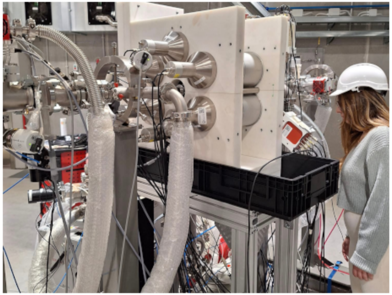
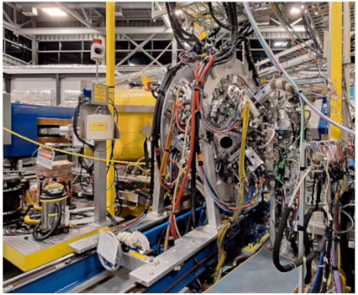
Measurements of the s process neutron sources
s, i & r Element Nucleosynthesis, Giulianova, IT



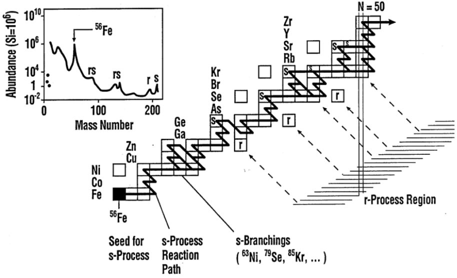


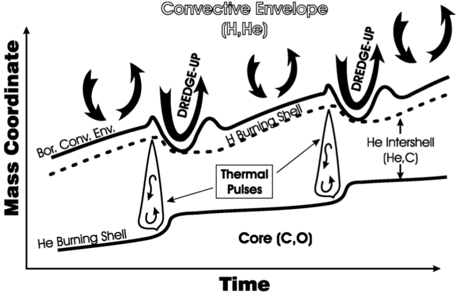
Andreas Best

INFN Naples
University of Naples "Federico II"

European Research Council
Established by the European Commission

s process

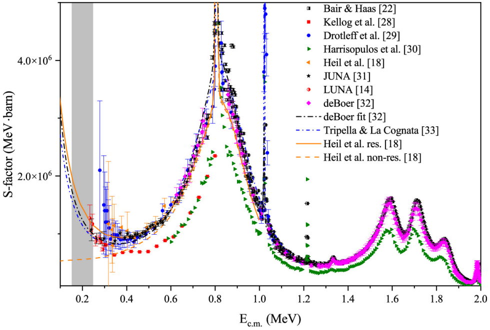


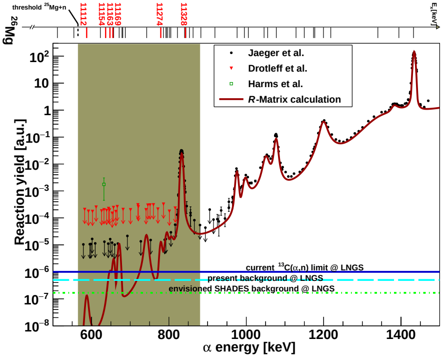


Kaeppeler et al. 2011 Straniero et al. 2006

- $\lambda_{(n,\gamma)} \ll \lambda_{\beta^-}$: nucleosynthesis follows valley of stability
- *Main s*: ^{13}C pocket in thermally pulsing AGB stars $^{13}C(\alpha, n)^{16}O$
- $^{13}C(\alpha, n)^{16}O$: T $\approx$ 90 MK, energy range 140 - 230 keV
- $^{22}Ne(\alpha, n)^{25}Mg$ late stages of main s process
- Strong, short neutron burst, T $\approx$ 250 MK: branch points
- $^{22}Ne(\alpha, n)^{25}Mg$ main source for *weak s* in massive stars: $60 < A < 90$

neutron source cross sections

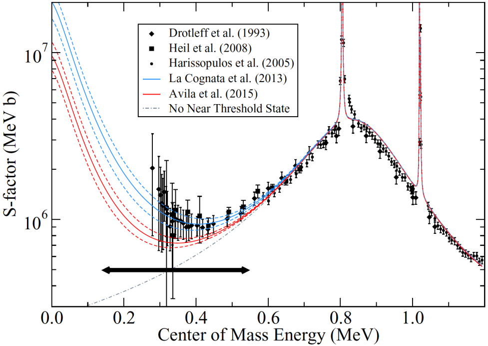


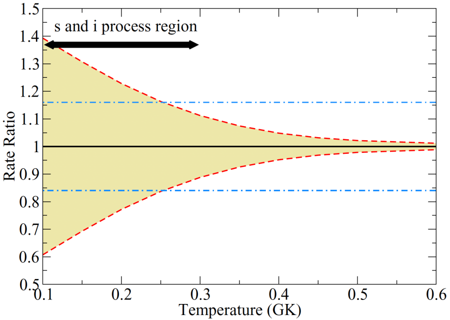


Csedreki et al. J Phys G 51 105201 (2024) R matrix courtesy of R. deBoer (JINA)

