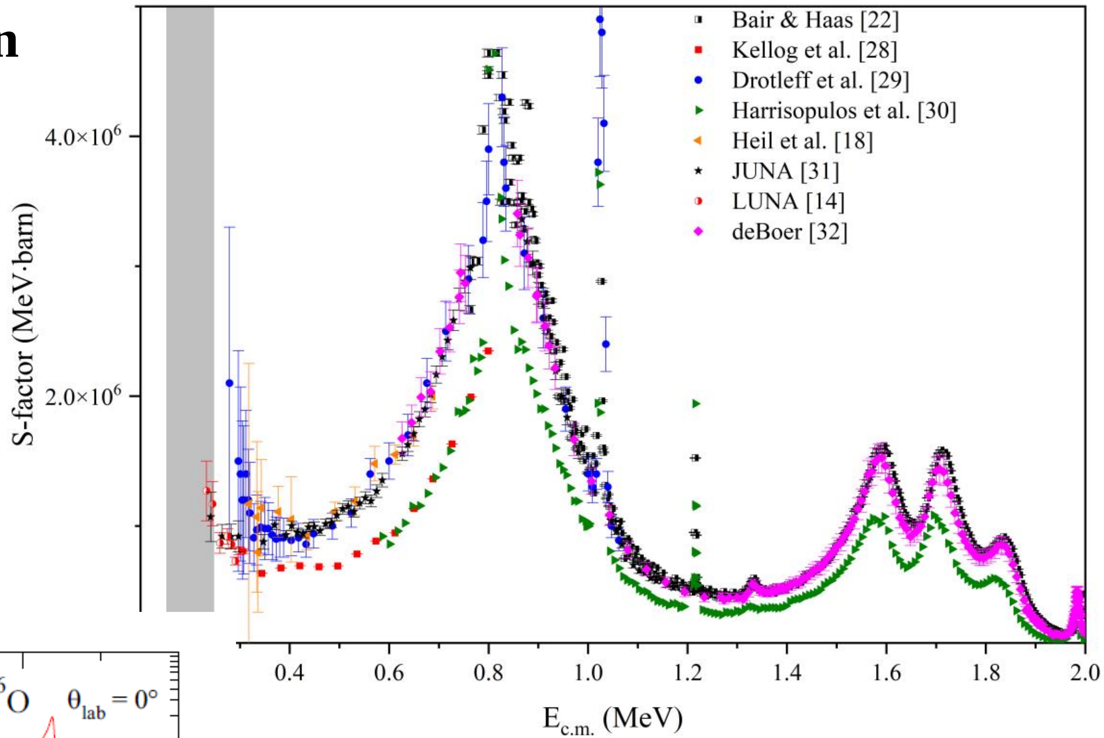


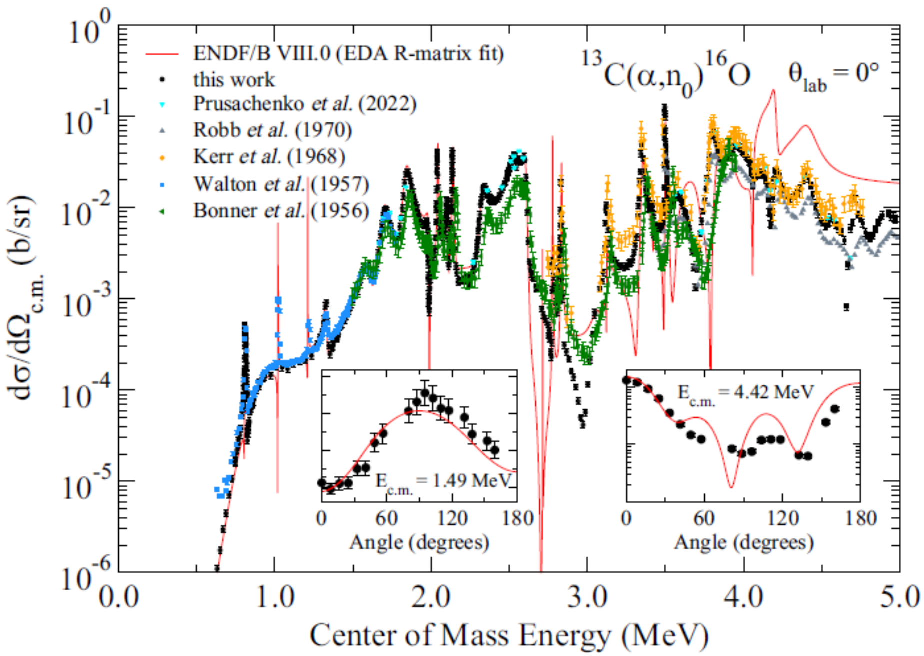
Figure 7. Calculated cross section of ^{13}C(α,n)^{16}O reaction (dashed red line) and helium profile (solid blue line) in thick carbon target at $E_\alpha = 0.8$ MeV beam after irradiation of $E_\alpha = 0.4$ MeV with a total of 3 C accumulated charge.

