$^{14}N(n,p)^{14}C$ MACS determination using activation measurements and AMS

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INFN - Napoli
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Contents

Maxwellian – Averaged Cross Section (MACS)

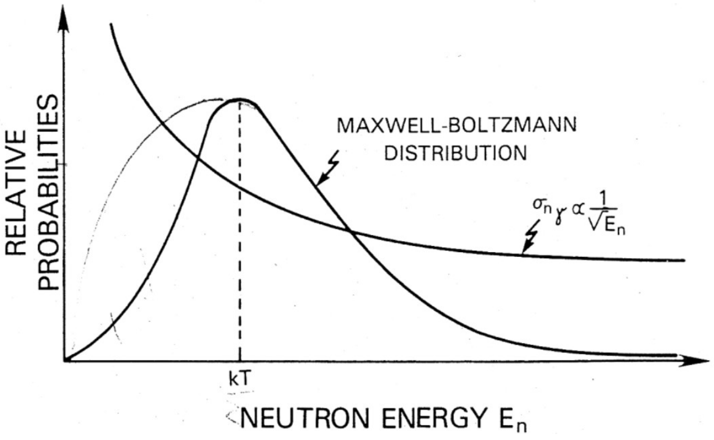
- Heavy elements → nucleosynthesis by neutron capture (s-process, r-process)
- Neutrons thermalized → Maxwell–Boltzmann distribution

  $E_0 = kT$
- Cross section dependence $\sigma_{n,\gamma} \propto \frac{1}{u} \propto \frac{1}{\sqrt{E}}$

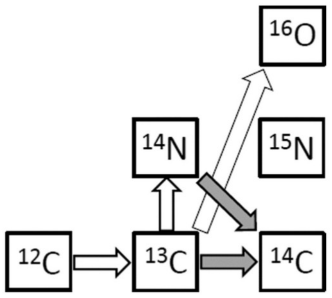
- Reaction rate per pair particle $<\sigma u> = const. = <\sigma> u_T$
- Maxwellian-Averaged Cross Section (MACS)

$$\text{MACS} = \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \int_0^\infty E\sigma(E) e^{-\frac{E}{kT}} dE$$

$$\text{SACS} = \frac{\int \sigma(E)\phi_n(E)dE}{\int \phi_n(E)dE}$$



Motivation and objectives

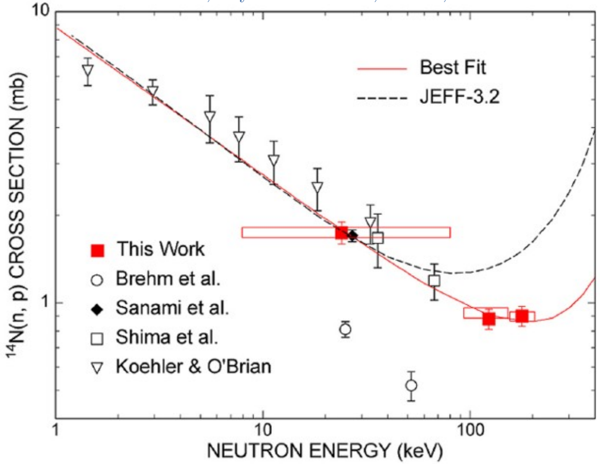


- $^{14}N(n,p)C^{14}$ neutron poison for the s-process
- Discrepancies exist between TOF & activation
- AMS + activation → very high sensitivity, high precision
- Irradiations at NEAR and LNL-INFN for validation and to benchmark the activation method at NEAR

kT (keV)	Wallner *et al.*	ENDF/B-VIII.0	n_TOF
5	3.78 ± 0.06	3.81	3.91 ± 0.10
8	3.12 ± 0.05	3.01	3.09 ± 0.08
10	2.89 ± 0.05	2.70	2.76 ± 0.07
15	2.47 ± 0.04	2.26	2.26 ± 0.06
20	2.21 ± 0.04	2.02	1.97 ± 0.05
23	2.09 ± 0.04	1.93	1.84 ± 0.04
25	2.03 ± 0.04	1.88	1.77 ± 0.04
30	1.93 ± 0.04	1.80	1.63 ± 0.04
40	1.85 ± 0.05	1.75	1.47 ± 0.03
50	1.83 ± 0.06	1.86	1.46 ± 0.03
60	1.84 ± 0.07	2.23	1.69 ± 0.04
80	1.84 ± 0.08	3.96	3.14 ± 0.10
100	1.83 ± 0.08	6.92	5.83 ± 0.20

