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Stellar nucleosynthesis in the laboratory: LUNA results and perspectives

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LUNA

INFN

UNIVERSITÀ DI PADOVA

A long time ago…

Laboratories for **U**nderground **N**uclear **A**strophysics

1994 — LUNA 50

2001 — LUNA 400

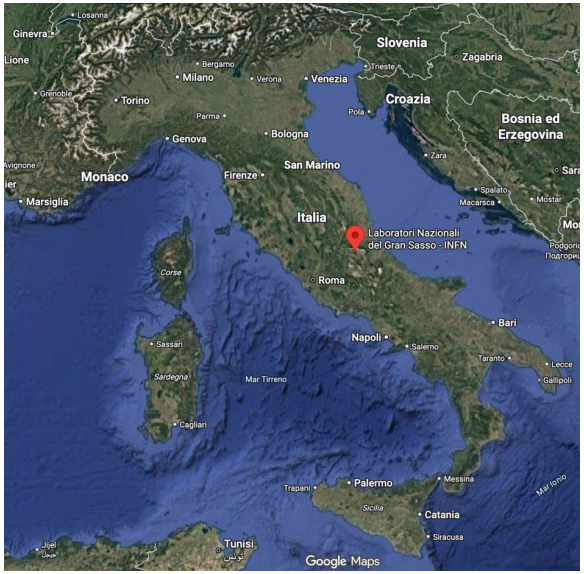
2003 — LUNA 50 (ended)

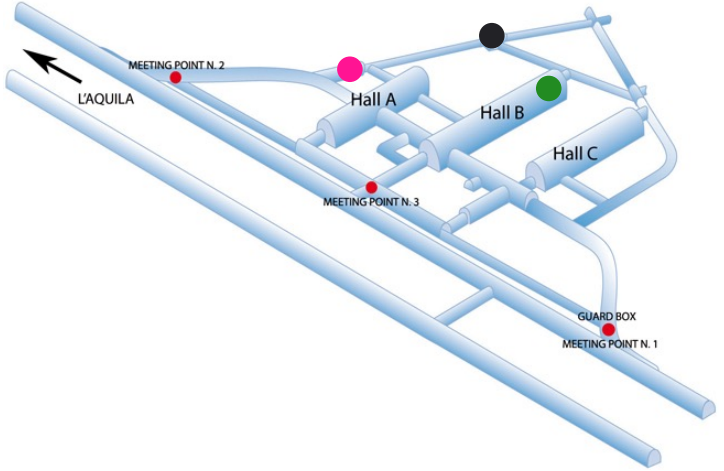
2022 — Bellotti IBF (LUNA MV)

2026 — LUNANOVA



Virtual tour

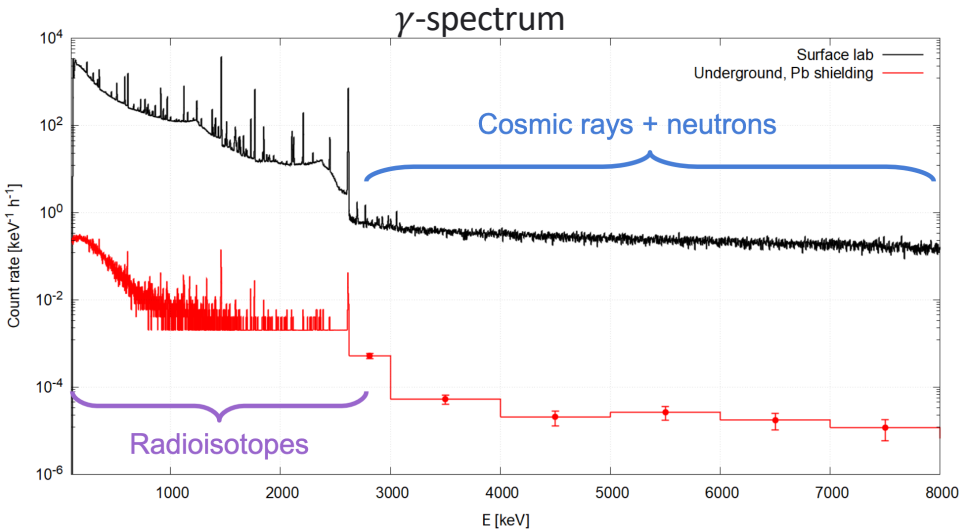




Why underground?

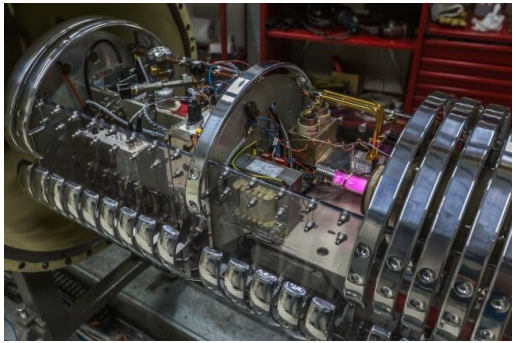
- Environmental γ background due to:
  - Environmental radioactivity from the decay chains of ^{235,238}U, ^{232}Th and ^{40}K
  - Cosmic rays (muons)
  - Neutrons from spallation and (α,n) reactions

- Component < 3 MeV suppressed with passive shielding (e.g. Pb/Cu)

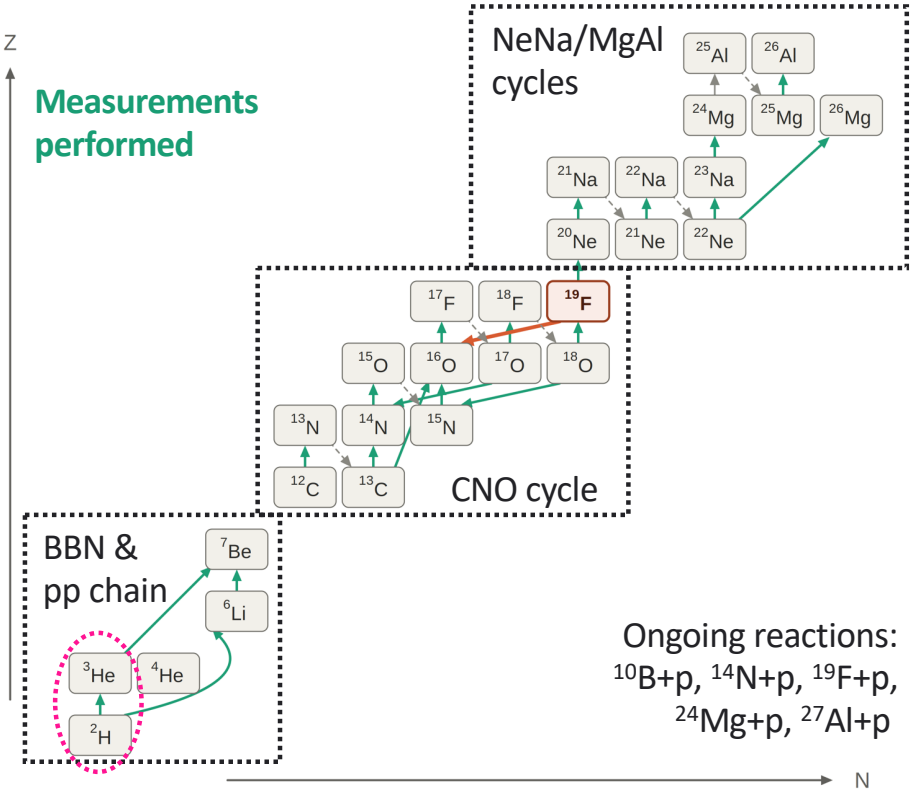


LUNA 400

- Extremely stable ^{1}H and ^{4}He beams (< 5 eV/h) with I < 500 μA and spread < 100 eV
- Targets: windowless gas (historical, decommissioned) and solid
- Production/analysis: LNL (magnetron-sputtering+RBS), HZDR (NRRA+ERDA) and ATOMKI (evaporation+NRRA)
- Detectors: HPGe, 6xBGO 4π and Si-array for the α channel



- ^{2}H(p,γ)^{3}He role in the destruction of primordial ^{2}H
- Observations report ^{2}H/^{1}H with 1% uncertainty $\longrightarrow \Omega_b h^2$ 2.7% uncertainty (cf. CMB uncertainty 0.9%)
- Cross-section measured to 3% in the 30-300 keV range with a $^{2}H_2$ gas target $\longrightarrow \Omega_b h^2$ 1.6% uncertainty



Mossa, V., Stöckel, K., Cavanna, F. *et al.*
The baryon density of the Universe from an improved rate of deuterium burning
Nature **587**, 210–213 (2020).