Critical points: Cooling, carbon build up, isotope ratio

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

- Lots of data
- Angular distribution data
- Different systematics ~40%
- Absence of experimental details
- Excited states in ^{16}O E_n>5 MeV





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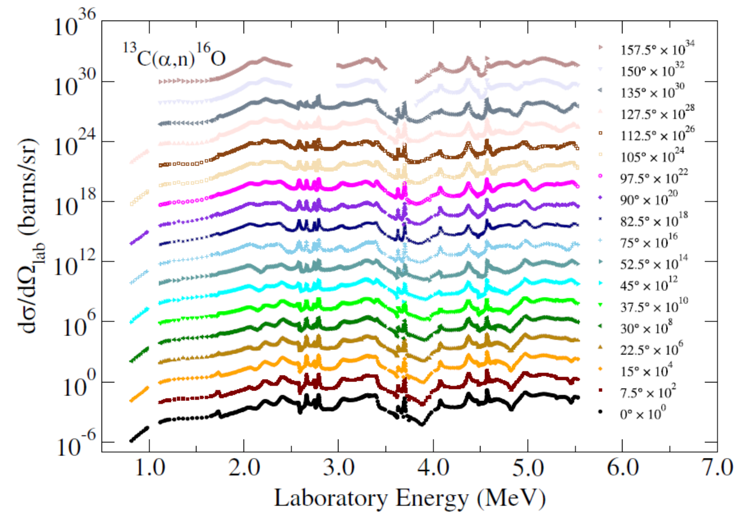
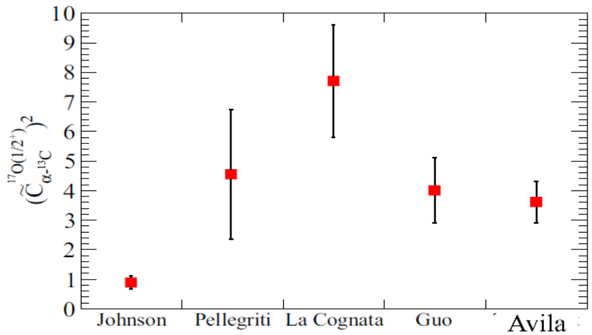


Indirect techniques

- *Asymptotic Normalisation Coefficient (ANC)*
- *Trojan Horse Methode (THM)*
- *Coulomb dissociation*

