Experimental work on Nuclear Astrophysics at JRC GELINA facility

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European Commission

Joint Research Centre, Geel (BE)

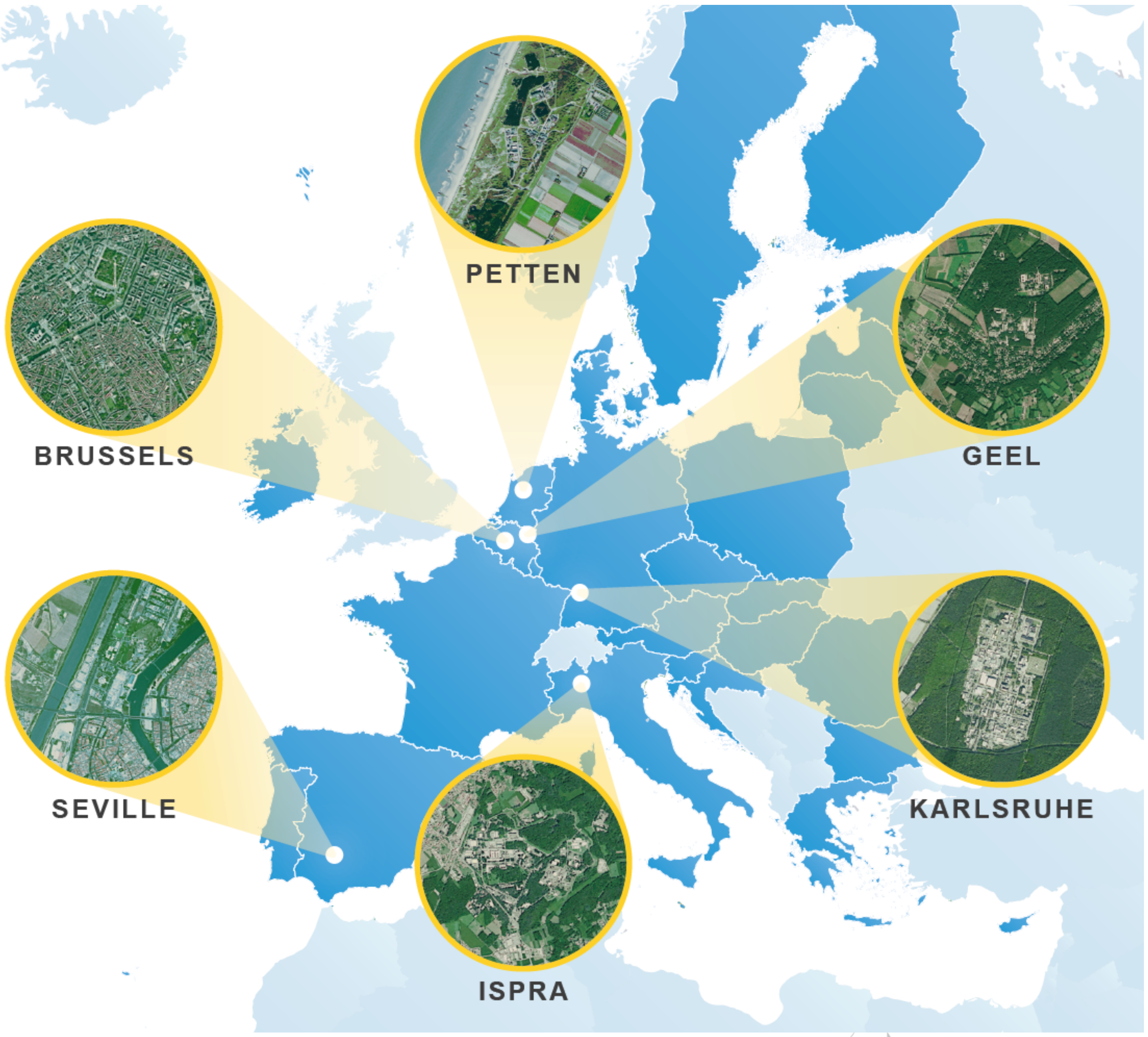
Nuclear Physics in Astrophysics – X

4-9 September 2022, CERN

Joint Research Centre

Headquarters in Brussels
and research facilities located
in 5 Member States:

- **Belgium (Geel)**
- Germany (Karlsruhe)
- Italy (Ispra)
- The Netherlands (Petten)
- Spain (Seville)



Nuclear facilities at JRC - Geel

GELINA (this presentation)
neutron time-of-flight facility for high-resolution neutron measurements

MONNET
tandem accelerator based fast neutron source

TARGET
nuclear target preparation laboratories

RADMET
laboratories for standardisation of radionuclide activity

HADES
low-level gamma-spectrometry laboratory

METRO
nuclear reference material and measurement facility

Operated by JRC.G.2 Unit (SN3S)
"Standards for
Nuclear Safety, Security and Safeguards"