Bellotti IBF

- ^{1}H, ^{4}He and ^{12}C beams with intensity < 1000 μA and spread < 100 eV, TV between 0.2-3.5 MV
- Targets: windowless gas and solid
- Detectors: HPGe and NaI (Si-array in the future)

- Measurement goals:

^{22}Ne(α,n) and ^{22}Ne(α,γ)	s-process
^{12}C(^{12}C,p)^{23}Na and ^{12}C(^{12}C,α)^{20}Ne	C-burning
^{12}C(α,γ)^{16}O	C/O ratio

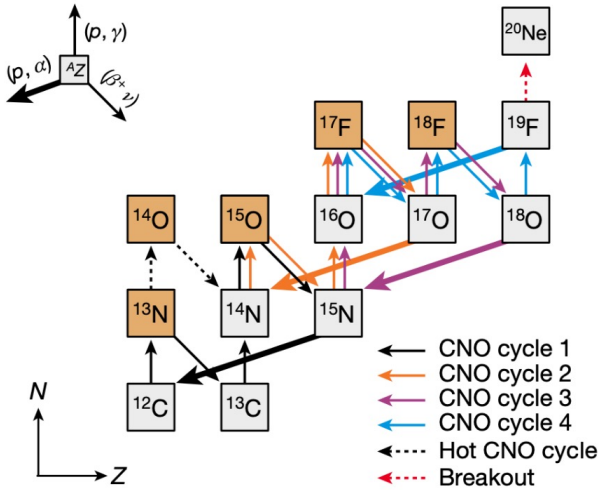
- ^{12}C+^{12}C determines M_{up} $\longrightarrow$ WD vs CCSN?
- Measured in the 2.1-3.5 MeV range with solid targets (1 mm thick ZXF graphite)

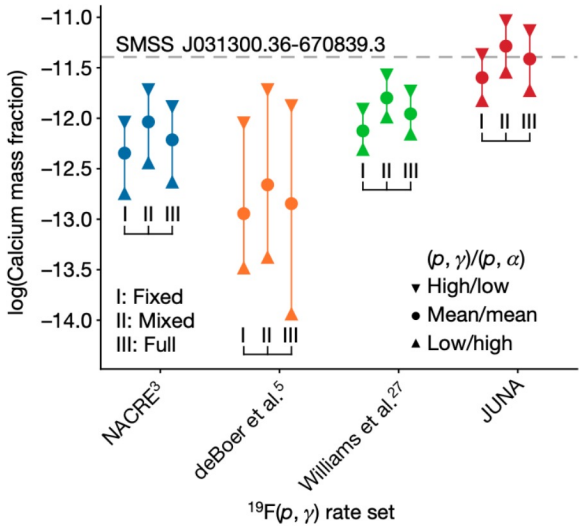
…and other (α,γ) reactions of astrophysical interest

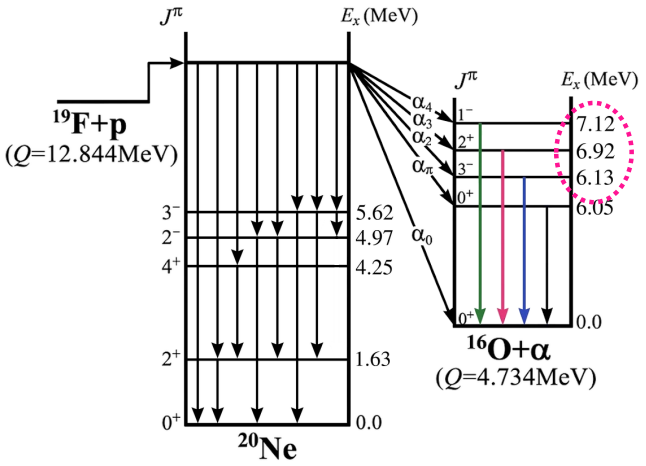


Astrophysical motivation and state of the art

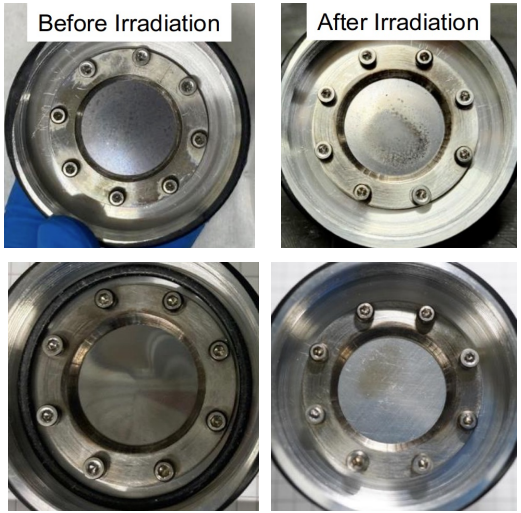
- The $^{19}F(p,\alpha\gamma)^{16}O$ and $^{19}F(p,\gamma)^{20}Ne$ reactions sit at a crucial branching point between the CNO and NeNa cycles
- They are believed to explain the ^{40}Ca abundance observed in metal-poor stars
- Zhang et al. (2022) observed an enhancement of the $^{19}F(p,\gamma)^{20}Ne$ cross section
- No other literature data are available below 300 keV



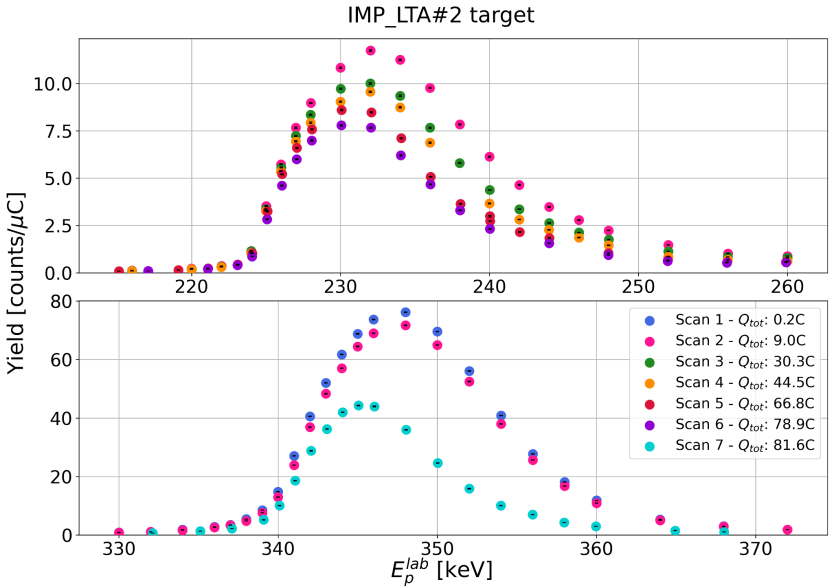




Targets & Yield Recovery



- Evaporated: CaF_2 with Ta and W backing
- Implanted: ^{19}F with Ta and Fe backing
- Fluorinated: TaF_5 with Ta backing



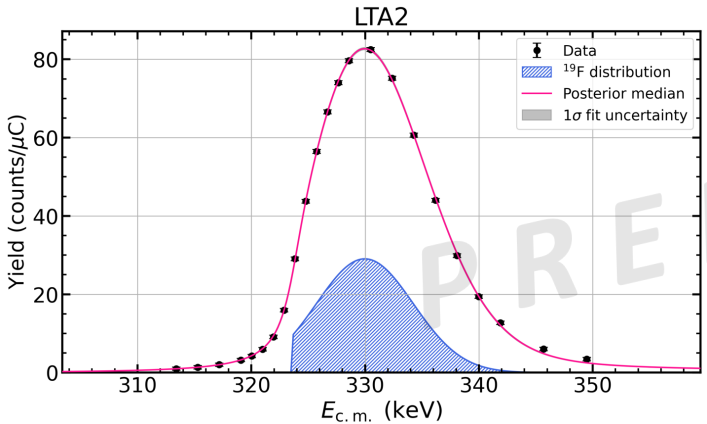
- Nuclear Resonant Reaction Analysis technique
- 6.130 MeV emission due to the de-excitation of ^{16}O
- The experimental procedure alternates scans (recover target status, resonance strengths $\omega\gamma$ and energies E_r) and long runs (recover branching ratios and cross-section)