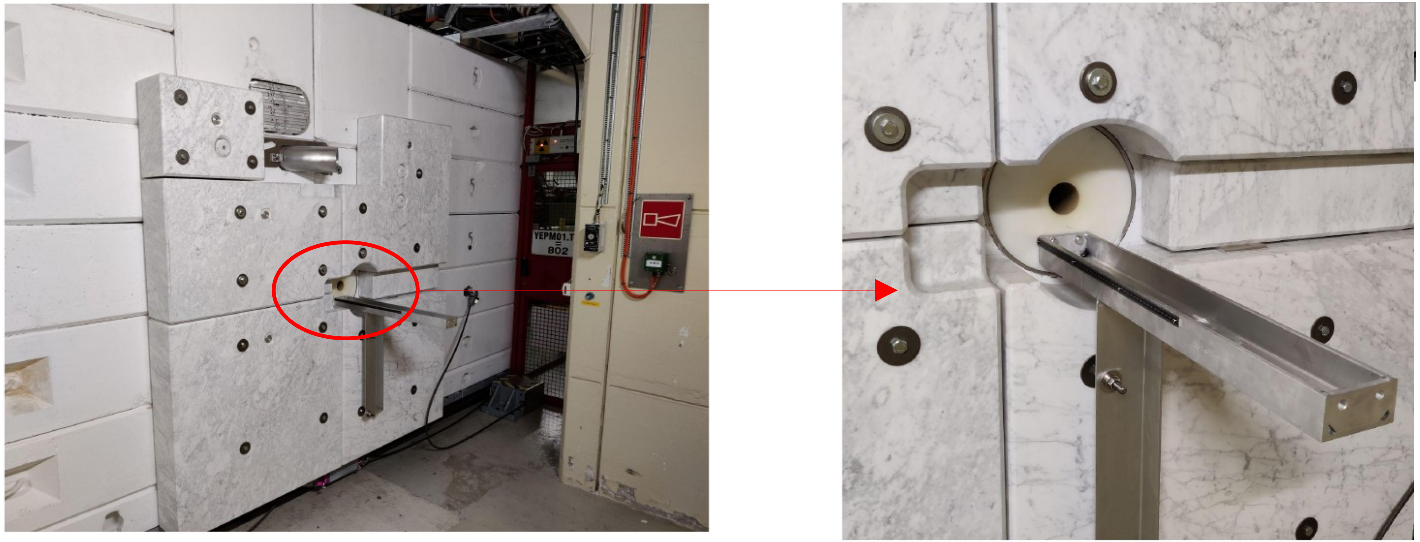
n_TOF Collaboration, Physical Review C. 2023 ; Vol. 107, No. 6

Wallner et al., Phys. Rev. C. 2016, Vol. 93, 045803



The n_TOF NEAR station

- The n_TOF facility: Pulsed neutron source, proton beam of 20GeV/c impinging on lead spallation target
- NEAR: activation station right outside the target bunker.



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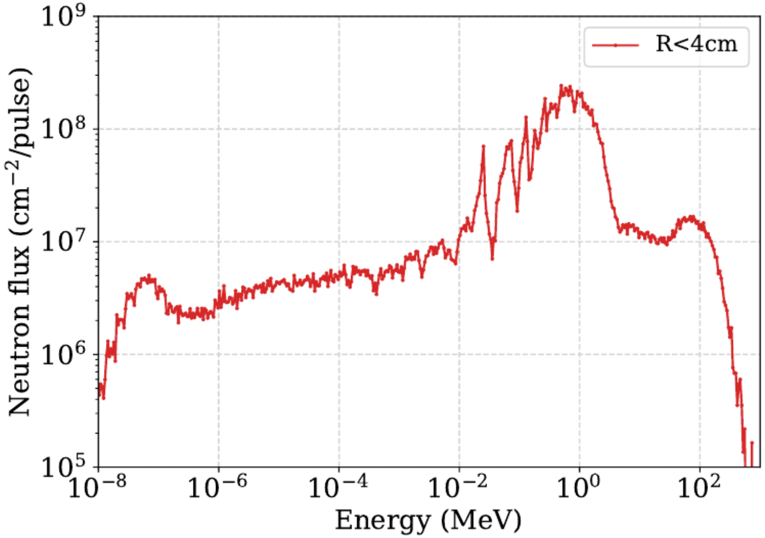
- Distance from target ~3m → high flux → white spectra