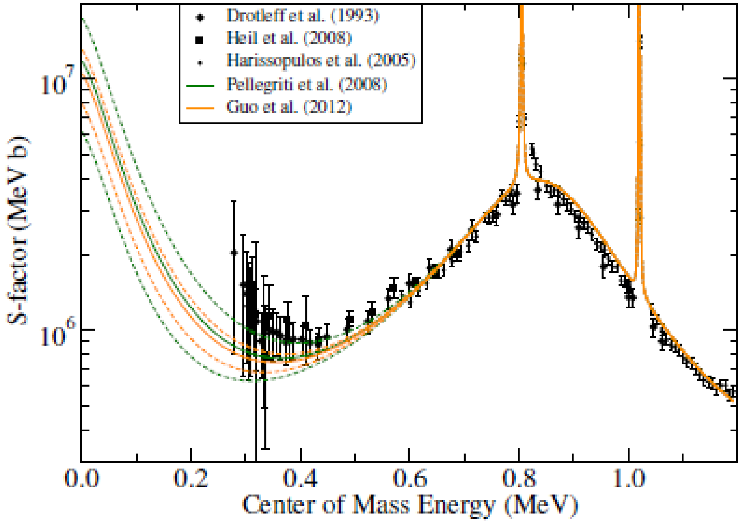


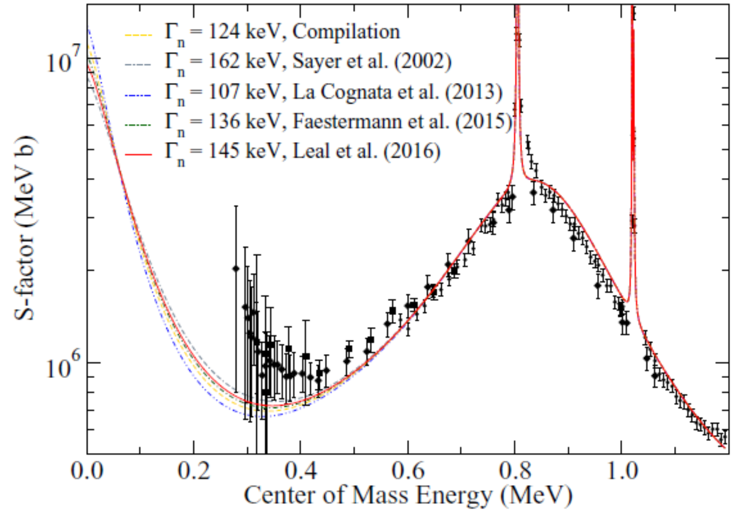
- Uncertainty of resonance parameters
    - Level energy
    - Neutron partial width (Γ_n)
    - α-particle partial width (Γ_α)
- Electron screening effect

Reference	Γ_n (keV)	ANC (fm^{-1})
Fowler et al. (1973)	124	⋯
Tilley et al. (1993)	124 ± 12	⋯
Sayer (2000)	162.37	⋯
Johnson et al. (2006)	124 ± 12	0.89 ± 0.23
Pellegriti et al. (2008)	124 ± 8	4.5 ± 2.2
Heil et al. (2008)	158.1	⋯
La Cognata et al. (2012)	83^{+9}_{-12}	$6.7^{+0.9}_{-0.6}$
Guo et al. (2012)	124	4.0 ± 1.1
La Cognata et al. (2013)	$107 \pm 5_{stat}{}^{+9}_{-5}{}_{norm}$	$7.7 \pm 0.3_{stat}{}^{+1.6}_{-1.5}{}_{norm}$
Faestermann et al. (2015)[a]	136 ± 5	⋯
Avila et al. (2015)	⋯	3.6 ± 0.7
Hebborn et al. (2024)		*2.8±0.5*
Gao et al. (2022)		*2.1±0.5*