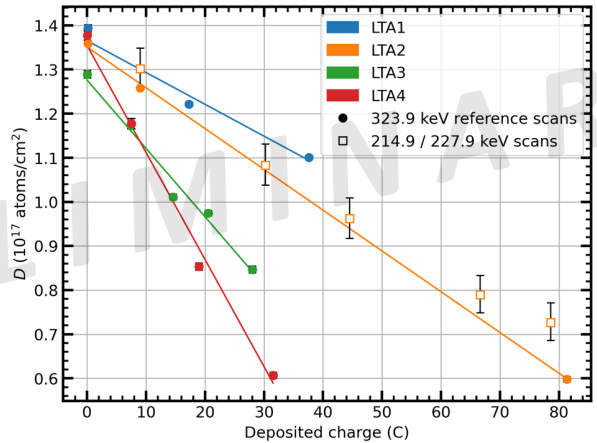
Results – Degradation profile

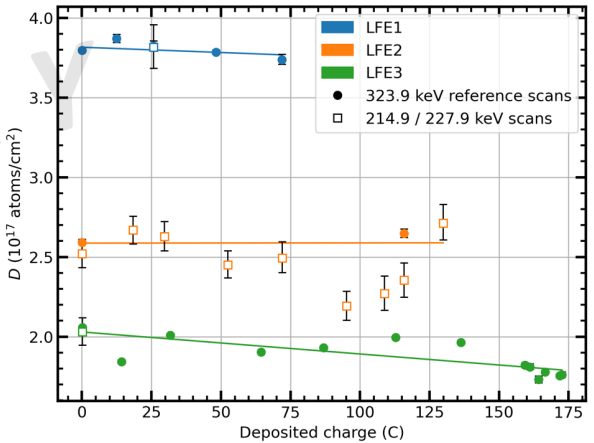
- The model accounts for the ^{19}F distribution in the target $P(E)$ and for the beam straggling $G\left(E', E, s(E)\right)$:

$$Y(E_0) = \int_{E_0-\Delta E}^{E_0} P(E) \left(\int_{-\infty}^{+\infty} \frac{\sigma(E')}{\varepsilon_{\text{eff}}(E')} G\left(E', E, s(E)\right) dE' \right) dE$$

- $\varepsilon_{\text{eff}}(E) = \varepsilon_F(E) + S \cdot \varepsilon_b(E) \longrightarrow S = n_b/n_F$ is the stoichiometry
- Scans @340 keV: $\boldsymbol{\theta_{340}} = \{\boldsymbol{\mu}, \boldsymbol{\sigma}, \boldsymbol{S}\} \longrightarrow D(Q) = \int \frac{P(\mu,\sigma;E)}{\varepsilon_{\text{eff}}(S;E)} dE \propto {}^{19}F$ atoms/cm^2
- LM algorithm (least squares) + MCMC



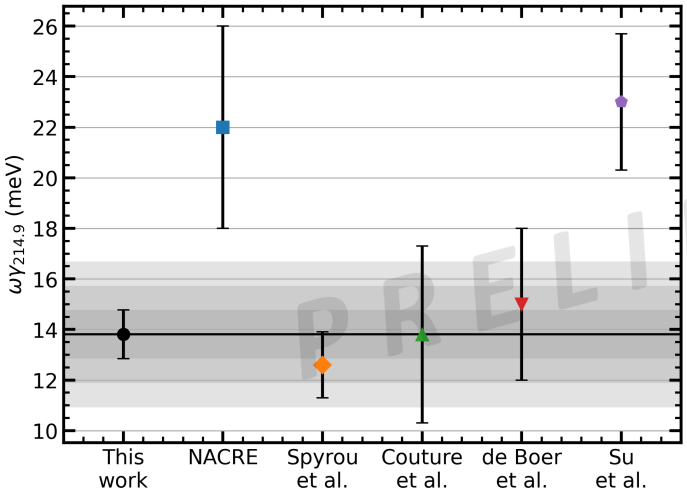


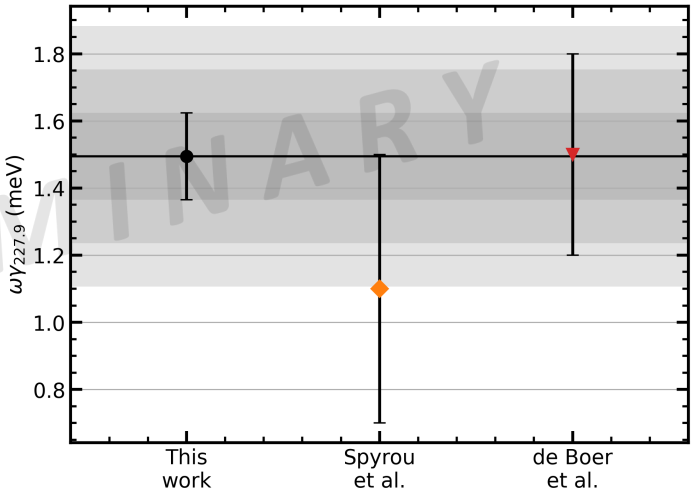


PRELIMINARY

Results – ωγ

- Scans @240 keV: $\{\mu, \sigma\}$ transformed $\theta_{340} \cdot \mathcal{E}_{\text{eff}}^{240}/\mathcal{E}_{\text{eff}}^{340} \longrightarrow \boldsymbol{\theta_{240}} = \{\boldsymbol{\omega\gamma_{225}}, \boldsymbol{\omega\gamma_{240}}, \boldsymbol{E_{225}}, \boldsymbol{E_{240}}\}$





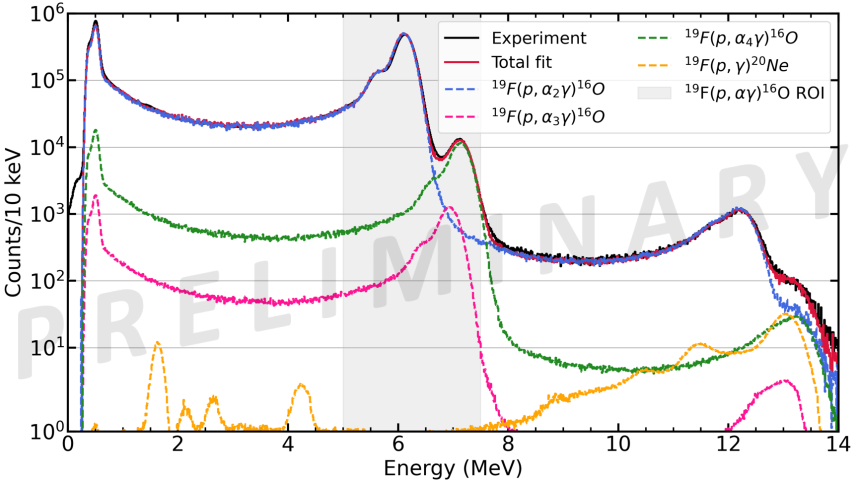
PRELIMINARY

$\omega\gamma_{225} = 13.8 \pm 1.1$ meV
$\omega\gamma_{240} = 1.5 \pm 0.2$ meV

$E_{225} = 213.6 \pm 0.1$ keV
$E_{240} = 226.8 \pm 0.2$ keV
$E_{340} = 324.0 \pm 0.1$ keV

Results – Branching Ratios

- Main ingredient: Geant4 (SimLUNA) simulations of the $\alpha_2/\alpha_3/\alpha_4$ cascades (6.13, 6.92, 7.12 MeV) accounting for the setup geometry and backing
- Simulated events folded with the measured response of each run: crystal resolution, thresholds, DAQ pile-up
- Fit of the sum spectrum simultaneously for multiplicities M = 1, 2, ≥ 3 (with non-negative amplitudes for $\alpha_2/\alpha_3/\alpha_4$ and $^{14}N(p,\gamma)^{15}O$ where present)
- BR(α_2) dominates overall (>97%) while BR(α_3) changes slightly and BR(α_4) increases with energy
- Croft et al. (1991, via HPGe) reports at the 323.9 keV resonance BR = (97.01, 0.33, 2.66)%



$E_r^{\mathrm{c.m.}}$ (keV)	B_{α_2}	B_{α_3}	B_{α_4}
214.9	99.39 ± 0.03	0.53 ± 0.04	0.08 ± 0.01
323.9	97.21 ± 0.06	0.39 ± 0.06	2.38 ± 0.02

Results – Non-resonant S-factor

- The S-factor removes the $1/E$ term and the Coulomb-barrier tunnelling probability:

$$S(E) = \sigma(E) \cdot E \cdot \exp[2\pi\eta(E)] \qquad \eta \approx 275/\sqrt{E}$$