M. E. Stamati et al., “The n_TOF NEAR Station Commissioning and first physics case,” EPJ Web Conf., 284, 06009 (2023).

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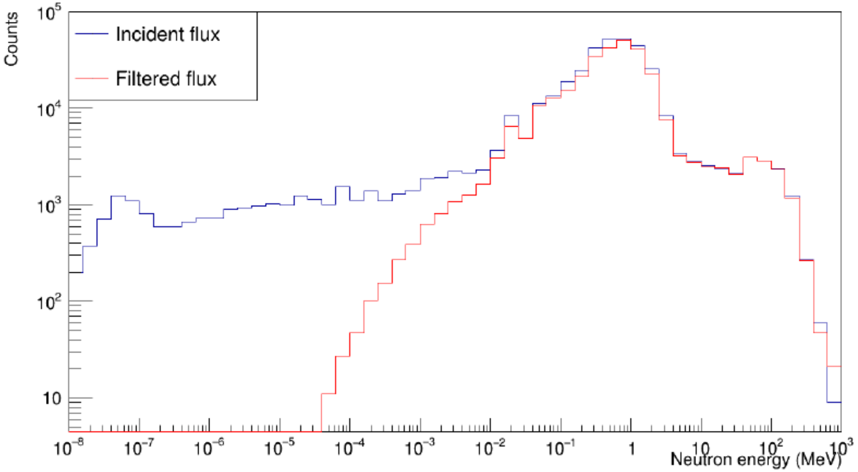
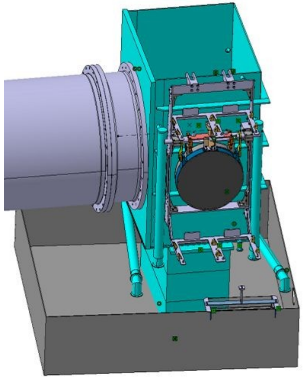
- B_4C filters for Maxwellian-like spectra+ Al_2O_3 moderator





E. Stamati et al., "Neutron capture cross section measurements by the activation method at the n_TOF NEAR Station," CERN, Rep. CERN-INTC-2022-008 / INTC-P-623, 2022.

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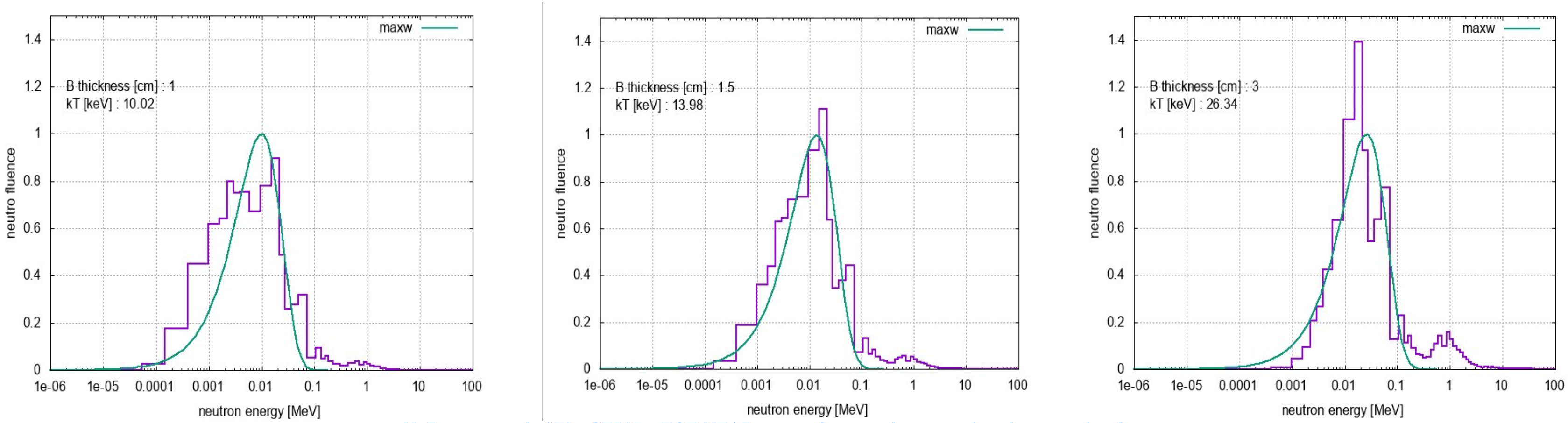
- NEAR: activation station right outside the target bunker.
- Distance from target ~3m → high flux → white spectra
- B_4C filters for Maxwellian-like spectra + Al_2O_3 moderator
- Different filter thickness → different kT



N. Patronis et al., "The CERN n_TOF NEAR station for astrophysics- and application-related neutron activation measurements," Eur. Phys. J. A, vol. 61, no. 9, p. 215, 2025

The NEAR irradiation campaign

- **Material Selection:**

  Goal: measure the SACS at ~5% precision and accuracy

  $\varepsilon_{AMS} = 10^{-4}$ for C^{14} detection → At least 10^8 C^{14} atoms

  Uracil ($C_4H_4N_2O_2$), Melamine ($C_3H_6N_6$), Silicon nitride (Si_3N_4)