3.6±0.7

E_x~6360 keV Large contribution to low energy S-factors





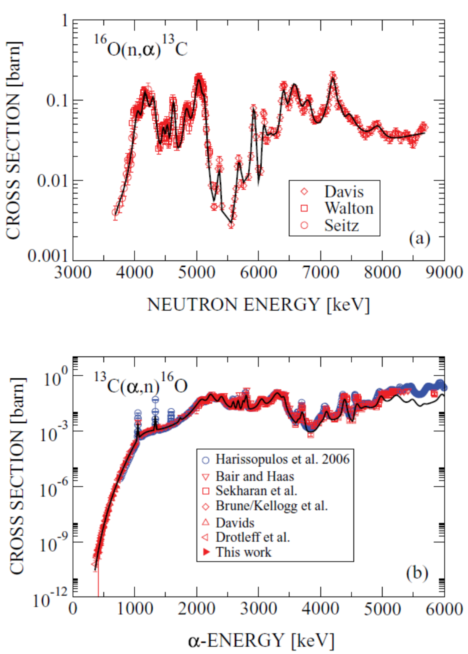
R. J. deBoer et al., 2020

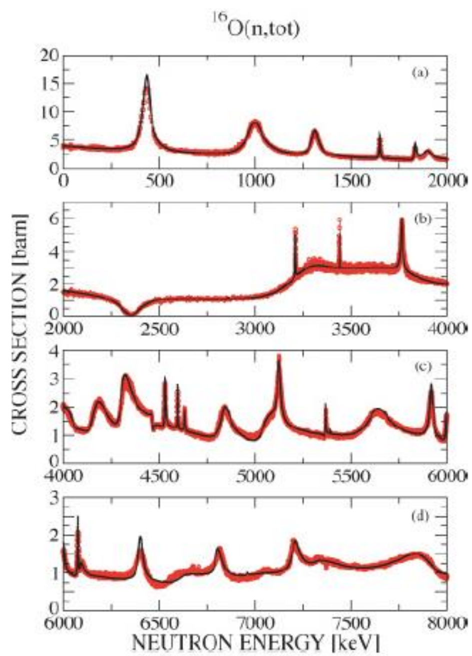
Ref.	$\tilde{C}^2$ (fm^{-1})	% unc. in S
Pellegriti *et al.* [43]	4.5(22)	50
La Cognata *et al.* [31][a]	$7.7 \pm 0.3_{stat}{}^{+1.6}_{-1.5}{}_{norm}$ 3.6±0.7	20
Guo *et al.* [44]	4.0(10)	25
Avila *et al.* [33]	3.6(7)	20
Mezhevych *et al.* [42]	5.1(15) or 4.5(14)	30
Uncertainty in DWBA fitting [29]		10
Γ_n		**5**

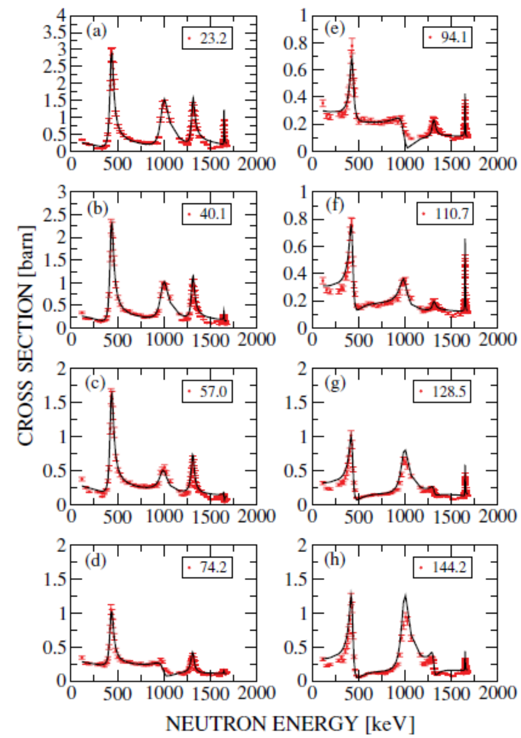
- Uncertainties of near threshold parameters propagate significant uncertainty in s-factor extrapolation
- Better estimate of systematic errors
- Normalisations to new direct data

R-matrix approach

- Multi-channel R-matrix fit
- Los Alamos National Laboratory (LANL) Energy Dependent Analysis (EDA) code
- AZURE2
- $^{13}C(\alpha,n)^{16}O$, $^{16}O(n,\alpha)^{13}C$, $^{13}O(\alpha,\alpha)^{13}C$, $^{16}O(n,tot)$, $^{16}O(n,n)^{16}O$ completed with ANC, Trojan Hourse data
- Bayesian Uncertainty analysis (BRICK)







How to handle systematic uncertainties?