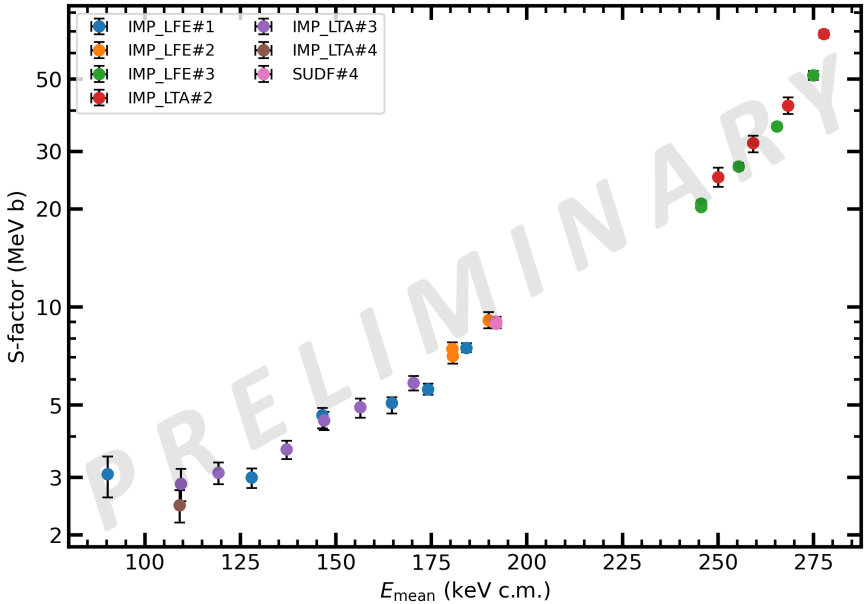
- The beam slows down in the target so each run measures the $\sigma(E)$ averaged over it

- Mean-energy approach (Lemut et al., 2008):

$$\sigma_{\text{eff}} = \frac{Y}{N_F} \propto \frac{\#\text{ reactions}}{\#\text{ projectiles} \cdot \#^{19}\text{F atoms in the target}}$$

$$E_{mean} = \frac{\int E \cdot \sigma_{th}(E) \cdot N_F \, dE}{\int \sigma_{th}(E) \cdot N_F \, dE}$$

$$S(E_{mean}) = \sigma_{\text{eff}} \cdot E_{mean} \cdot \exp[2\pi\eta(E_{mean})]$$



THE FUTURE

LUNANOVA

What it is

- ERC Synergy Grant: ***L****aboratory* ***U****nderground for* ***N****uclear* ***A****strophysics –* ***N****ew* ***O****bser****va****tory for Solar Neutrino Reactions*
- Collaboration of HZDR, INFN, UniNa and ICE-CSIC
- €14M over 6 years

CSIC Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

INFN Istituto Nazionale di Fisica Nucleare

Main goal

Solar models have larger uncertainties than the experimental data

The $\nu(^8B)$ flux is measured to $\pm 1.9\%$ but predicted to $\pm 13\%$

We measure solar neutrinos better than we can predict them!

The dominant uncertainty in the prediction is nuclear

Mission

New 600 kV underground accelerator at LNGS (p and α beams)

Reactions of interest:
$^{14}N(p,\gamma)^{15}O$
$^{3}He(\alpha,\gamma)^{7}Be$
$^{7}Be(p,\gamma)^{8}B$

Cross-section precision ~2%

LUNANOVA

THANK YOU FOR YOUR ATTENTION!

INFN/GSSI
T. Chillery, D. Basak, F. Ferraro, M. Junker, G.F. Ciani, P. Corvisiero, P. Prati, M. Rossi, S. Zavatarelli, M. Campostrini, V. Rigato, R. Depalo, G. Gosta, A. Guglielmetti, A. Best, D. Dell'Aquila, A. Di Leva, G. Imbriani, S. Montella, D. Rapagnani, R. Biasissi, C. Broggini, A. Caciolli, R. Menegazzo, D. Piatti, J. Skowronski, S. Turkat, A. Formicola, C. Gustavino, R. Parakash Yadav, M. Vagnoni, O. Straniero, U. Battino, F. Cavanna, P. Colombetti, G. Gervino, R. Gesuè, G. Saturno

University of Edinburgh
M. Aliotta, L. Barbieri, C.G. Bruno, R. Bonnell, A. Compagnucci, T. Davinson, L. Dalla Vedova, J. Marsh

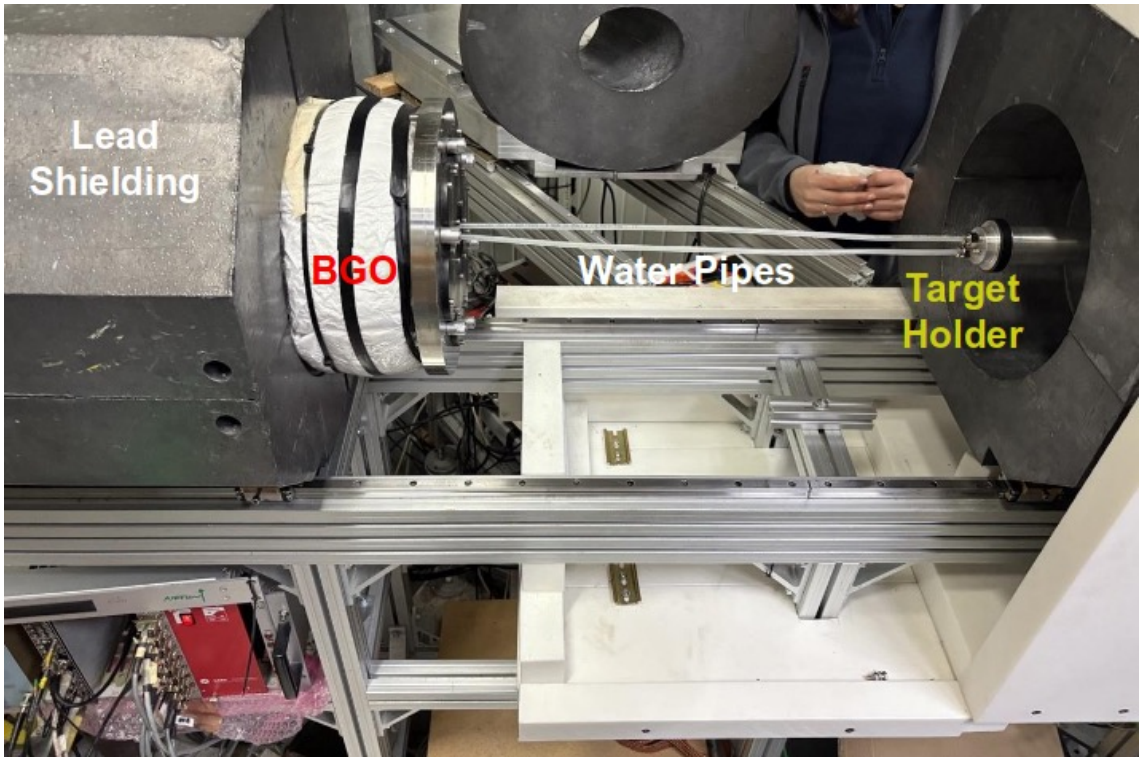
HUN-REN ATOMKI
M. Lugaro, L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs

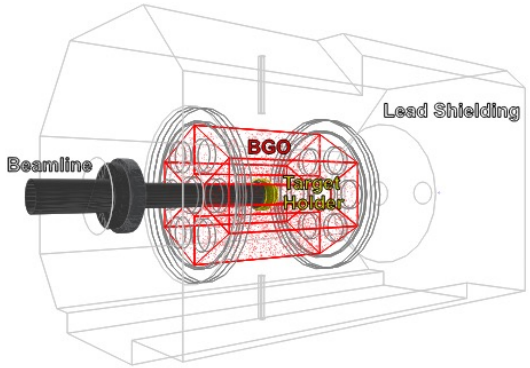
HZDR
D. Bemmerer, A. Boeltzig, M. Lukyanova, E. Masha