- To model s process yields, require low energy source cross sections
- ^{13}C(α, n)^{16}O: Q = 2.216 keV, “valley” between broad resonance and near threshold state
- ^{22}Ne(α, n)^{25}Mg: Q = - 478 keV, high level density, many possible resonances
- In both cases, reaction yield counts/hour or less - very difficult to measure
- Indirect infomation helps but does not provide full picture

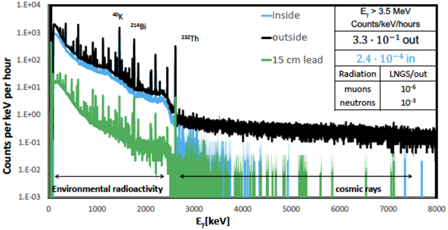
$^{13}C(\alpha,n)^{16}O$





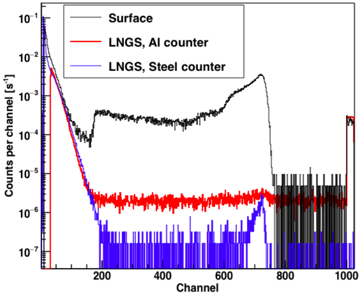
- A lot of direct measurements, inconsistent normalization
- Near threshold state - ANC, energy + n width measurements (see deBoer et al PRC 101 45802 (2020))
- Background too strong on surface to go lower in E
- Direct campaigns moved underground (LUNA, JUNA, CASPAR)
- THM data exist, but either anchored to ANC or to high E cross section

Why go underground? (it's cold, dark, wet...)



J. Phys. G: Nucl. Part. Phys. **45** (2018) 025203

- Muons major high-energy (> 3 MeV) background in γ-detection
- Cosmic muons absorbed by rock
- "Automatic" suppression by 3 o.o.m
- Below 3 MeV bg comes from rocks etc, but can build very massive shield
- 3 o.o.m. reduction achieved with lead, copper, radon box



- Atmospheric neutrons removed
- Remainder (10^{-3}): decays in environment
- Material choice now makes a difference
- Add PSD and passive shielding
- Example: $^{13}C(\alpha,n)^{16}O$ 1 bg count/hour with 18 ^{3}He counters

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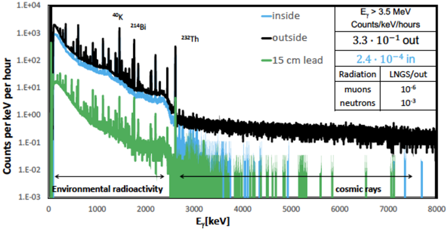

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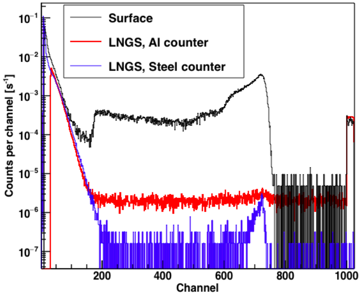

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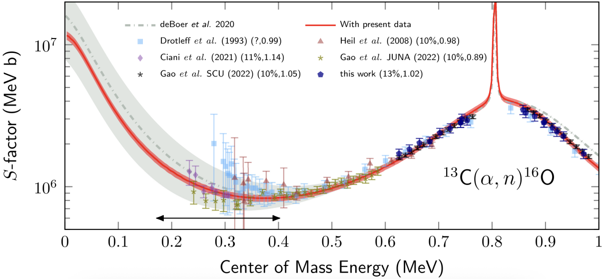
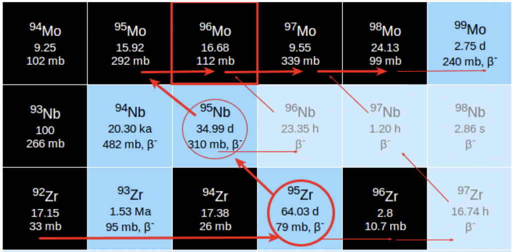
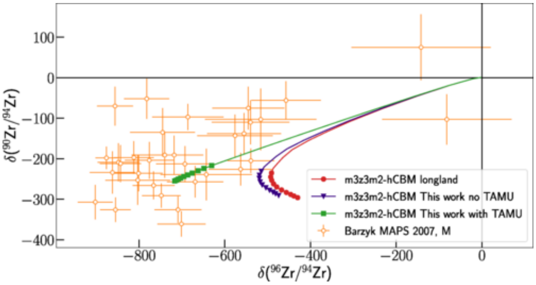
^{13}C(α,n)^{16}O "annus mirabilis"