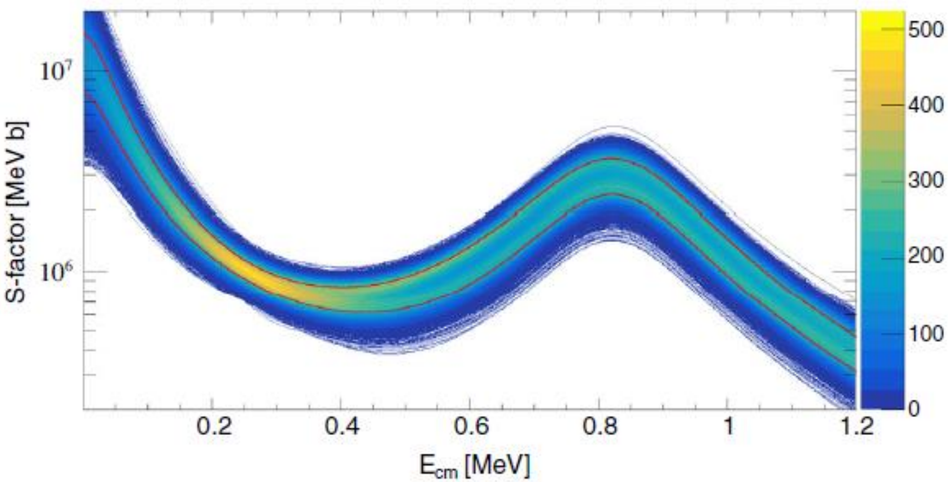


Table 4. Uncertainty budget of direct cross-section measurements of the $^{13}C(\alpha,n)^{16}O$ reaction. The tabulated values are given in % unless noted otherwise.

Data	Stat.	Sys.				E. calib.
		η_n	Target thickness	Stopping power	Beam current	
Heil *et al* [18]	0.1–92		5–40			n.d.
Bair *et al* [22]	n.d.		15–18			0.15%
Davids [51]	2.3–10.7	10[a]	n.d.	10	5	
Drotleff *et al* [29]	n.d.			n.d.		
Brune *et al* [23]						0.1%
Harrisopulos *et al* [30]	1.6[a]	1.7	3	3	2	3 keV
Ramström and Wiedling [24]		8.2				
Kellogg *et al* [28]						
Sekharan *et al* [75]		12	16		2	3 keV
Ciani *et al* [14]	2.2–18.1	8		5	3	0.1%
Gao *et al*[b] [31]	<15; 3–8[c]; 2–3[d]	7		6	5	n.d.
Febbraro *et al* [12]		Origin of uncertainties not described				
Brandenburg *et al*[e] [50]	1–7	16	4	7	1	0.2%
deBoer [32]	<10	5 and 10[f]	5	3		

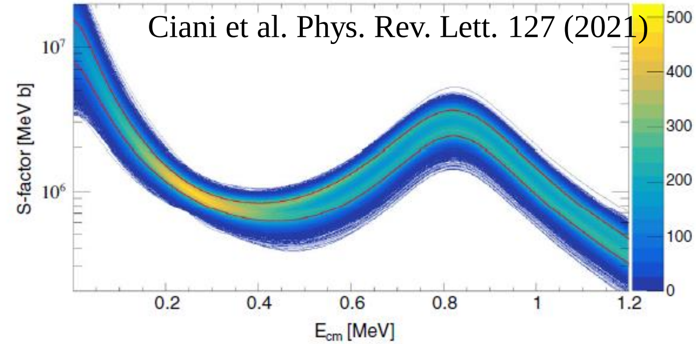
[a] At $E_\alpha = 1$ MeV.
[b] 2% and 4% implied by angular distribution.
[c] Originated from beam tuning and possible carbon build-up.
[d] Reproducibility of thin and thick target measurement.
[e] 10% and 14% implied by angular distribution in <5 MeV and >5 MeV, respectively.
[f] Intristic and MCNP/geometry efficiency, respectively.

Normalisation of different datasets:

- ND data 0.95-1.05 for different angles
- JUNA 3-8% between different datasets
- General systematic uncertainties (even energy dependent e.g. η_n)