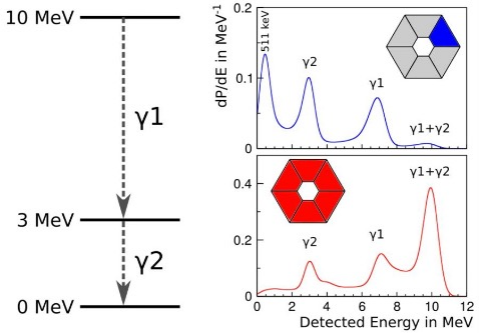
Backup

LUNA 400 setup for the $^{19}F(p,\alpha\gamma)^{16}O$ reaction





Total Absorption Spectroscopy

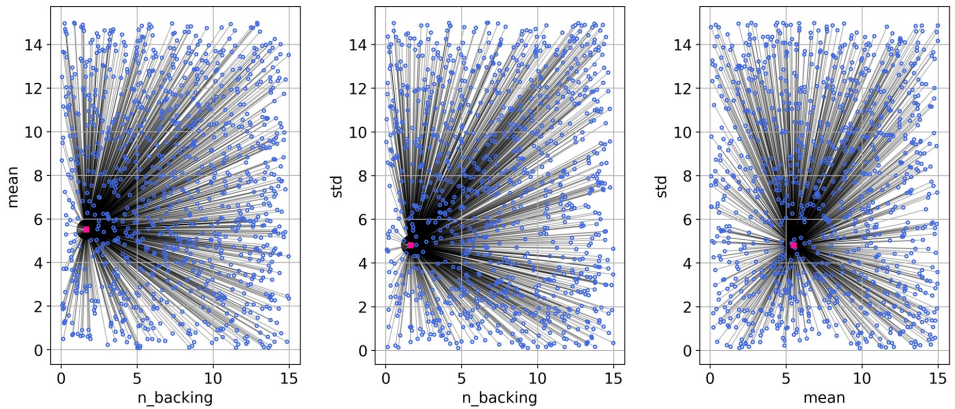


Convergence Sanity Check @340keV

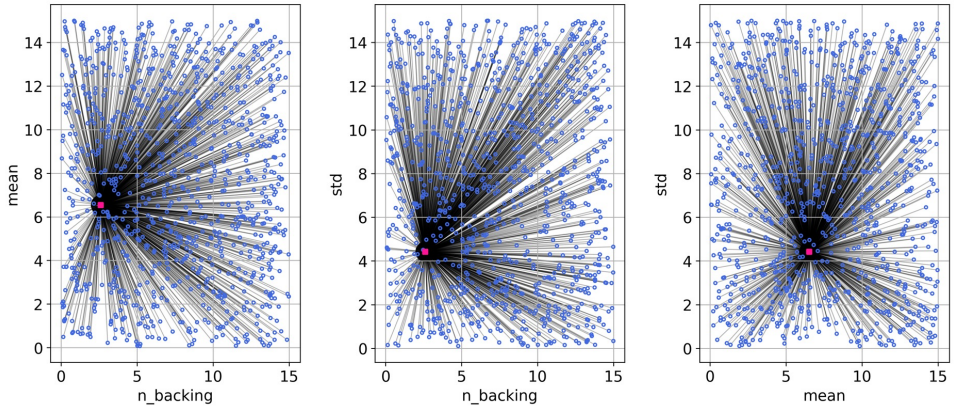
- How can we be sure that our initial guesses converges to the “correct” values?

- MC to generate random triplets and verify that:
  - All triplets converge
  - All triplets converge to the same triplet

IMP_LFE#2 Scan 1 – 1000 random initial guesses



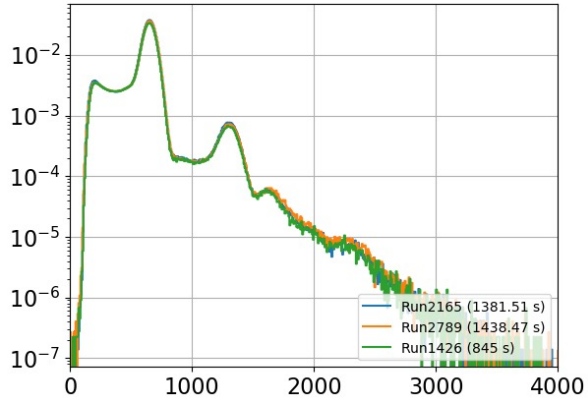
IMP_LTA#2 Scan 1 – 1000 random initial guesses

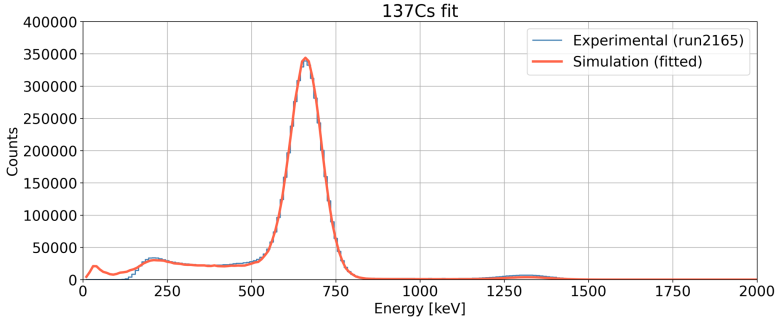


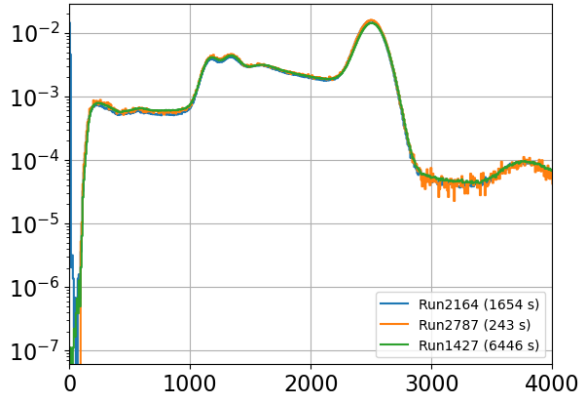
Initial guess o ⟶ □ Converged value

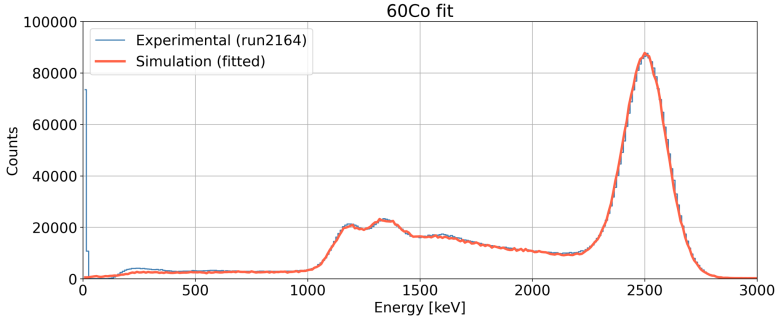
BACKUP

Radioactive Sources Check









Good reproducibility between experimental spectra and simulations

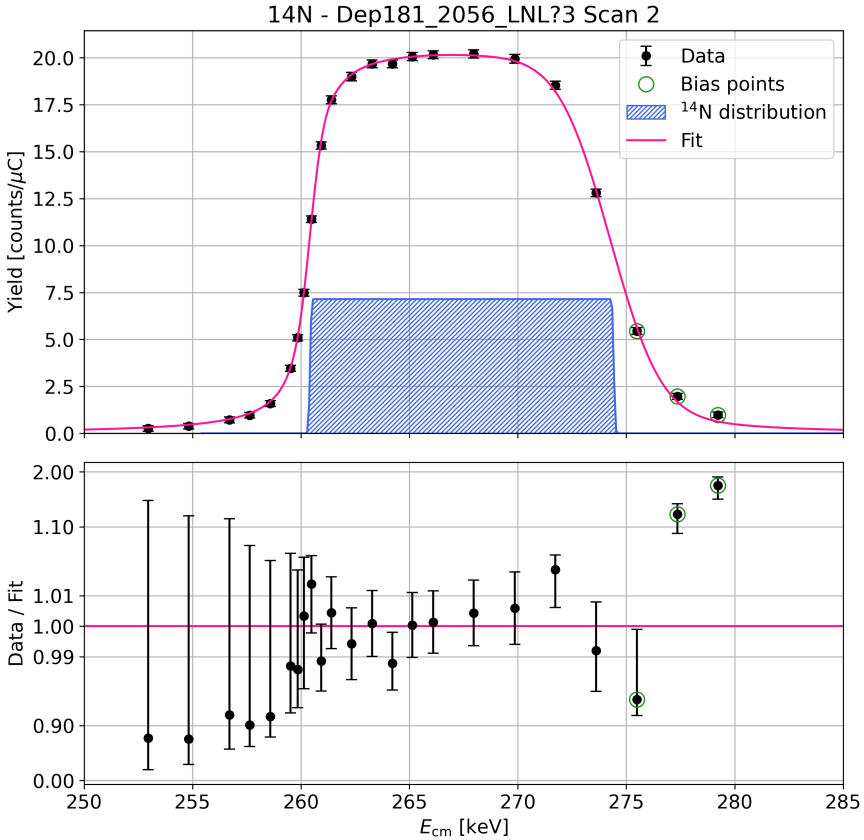
BACKUP

^{14}N Efficiency Check

In the 7-8 MeV ROI, the expected efficiency is of ≈49%
We expect the stoichiometry to be 1:1 between N:Ti (fixed)

Procedure:
→ Simulate a Breit-Wigner resonance @278keV with literature $\omega\gamma$
→ Fit the scans with the usual method to recover efficiency

Fitted efficiency [%]:
Scan2: 50.50±0.24



Scans Fitting Procedure: MCMC

- The model accounts for the ^{19}F distribution in the target $P(E)$ and for the beam straggling $G\left(E', E, s(E)\right)$:

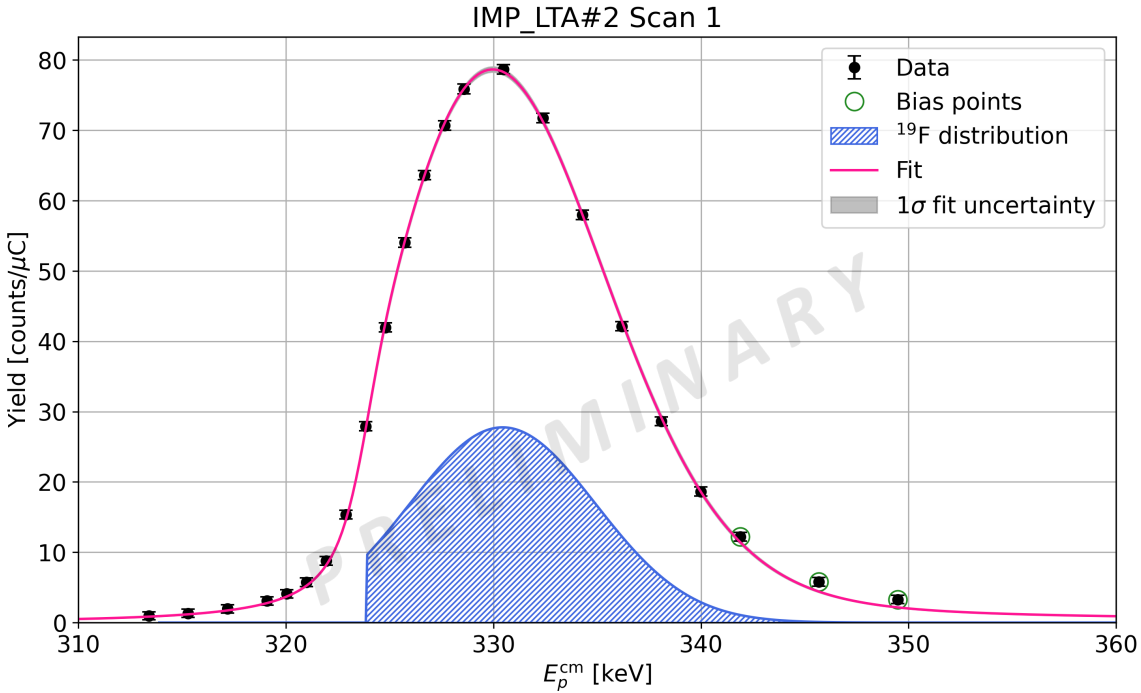
$$Y(E_0) = \int_{E_0-\Delta E}^{E_0} P(E) \left(\int_{-\infty}^{+\infty} \frac{\sigma(E')}{\mathcal{E}_{\text{eff}}(E')} G\left(E', E, s(E)\right) dE' \right) dE$$

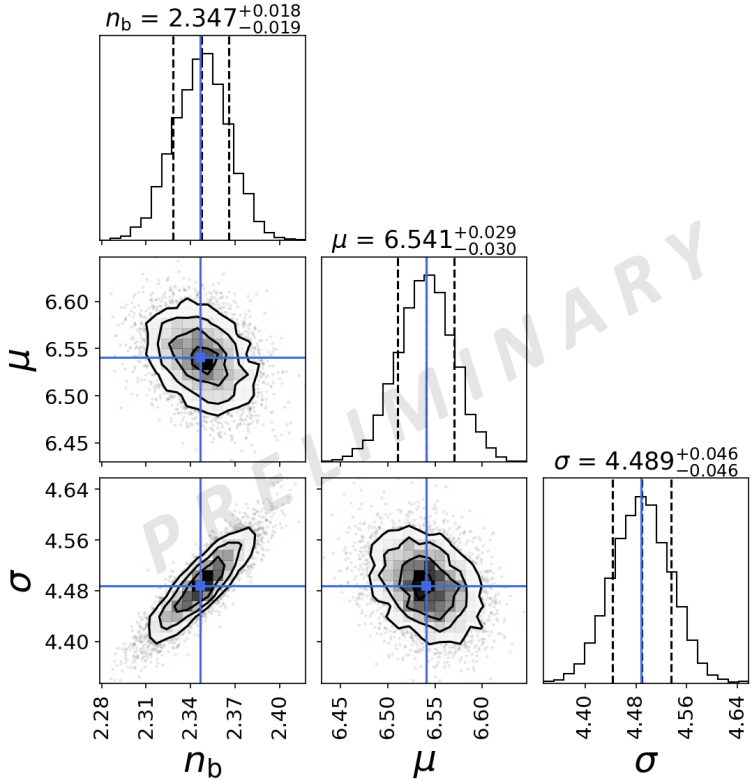
- $\mathcal{E}_{\text{eff}} = \mathcal{E}_F + S \cdot \mathcal{E}_b \rightarrow S = n_b/n_F$ is the stoichiometry
- Scans @340 keV: $P(\Delta E)$ Gaussian $\rightarrow \boldsymbol{\theta_{340}} = \{\boldsymbol{\mu}, \boldsymbol{\sigma}, \boldsymbol{S}, \boldsymbol{E_{340}}\}$ → Target parameters
- Scans @240 keV: S fixed and θ_{340} transformed through $\mathcal{E}_{\text{eff}}$ as $\theta_{340} \cdot \mathcal{E}_{\text{eff}}^{240}/\mathcal{E}_{\text{eff}}^{340} \rightarrow \boldsymbol{\theta_{240}} = \{\boldsymbol{\omega\gamma_{225}}, \boldsymbol{\omega\gamma_{240}}, \boldsymbol{E_{225}}, \boldsymbol{E_{240}}\}$
- Limitations of a classic least-squares fit (e.g. Levenberg-Marquardt algorithm, LM):

⚠️ ⚠️	✅ ✅
Symmetric uncertainties on the θ	Posterior distribution of the θ obtained with a Markov Chain Monte Carlo (MCMC)
High χ^2_{red}	Apply a systematic bias to the experimental uncertainties

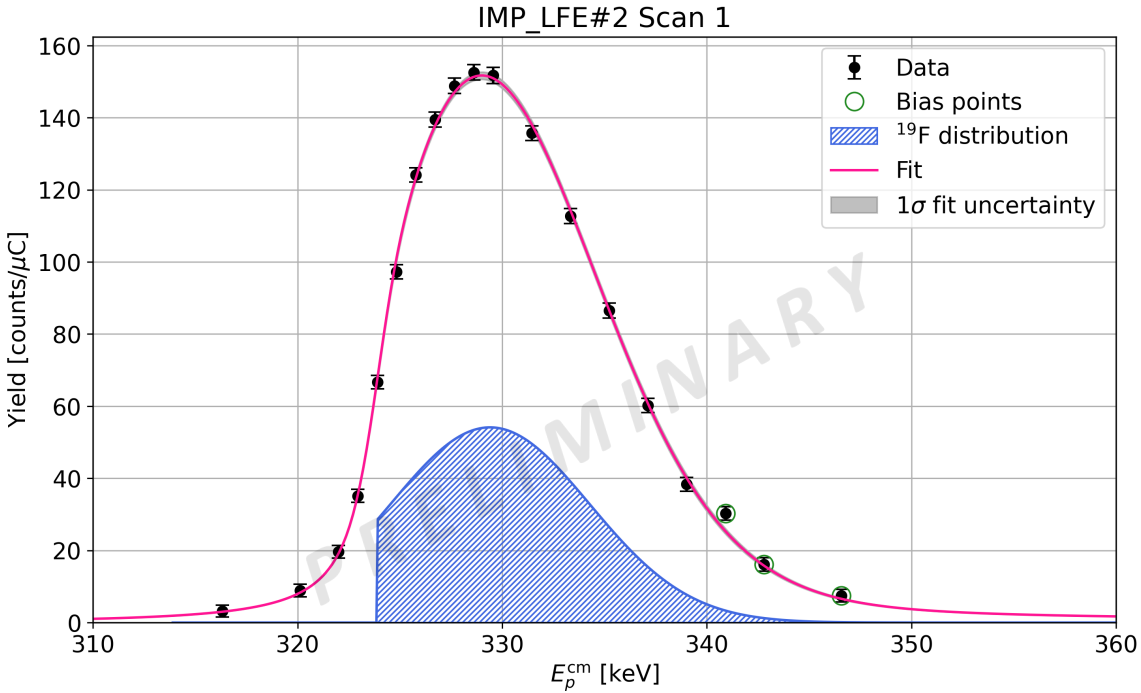
- The final algorithm mixes LM+MCMC with a bias on the experimental uncertainties