- Ciani et al. PRL 127 (2021), 152701 LUNA
- Gao et al. PRL 129, 132701 (2022) JUNA
- de Boer et al. PRL 132, 062702 (2024) OSU ($>$ 800 keV)
- Two parallel "competing" underground campaigns
- Also higher energy campaign
- Detailed combined analysis → **now have a consistent picture for s process energies**
- Another JUNA paper in preparation, planning on releasing consensus recommended rate

$^{22}\mathrm{Ne}(\alpha, [n, \gamma])^{25,26}\mathrm{Mg}$

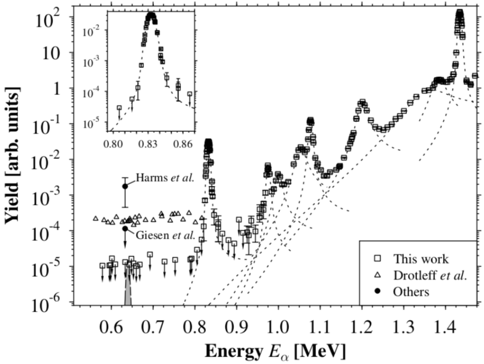


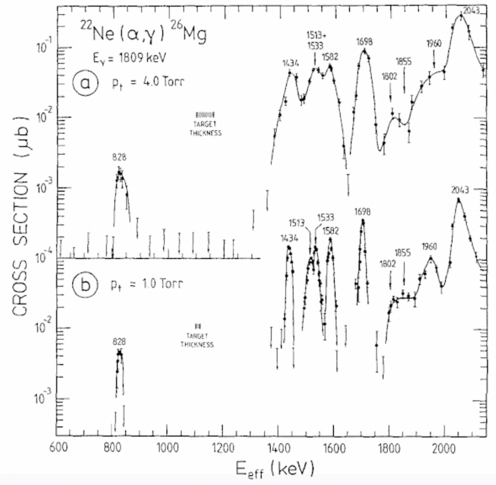


Adsley et al. PRC 103, 015805

- $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ contributes during late stages of main s process
- Determines branch point population
- Main source for weak s process
- Mg isotope observations in stellar atmospheres: γ vs. n channel
- Both channels important, both channels highly uncertain
-
  - D. Mercogliano on Thursday 9:30: γ channel
  - T. Chillery poster
  - D. Rapagnani poster / talk Friday???

State of the Art





- (α, n): Jaeger et al. 2001
- (α, γ): Wolke et al. 1989
- Some remeasurements at $E_\alpha = 835$ keV since then (Hunt et al. 2019, Shahina et al. x2 (2022/24))

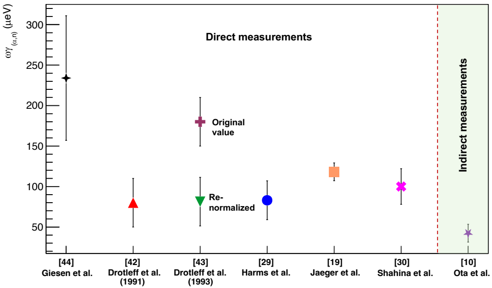
Low-energy states

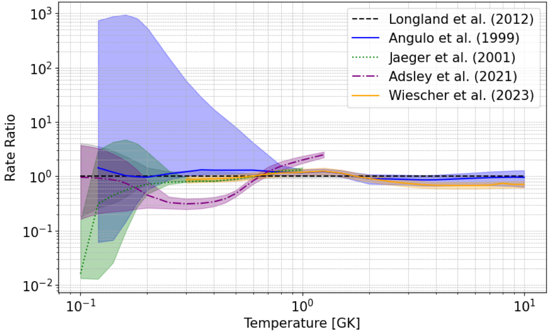
Table 1. Properties of states in ^{26}Mg between the neutron threshold and the 832 keV resonance. Values taken from [15], except for the last row, which is from [14].

