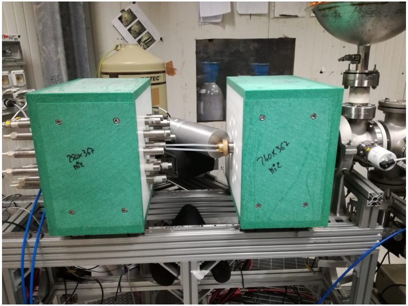
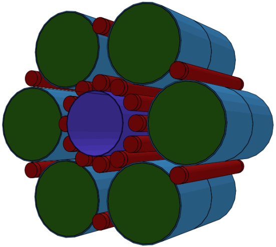
Measurements of s process neutron source cross sections





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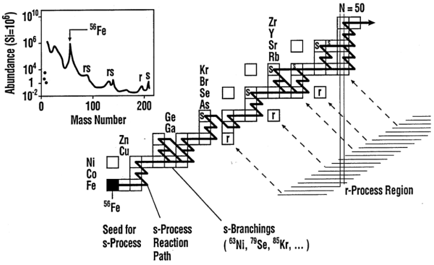
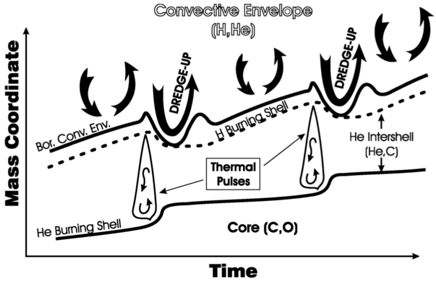
Main s process

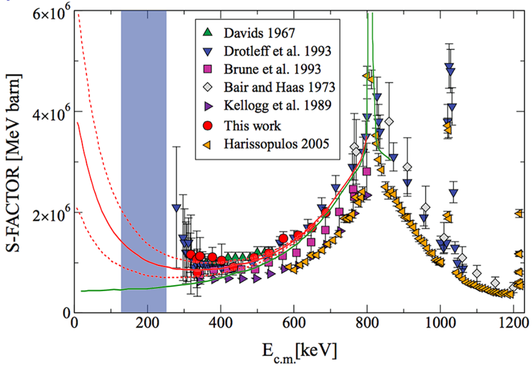




Kaeppeler et al. 2011 Straniero et al. 2006

- $\lambda_{(n,\gamma)} \ll \lambda_{\beta^-}$: nucleosynthesis follows valley of stability
- Takes place in "^{13}C pocket" in thermally pulsing AGB stars
- ^{13}C(α, n)^{16}O main neutron sources for s process
- ^{13}C(α, n)^{16}O: T $\approx$ 90 MK, energy range 140 - 230 keV
- Also possible neutron source for i-process ($\sim$ 280 MK, 285 - 510 keV)
- ^{22}Ne$(\alpha, n)^{25}$Mg small contribution during late stages of main s process

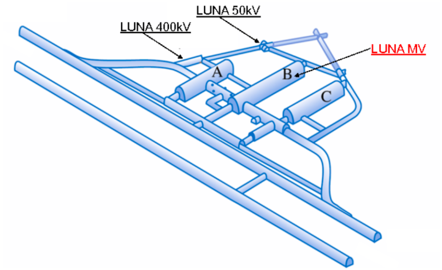
$^{13}C(\alpha, n)^{16}O$ state of the art

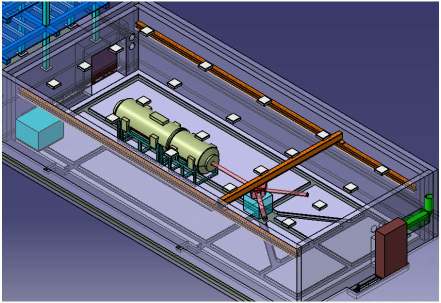


Heil et al. 2008

- Heil et al.: down to 317 keV, large uncertainties below 400 keV
- Drotleff et al.: $E_{cm,min} = 279$ keV, large uncertainties below 350 keV
- Environmental background
  - Heil 340 counts/hour
  - Drotleff 290 counts/hour
- At higher energies strong differences in normalization
- Trojan horse data anchor to ANC/high-energy c.s.