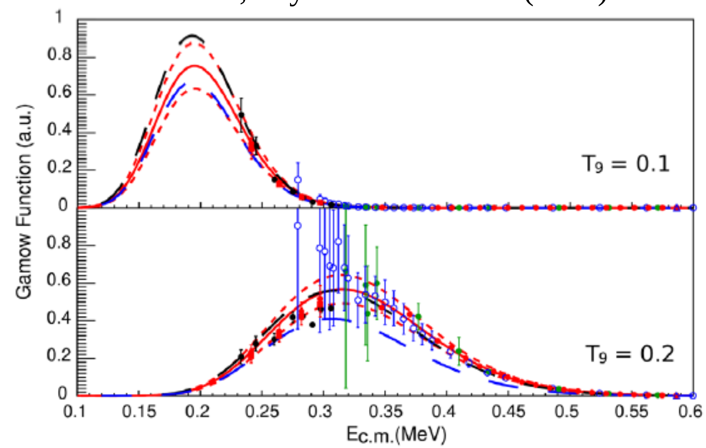
Results

- **LUNA**
  - ^{3}He 4π
  - 2 different normalisation
  - ANC and Γ_n fixed (Avila, Tilley)
  - Simple R-matrix fit
  - Data and inputs sampled with Gaussian
- **JUNA**
  - ^{3}He 4π
  - 2 different campaign
  - Independent fit together with ^{16}O+n
  - Obtained ANC and screening potential
- **ND**
  - ODeSA
  - $E_{\alpha}>0.8$ MeV
  - Angle integrated and diff. Cross section
  - LANL-EDA + ^{16}O(n,tot)
  - Different normalizations (-11% -- 14%)

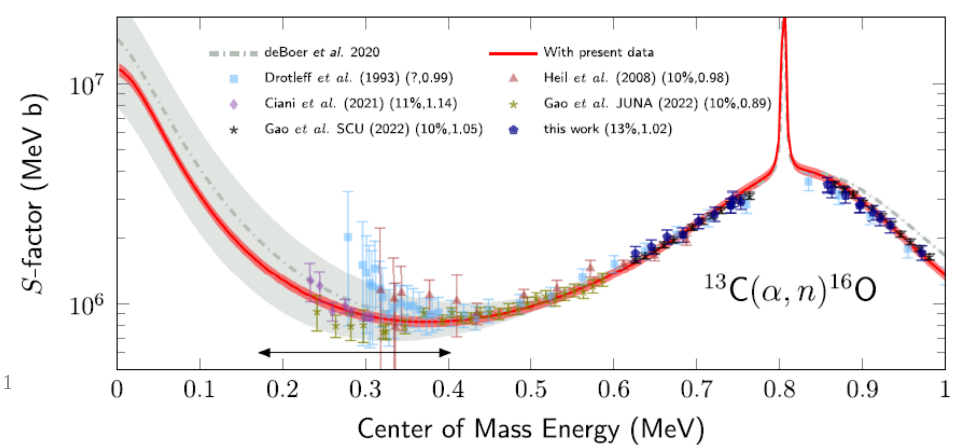


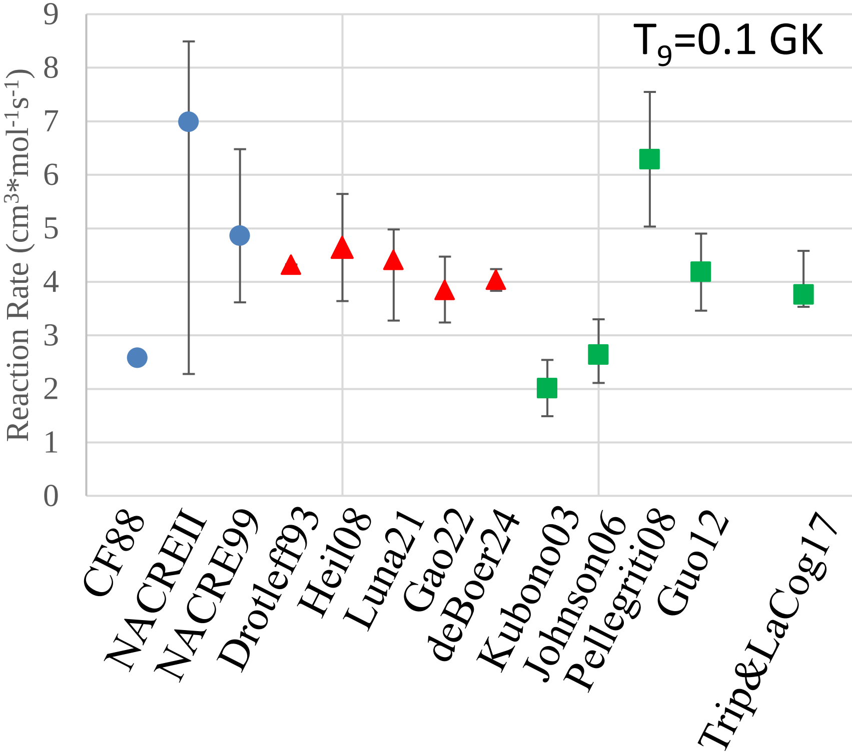
Ciani et al. Phys. Rev. Lett. 127 (2021)