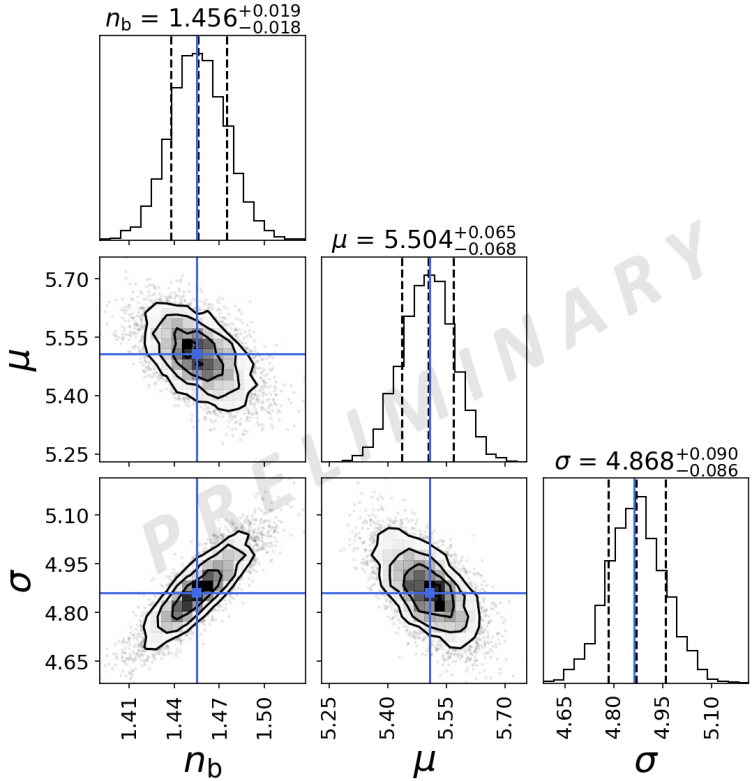
IMP_LTA#2 Fitting @340keV



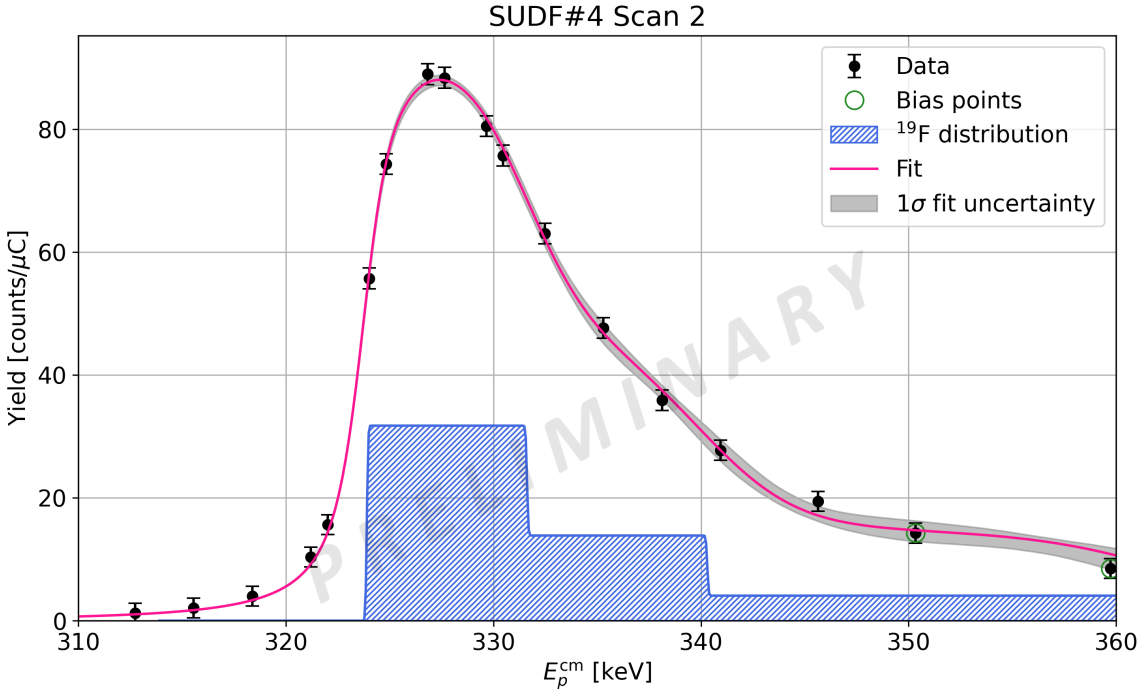


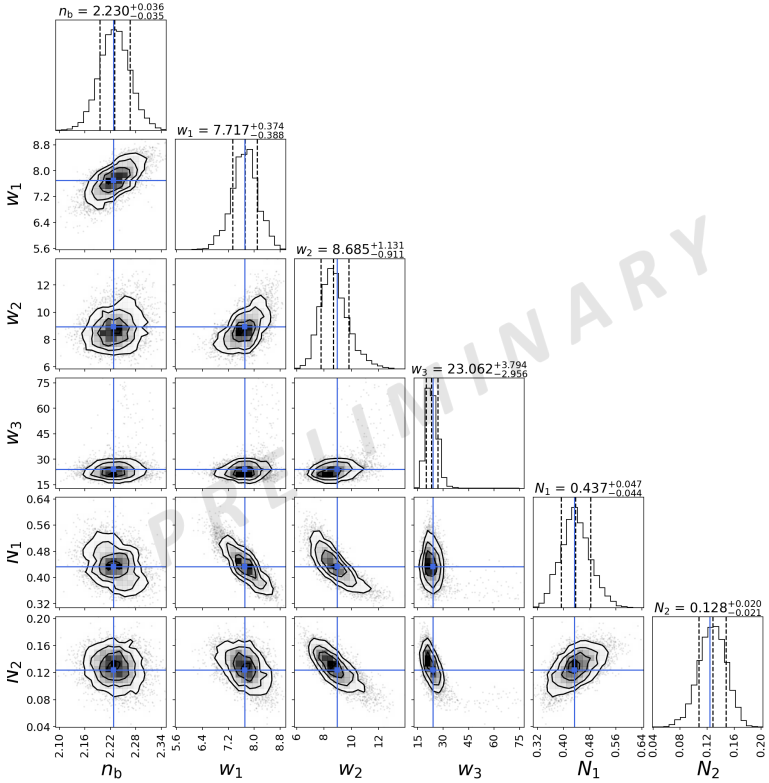
IMP_LFE#2 Fitting @340keV





IMP_LFE#2 Fitting @340keV





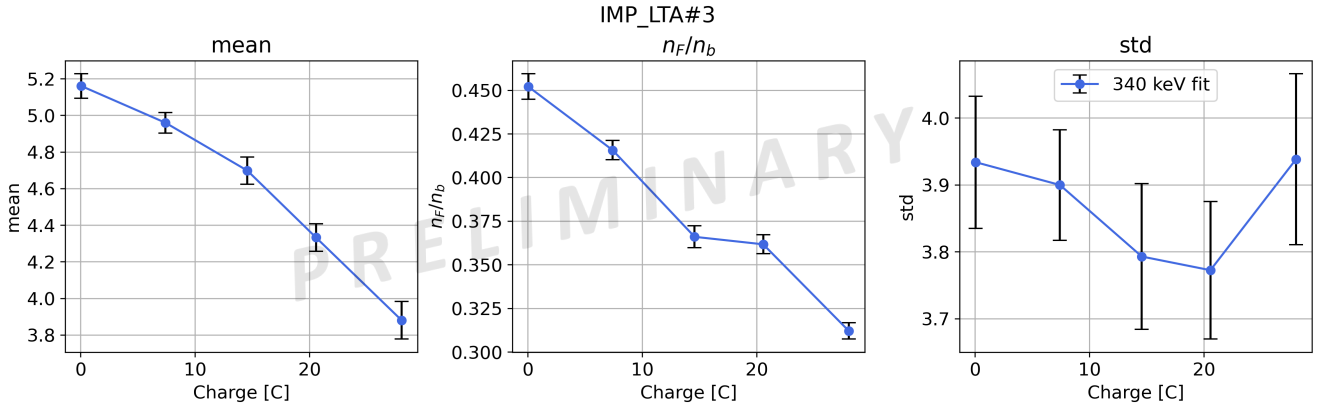
PRELIMINARY

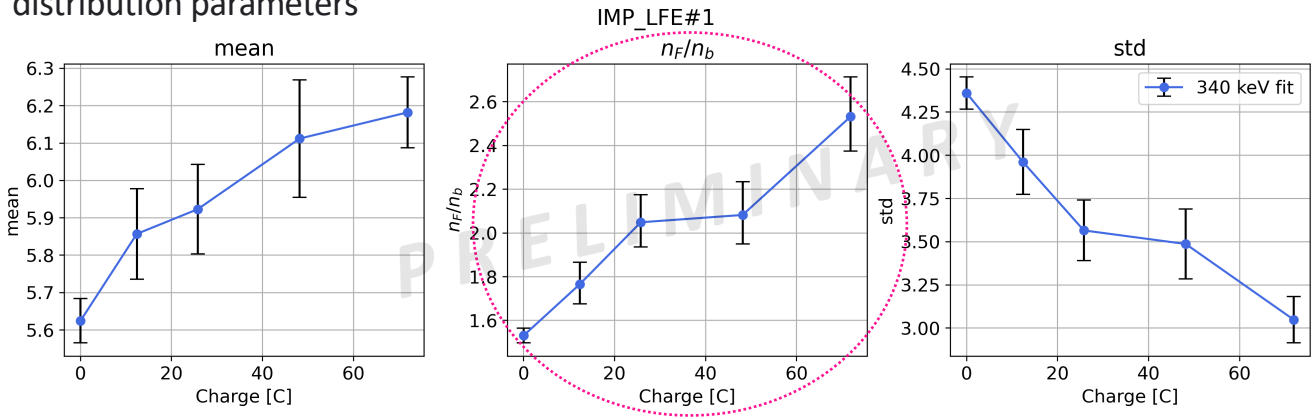
Parameters Evolution @340keV

n_F: ^{19}F stoichiometric coefficient

n_b: backing stoichiometric coefficient

mean and std: ^{19}F distribution parameters

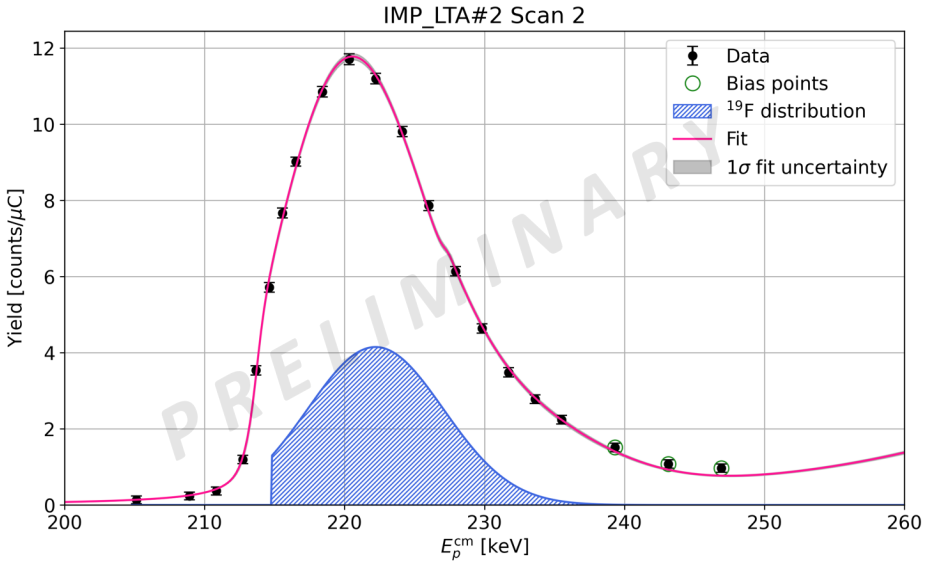


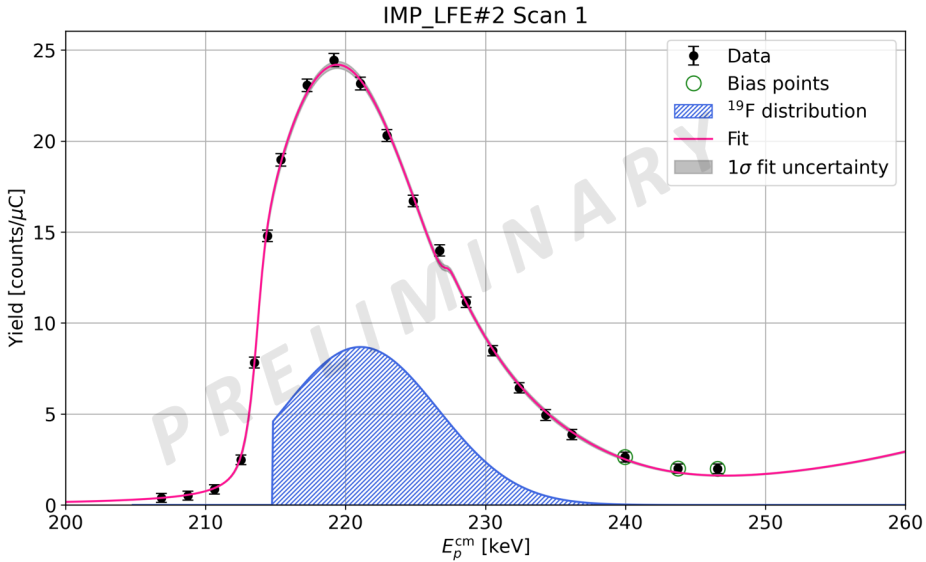


The Fe-implanted targets seem to behave anomalously!

BACKUP

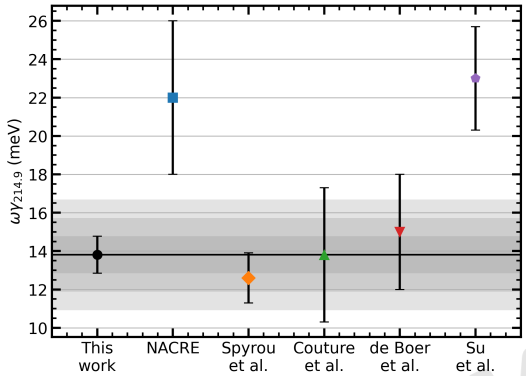
Fitting @240keV