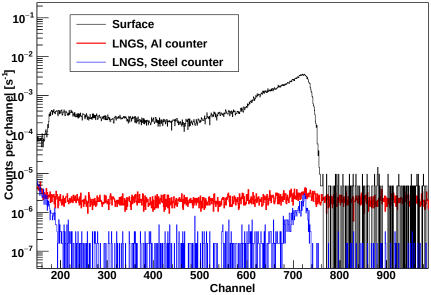
LUNA / MV campaigns

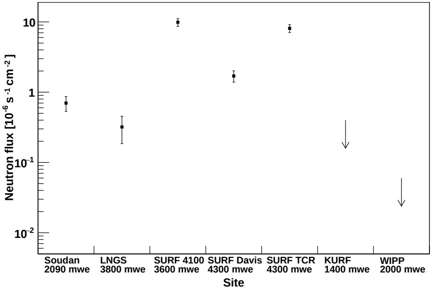




- Can cover 50 - 3500 keV with two accelerators
- Same setup(s) for both campaigns, energy overlap 350 - 400 keV
- Opportunity to calibrate using more reactions at higher energies
- p/α beam currents order of hundreds of μA

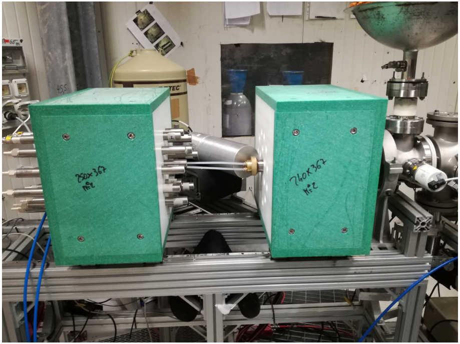
Advantages of going underground





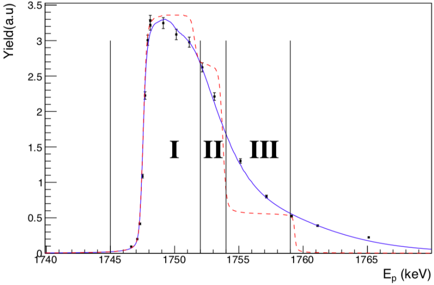
- Direct low-energy measurements limited by natural background
- LNGS ≈ 3400 m.w.e. underneath Gran Sasso mountain chain
- Cosmic-ray induced neutrons efficiently shielded against
- Residual flux from (α, n) and fission in rocks
- Neutron flux underground suppressed by ≈ 1000 w.r.t. surface

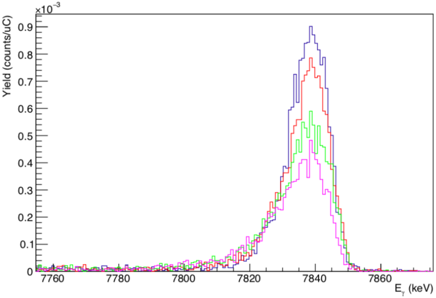
Setup - Detector



- 6 × 25 cm, 12 × 40 cm long, 10 bar ^{3}He counters in polyethyelene
- Efficiency ≈ 30% (^{51}V(p,n)^{51}Cr, AmBe)
- 2" 5% borated PE shielding
- 1-2 counts/hour total (internal+external) background
- Csedreki et al. NIM A A 994 (2021) 165081