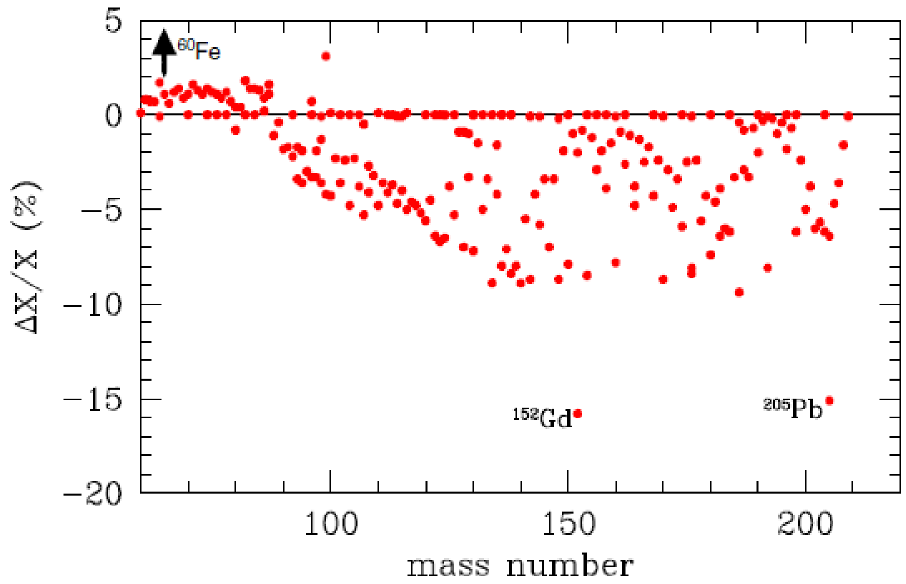
Gao et al., Phys. Rev. Lett. 129 (2022)



deBoer et al., Phys. Rev. Lett. 132 (2024)







- Recent rates suggest lower reaction rate of $^{13}C(\alpha,n)^{16}O$ in TP-AGB scenario
- FuNS code suggest ($M=2M_{\odot}$, $Z=0.02$, $Y=0.27$) more ^{13}C survives in ^{13}C-pocket and contribute to TP neutron density
- Extra neutrons in thermal pulses affects the ^{60}Fe, ^{205}Pb and ^{152}Gd abundances

Summary

- Importance of **$^{13}C(\alpha,n)^{16}O$** reaction in heavy elements nucleosynthesis, source of background in rare event experiments, help to constrain **$^{16}O(n,\alpha)$ ^{13}C**
- Sizeable variations of the **^{60}Fe, ^{152}Gd** and **^{205}Pb** yields
- More constrain on level structure and near threshold data
- Reduce systematic uncertainties
  - More passive shielding and improved PSD to limits Background
  - Neutron detection efficiency: e.g. experimental data in wider E_n, benchmarked Geant4 simulation
  - Beam effects: wobbling, beam focus to limits BIB
  - Improve target properties: impurities, cooling effect
- Global R-matrix fit with critical study of systematic uncertainties of data
- More extended set of AGB models required

Futher plans

https://doi.org/10.1016/j.nuclphysa.2025.123112
JUNA: measurements aiming to reduce background noise and improve precision at *E*c.m.=0.19 MeV to below 20% uncertainty. (Weiping Liu's talk)

Talk of deBoer on Nuclear Reaction Rates for the s-process, February 22-23 2024, Rome: **NSL-ND** ^{7}Li, ^{10}B, ^{11}B, ^{13}C, ^{19}F(α,n)

LUNA: ^{13}C(α,n)^{16}O at IBF MV accelerator (F. Ferraro's talk)

Comprehensive global **R-matrix** fit

ATOMKI: study of monoenergetic neutron sources; angular distribution E_α <0.8 MeV; and resonance parameters E_α ~ 1.05 and 1.55 MeV

Thank you for your attention!

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