  Measured background C^{14} content

```
#14N(n,p)14C
#nspectrum              :  NEAR-SKop-wmod-20cm
#sample                 :  Si3N4
#mass               [g]:       1.001
#density       [g/cm3]:       3.170
#diameter          [cm]:       1.300
#thickness         [cm]:       0.238
#target nuclei         :  1.723e+22
#protons/day           :  1.350e+17
#neutrons/day          :  1.765e+12
#SACS               [b]:       0.118
#f-SACS             [b]:       0.016
#ssf_SACS           [b]:       0.016
#B4C thickness     [mm]:      10.000
#kT               [keV]:       4.892
#reaction rate    [1/h]:     2.1e+07
#N[C14]           [1/d]:     5.0e+08
```

$3*10^9$ for 6-day irradiation

(Simulations performed by A.Mengoni)

```
#14N(n,p)14C
#nspectrum              :  NEAR-SKop-wmod-20cm
#sample                 :  Si3N4
#mass               [g]:       1.001
#density       [g/cm3]:       3.170
#diameter          [cm]:       1.300
#thickness         [cm]:       0.238
#target nuclei         :  1.723e+22
#protons/day           :  1.350e+17
#neutrons/day          :  6.639e+11
#SACS               [b]:       0.118
#f-SACS             [b]:       0.019
#ssf_SACS           [b]:       0.020
#B4C thickness     [mm]:      30.000
#kT               [keV]:      29.838
#reaction rate    [1/h]:     9.3e+06
#N[C14]           [1/d]:     2.2e+08
```

$2.6*10^9$ for 12-day irradiation

```
#14N(n,p)14C
#nspectrum              :  NEAR-SKop-wmod-20cm
#sample                 :  Si3N4
#mass               [g]:       1.001
#density       [g/cm3]:       3.170
#diameter          [cm]:       1.300
#thickness         [cm]:       0.238
#target nuclei         :  1.723e+22
#protons/day           :  1.350e+17
#neutrons/day          :  4.211e+12
#SACS               [b]:       0.118
#f-SACS             [b]:       0.118
#ssf_SACS           [b]:       0.118
#B4C thickness     [mm]:       0.000
#kT                [eV]:       0.037
#reaction rate    [1/h]:     3.6e+08
#N[C14]           [1/d]:     8.6e+09
```

$5*10^{10}$ for 6-day irradiation

Similar numbers for uracil and melamine

The NEAR irradiation campaign

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  Uracil ($C_4H_4N_2O_2$), Melamine ($C_3H_6N_6$), Silicon nitride (Si_3N_4)

  Masured background C^{14} content

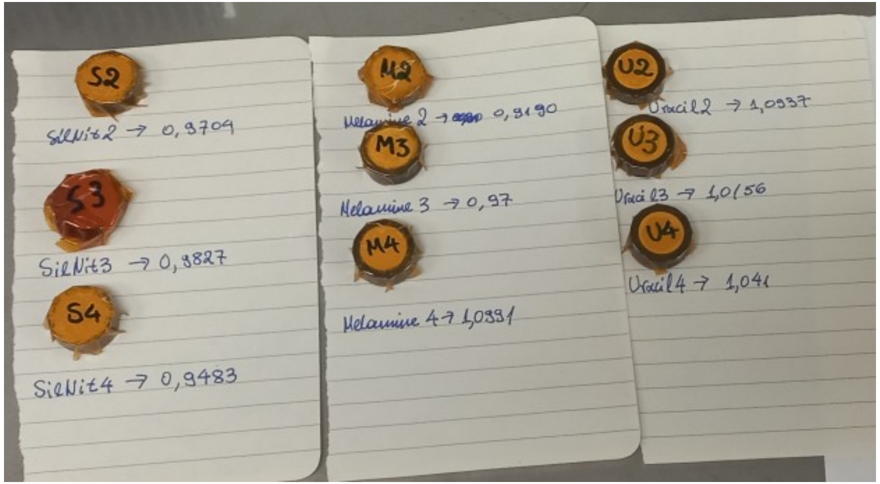
- **Irradiations plan:**

  Four irradiations

  - No filter
  - 10mm B_4C (front) – 10mm B_4C (back) → 10 keV
  - 15mm B_4C (front) – 5mm B_4C (back) → 15 keV
  - 30mm B_4C (front) – 5mm B_4C (back) → 30 keV