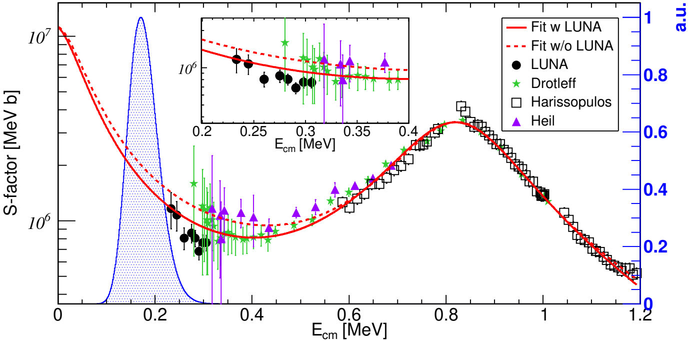
Measurement strategy





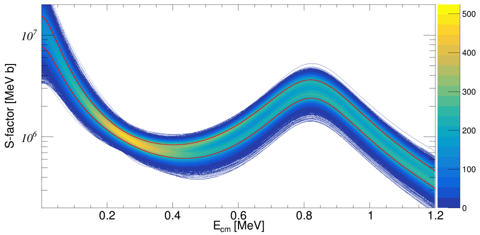
- Solid target (99 % ^{13}C on Ta) $\rightarrow$ degradation under beam
- Normally, use resonance yield profile to monitor target
- No ^{13}C resonances in LUNA 400 energy range!
- Switch to H^+ beam, measure ^{13}C(p,γ) gamma ray shape
- Ciani et al., EPJ A 56 (2020), 75

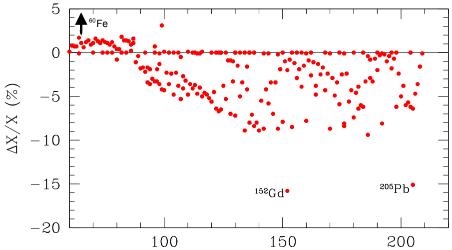
Results



- Covered 235 - 300 keV, 50 keV lower than before
- $\approx$ 100 C for lowest point
- Problem remains connection to different normalizations
- Ciani et al. PRL 127, 152701 (2021)

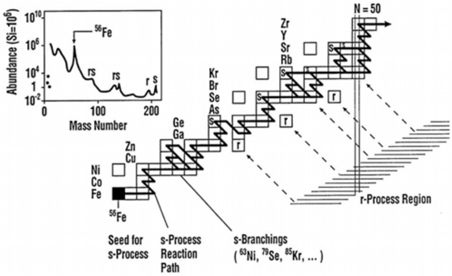
R matrix + astro

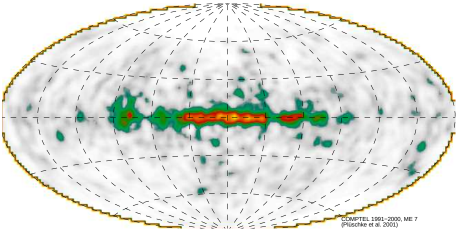




- Adopted two normalizations: Harissopulos, Drotleff&Heil
- LUNA data kept fixed, others rescaled
- MC R matrix fits for each set for combined reaction rate PDF
- Lower limit used to test maximal impact on stellar output

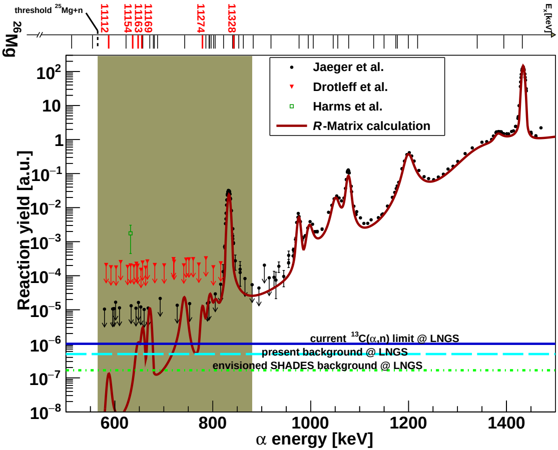
$^{22}Ne(\alpha, n)^{25}Mg$ physics case: production of the heavy elements, and more





- Residual elemental abundances attributed to other n-processes
  $N_r = N_{\odot} - N_s$
- Formation of early solar system - cosmic grains in meteorites
- Astronomical observation of gamma-rays (COMPTEL, INTEGRAL)
- Mg isotope observations in stellar atmospheres