E_n [keV]	E_x [keV]	E_α [keV]	Jπ	Neutron width [eV]
19.92	11112	589	2+	2095
72.82	11163	649	2+	5310
79.23	11169	656	3-	1940
187.95	11274	779	2+	410
194.01	11280	786	3-	1810
243.98	11328	843 ?	?	171
235 [14]	11319	832	2+	Total width = 250 eV

- nTOF study of energies and neutron widths (Massimi et al. PLB 768 (2017), 1)
- 835 keV res still a bit unclear w.r.t. n/α channel, energy
- No α widths are known
- Many other indirect data campaigns, not conclusive

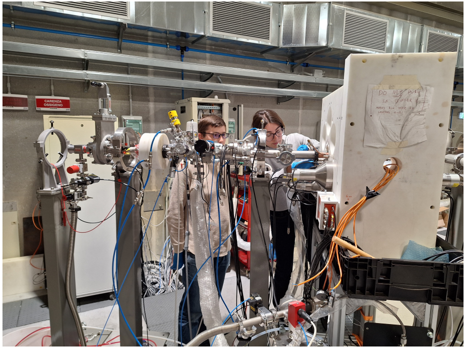
Recent progress

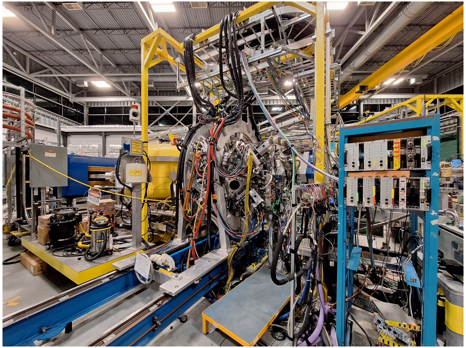




- Bunch of nuclear transfer/scattering experiments
- Comprehensive synthesis in Longland et al. 2012
- Measurements Adsley et al., Talwar et al. Jaytissa et al.. . . .
- Situation summarized in Adsley et al. 103, 015805 (2021)
- Updated in Wiescher et al. EPJ A (2023) 59:11
- Updated again + outlook in Best et al. EPJ A (2025) 61:99

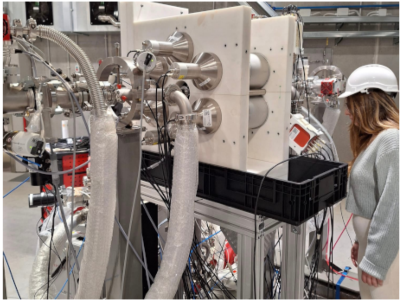
Local efforts

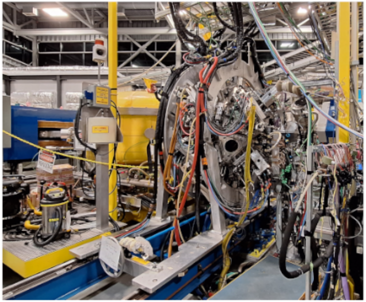




- ^{22}Ne$(\alpha, n)^{25}$M: SHADES ERC project @ LNGS to close this year: D. Mercogliano
- ^{22}Ne$(\alpha, \gamma)^{26}$Mg: EASγ MUR project @ LNGS to start next year: D. Vagnoni
- ^{22}Ne$(^{7}$Li, t$)^{26}$Mg: S2223 TRIUMF w. EMMA-TIGRESS 12/2024: T. Chillery

Summary





- ^{13}C(α,n)^{16}O: worldwide effort has pushed data to a good spot
- ^{22}Ne(α, [n, γ])^{25,26}Mg
  - Steady influx of indirect data, need some direct input
  - Push direct cross section into Gamow energy with SHADES/EASγ
  - LUNA campaign ongoing, sensitivity now **surpasses Jaeger et al.**
  - CASPAR measurement of 835 keV res. done, some systematic problems
  - JUNA direct UG campaign in preparation
  - Indirect recently at TRIUMF (EMMA-TIGRESS), planned at Texas A&M and more