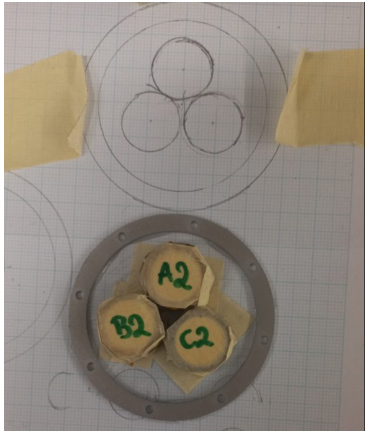
The NEAR irradiation campaign

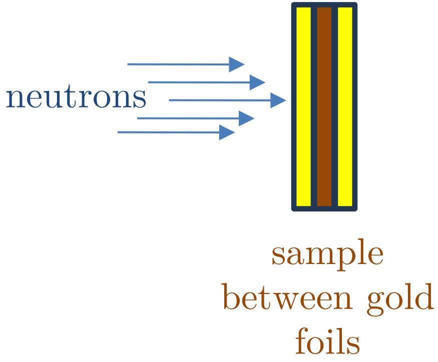
- **Target configuration:**
  - Samples (1gr) pressed in plastic capsules (13mm diameter, 6mm thickness)

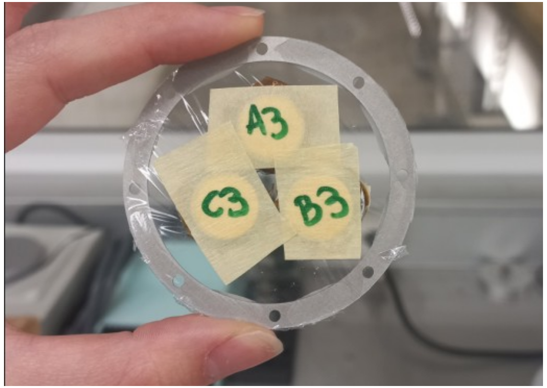


The NEAR irradiation campaign

- **Target configuration:**
  - Samples (1gr) pressed in plastic capsules (13mm diameter, 6mm thickness)
  - Au foils to make reference measurement (~50mg, 20µm thickness, 13 mm diameter)

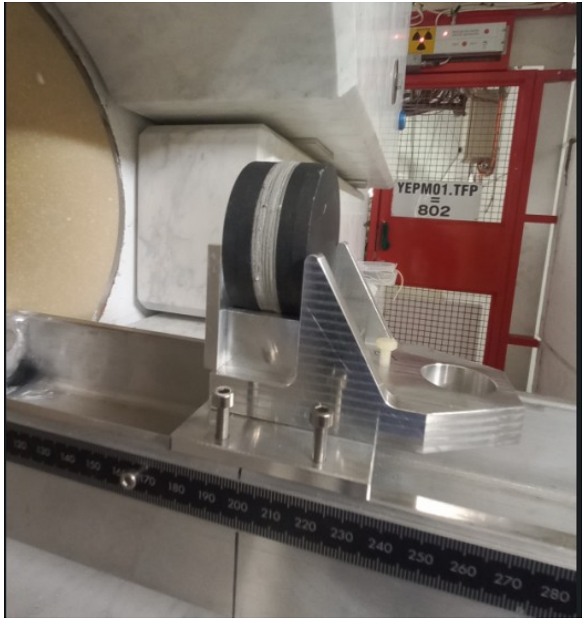






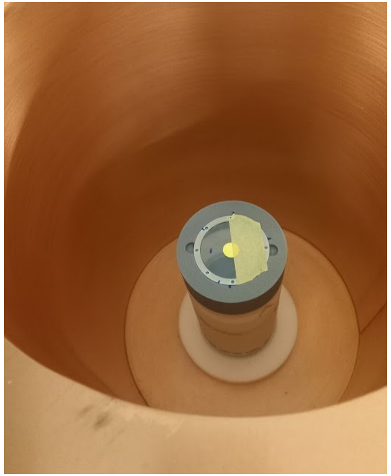
The NEAR irradiation campaign

- **Target configuration:**
  - Samples (1gr) pressed in plastic capsules (13mm diameter, 6mm thickness)
  - Au foils to make reference measurement (~50mg, 20μm thickness, 13 mm diameter)
  - Placed at 20cm from collimator hole