$^{22}Ne(\alpha, n)^{25}Mg$ cross section



R matrix courtesy of R. J. deBoer, University of Notre Dame/JINA

- Capabilities on surface exhausted (20 years since last data)
- Current lowest data 2 reactions/minute
- Covers one resonance close to Gamow
- 300 keV of upper limits. . .
- Many states that can contribute
- Need improvement by more than 2 orders of magnitude

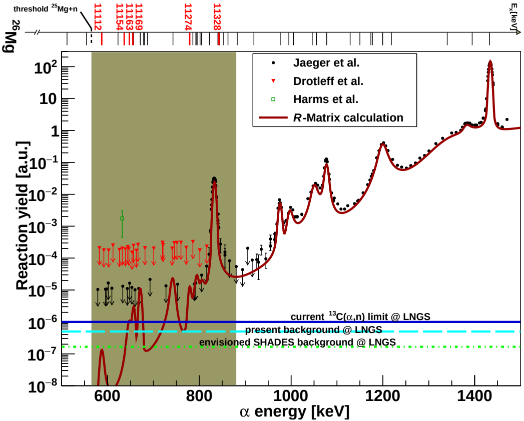
Low-energy states

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

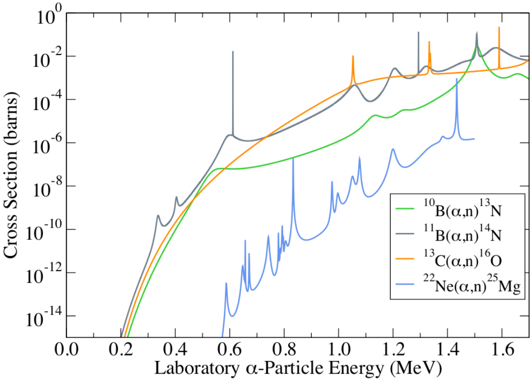
- Recent nTOF study of energies and neutron widths (Massimi et al. PLB 768 (2017), 1)
- 832 keV state still a bit unclear w.r.t. n/α channel, energy
- No α widths are known

What to do?



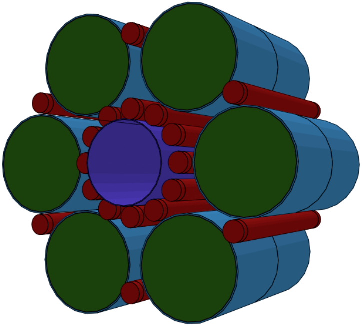
- Drastic background reduction
- Large beam current increase
- Suppression/identification of beam-induced background

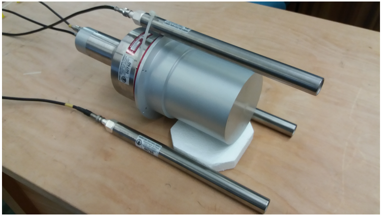
Beam-induced backgrounds



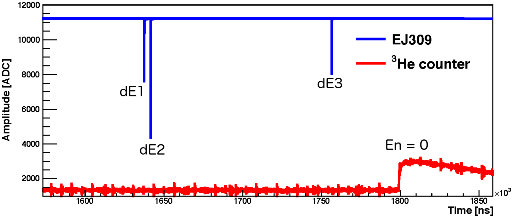
- Q-values:
  - ^{22}Ne = - 478 keV
  - ^{10}B = 1059 keV
  - ^{11}B = 158 keV
  - ^{13}C = 2216 keV

Detector array

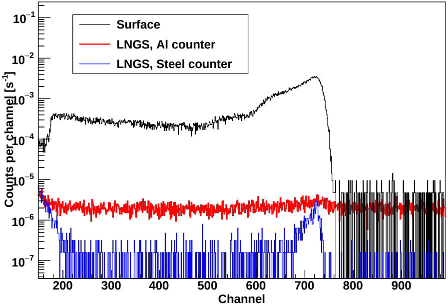


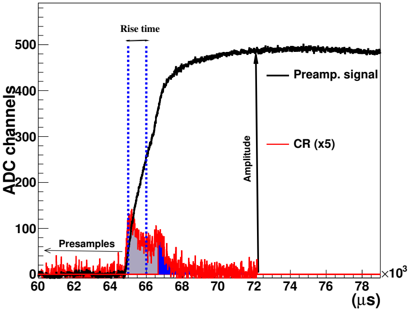


- Need to measure very low event rates
- Require some sort of energy sensitivity
- Hybrid detector array: ^{3}He counters & liquid scintillator
- High efficiency + energy sensitive
- Prototype built & tested