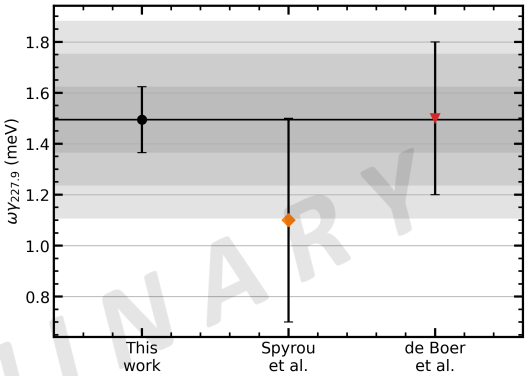




Results – ωγ

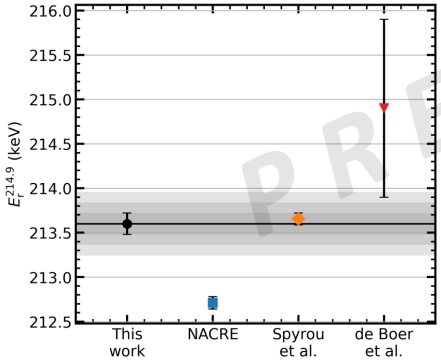
- Scans @240 keV: $\{\mu, \sigma\}$ transformed $\theta_{340} \cdot \mathcal{E}_{\text{eff}}^{240}/\mathcal{E}_{\text{eff}}^{340} \rightarrow \boldsymbol{\theta_{240}} = \{\boldsymbol{\omega\gamma_{225}}, \boldsymbol{\omega\gamma_{240}}, \boldsymbol{E_{225}}, \boldsymbol{E_{240}}\}$

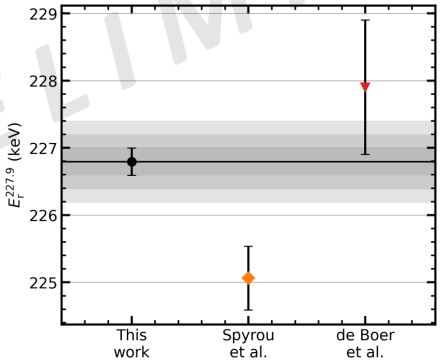


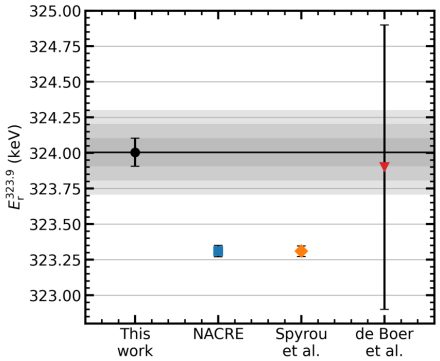


$\omega\gamma_{225} = 13.8 \pm 1.1$ meV
$\omega\gamma_{240} = 1.5 \pm 0.2$ meV

$E_{225} = 213.6 \pm 0.1$ keV
$E_{240} = 226.8 \pm 0.2$ keV
$E_{340} = 324.0 \pm 0.1$ keV







PRELIMINARY