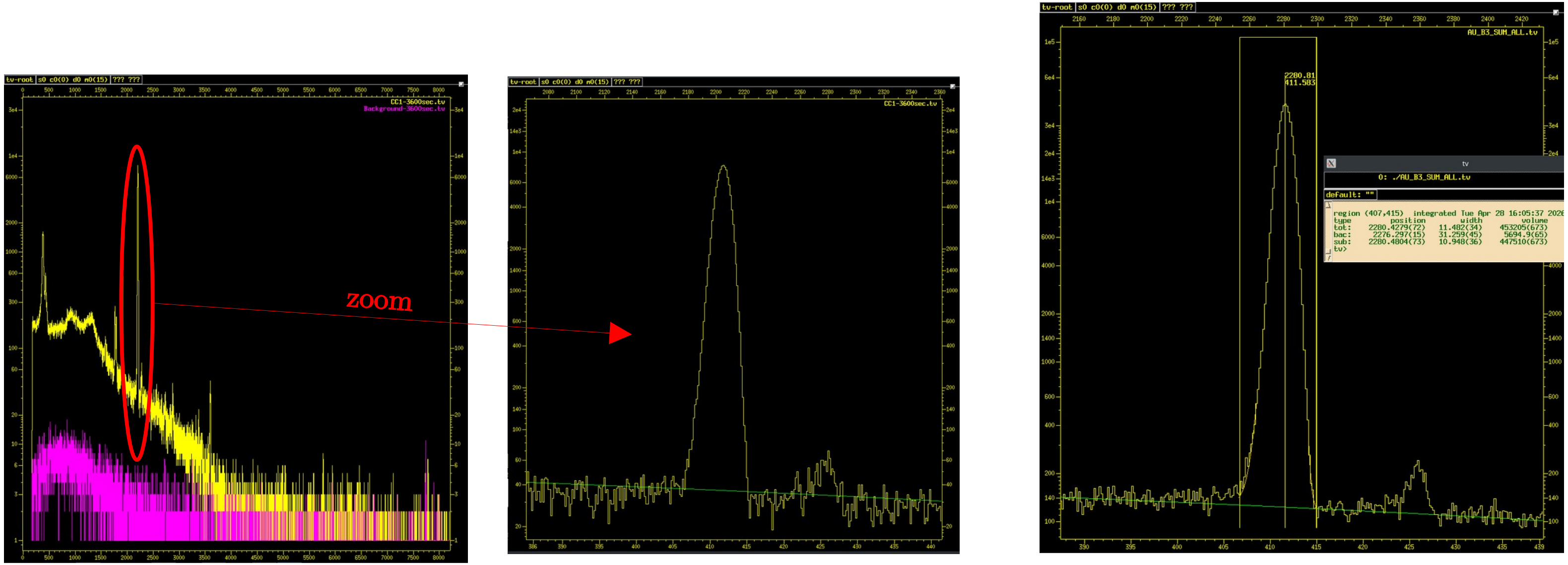
Gamma spectra analysis of the gold foils

- **GEAR station** (HPGe detector with lead shield)
  - High efficiency from 3 keV up to the 10 MeV
  - Measurements at different source-to-detector distances

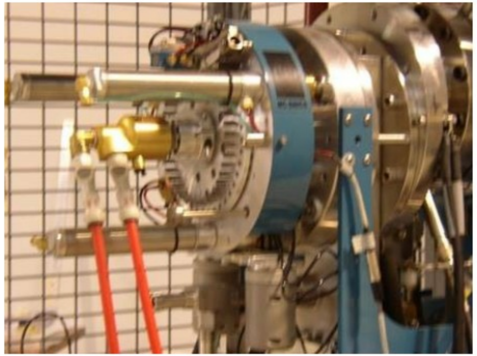


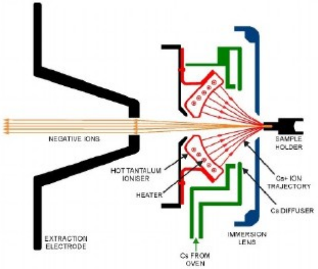
Gamma spectra analysis of the gold foils

- **GEAR station** (HPGe detector with lead shield)
  - High efficiency from 3 keV up to the 10 MeV
  - Measurements at different source-to-detector distances
- **Spectra analysis with tv software**