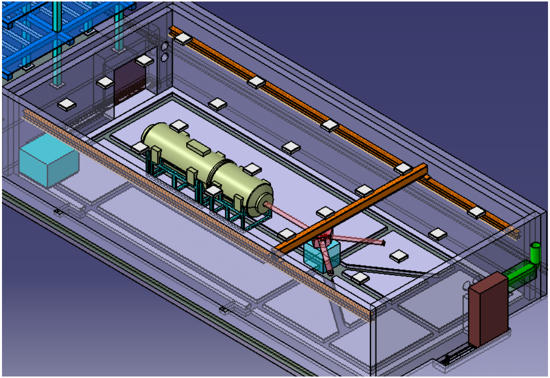
Background reduction





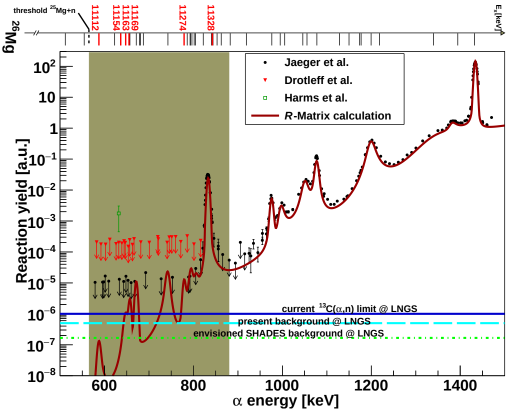
- Deep underground @ LNGS: Suppression of (thermal) neutron background by > 1000
- Additional clean detector material & PSD
- Extended gas target with enriched ^{22}Ne
- Coincidence/Anticoincidence
- Total background < 1 count/hour

Top-of-the-line accelerator



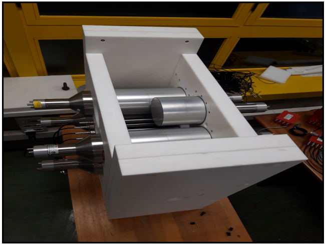
- Specifically designed to fit nuclear astrophysics needs
- Reaction rates of $< 1/\text{hour}$:
  - Beam current ($\approx 5\times$ Jaeger et al.): push signal-noise ratio
  - Current stability: measurements of the order of weeks
  - Energy stability: must not drift over long periods
- 300 - 3500 kV: cover entire astrophysical energy range

Goals



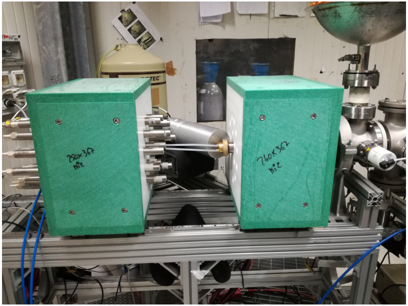
- Cover from threshold to 3.5 MeV
- $>$ two orders of magnitude improvement
- Comprehensive *R* matrix analysis
- Perform nucleosynthesis calculations with new data

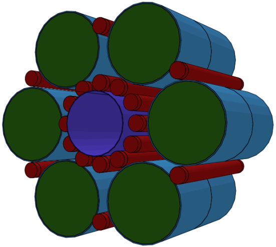
Status



- 5(+1)-year, since February 2020
  - Target+detector assembled
  - Target characterisation at CIRCE
  - Detector background investigated
  - DAQ development underway
  - Detector characterisation at FRANZ
- Assembly at LNGS end of year
- Underground campaign at LUNA MV
- Data evaluation and astrophysical impact - collaboration with M. Pignatari/Budapest

Summary





- Good times for s process
- $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$
  - Wealth of new data, low-E, high-E
  - Global R matrix analysis in planning
- $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$
  - Steady influx of indirect data
  - Push direct cross section towards Gamow energy with SHADES

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