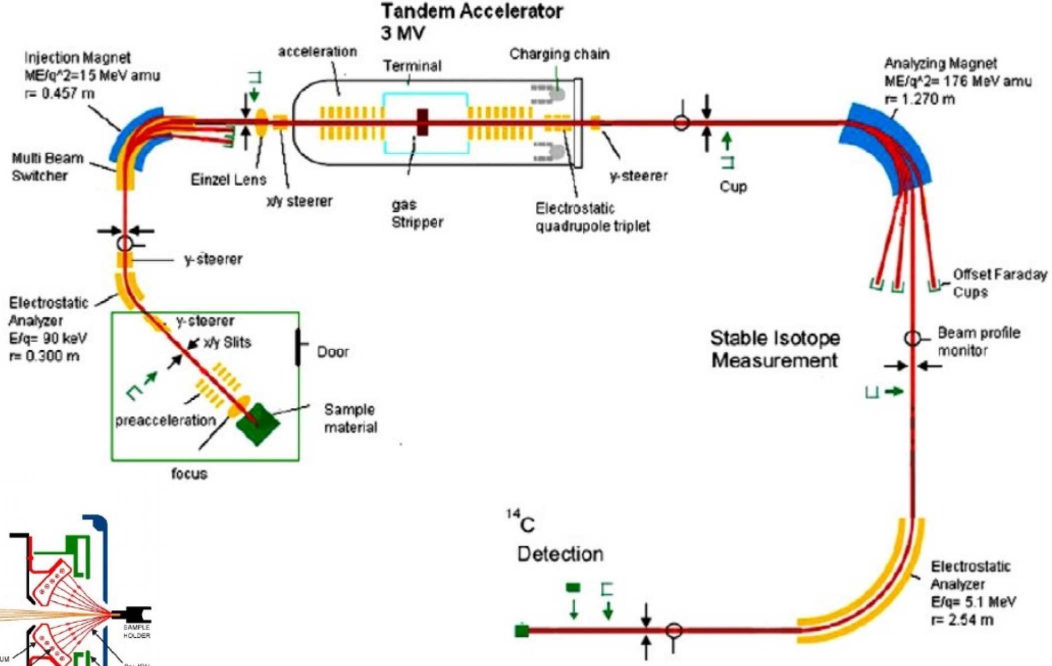


Accelerator Mass Spectrometry @ CIRCE





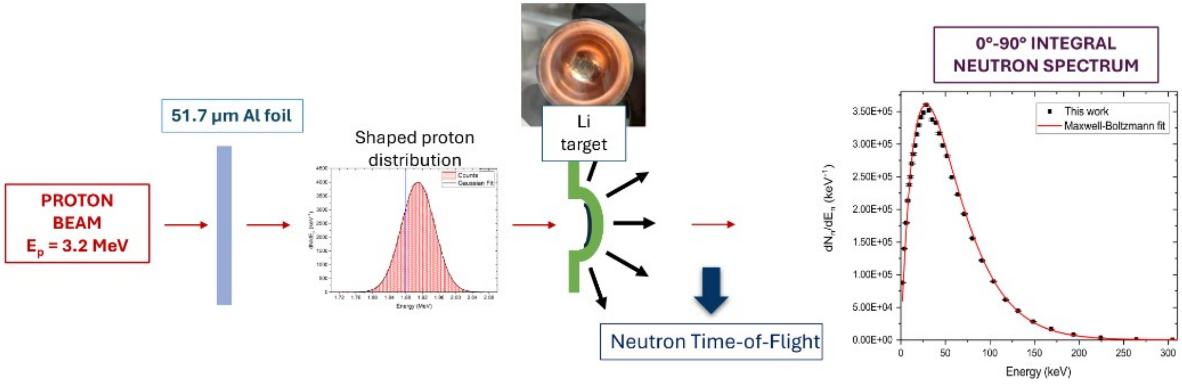
L. K. Fifield, ANU, “The Methodology and Physics of Accelerator Mass Spectrometry,” 2025.



F. Terrasi, et al., High precision 14C AMS at CIRCE, Nucl. Instrum. and Methods B 266, (2008) 2221

Next steps

- Analysis of Au foils → ongoing
- AMS measurements at CIRCE
- Irradiations at LNL-INFN



- Compare NEAR vs LNL activation results
- Benchmark NEAR feasibility for MACS determination

Acknowledgements

- Many thanks to the n_TOF local team

- This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 10105751

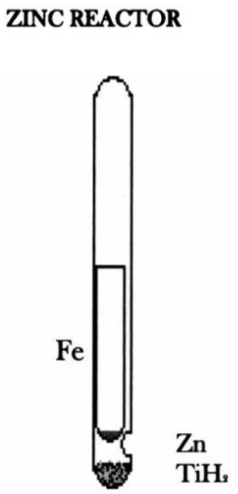
Thank you for your attention :)

Backup slides

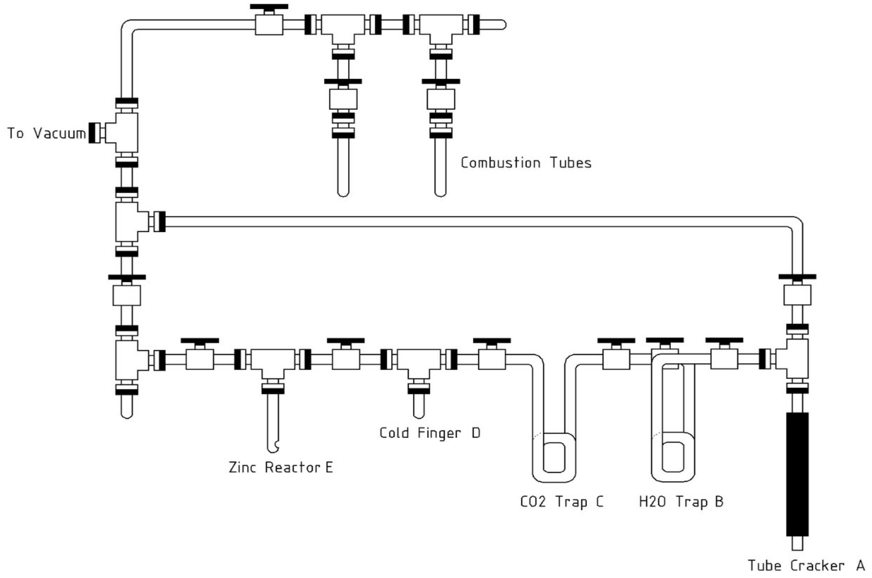
Sample preparation (1)

- The goal is to convert the samples into a solid graphite target for AMS measurements
- Oxidation of the carbon to CO_2.
- Quarz tube → sample (1mg graphite) + CuO → combustion (880°C for 6.5hrs)

  $C(\text{from sample}) + 2CuO \rightarrow CO_2 + 2Cu$
- Graphitization using the sealed tube Fe-Zn-TiH_2 method
- Clean reagents in muffle furnace at 300°C for 1 hour.
- Zn + TiH_2 in 9mm pyrex, Fe in 6mm pyrex



Sample preparation (2)



- Remove H_2O using ethanol/dry ice bath
- Trap the CO_2 using liquid nitrogen gas
- Flame seal tube
- Graphitization 500°C for 3hrs, 545°C for 5hrs
- Graphitization reactions

  $TiH_2 \rightarrow Ti + H_2$

  $CO_2 + H_2 \rightarrow CO + H_2O$

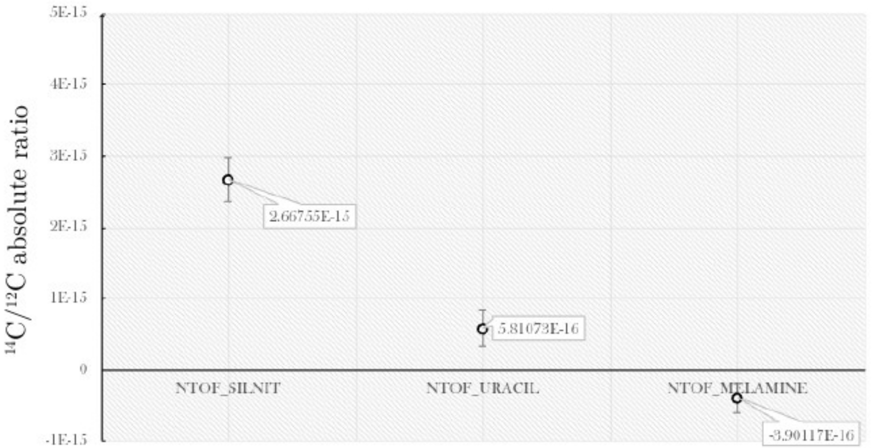
  $CO + H_2 \rightarrow C_{graphite} + H_2O$

  $Zn + H_2O \rightarrow H_2 + ZnO$

- Press into 1mm Al cathodes

Accelerator Mass Spectrometry @ CIRCE – Background measurements

- Standards with known ^{14}C content → normalization of the measurements (OXII), quality checks (C3, C7)
- Blanks (graphite) → quantify ^{14}C contamination
- Measure $^{14}C/^{12}C$ ratio and normalize to the standards
- Measure $^{13}C/^{12}C$ to correct for mass fractionation
- Subtract the blank background and get the corrected ratio $^{14}C/^{12}C$



(Analysis by F. Marzaioli)

Analysis of Au foils

- Goal: Get the activity of the irradiated Au foils → derive the MACS → use as reference for $^{14}N(n,p)C^{14}$
- Number of produced nuclei during activation

$$N_{act} = \frac{C_\gamma}{\varepsilon_\gamma I_\gamma} \frac{1}{1-e^{-\lambda t_{live}}} \frac{1}{e^{-\lambda t_{decay}}} \frac{\lambda t_{irr}}{1-e^{-\lambda t_{irr}}}$$

- Where C_γ net counts in peak

  ε_γ efficiency of the detector

  I_γ intensity of gamma line

  t_{live} measurement time

  t_{decay} time between stop of irradiation and start of measurement

  t_{irr} time of irradiation
- Based on this, the activity of the sample is given by

$$A_{act} = \frac{C_\gamma}{\varepsilon_\gamma I_\gamma} \frac{\lambda^2 t_{irr} e^{\lambda t_{decay}}}{\left(1-e^{-\lambda t_{live}}\right)\left(1-e^{-\lambda t_{irr}}\right)}$$