- Nuclear data
- Radionuclide measurements
- Nuclear safeguards metrology

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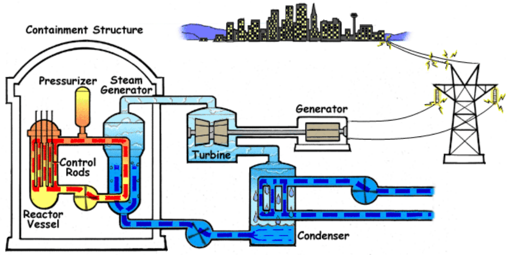
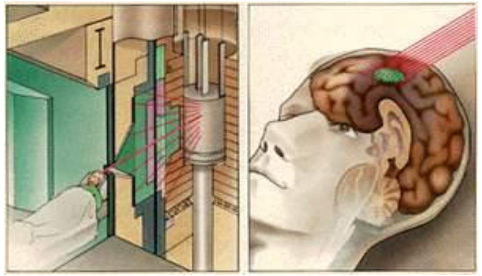
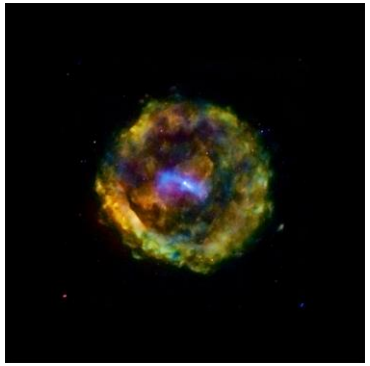
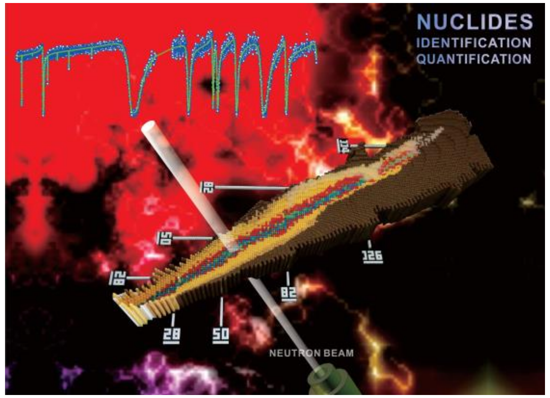
Applications

- **Nuclear data for energy technology**
  - Safety of current systems
  - Development of innovative systems (e.g. MYRRHA)
  - Back-end: Spent Nuclear Fuel (Burn Up Credit, Decay heat, …)
    - *Intermediate storage*
    - *Transport of SNF*
    - *Reprocessing facilities*
    - *Final Disposal of SNF*
- Nuclear physics
- Nuclear medicine: diagnostics and therapy
- Nucleosynthesis and nuclear astrophysics
- Detector development
- Materials research (NAA, PGAA, **N**eutron **R**esonance **A**nalysis, …)
- ….









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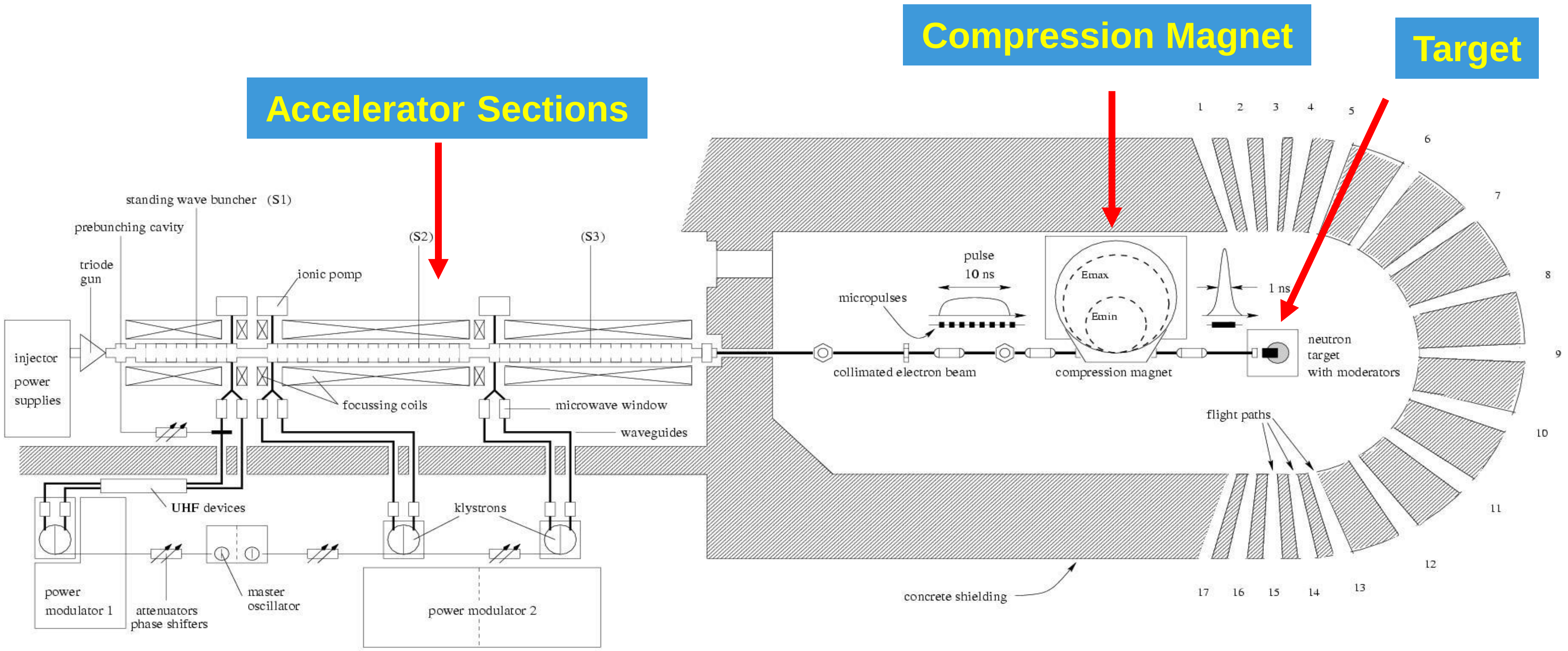
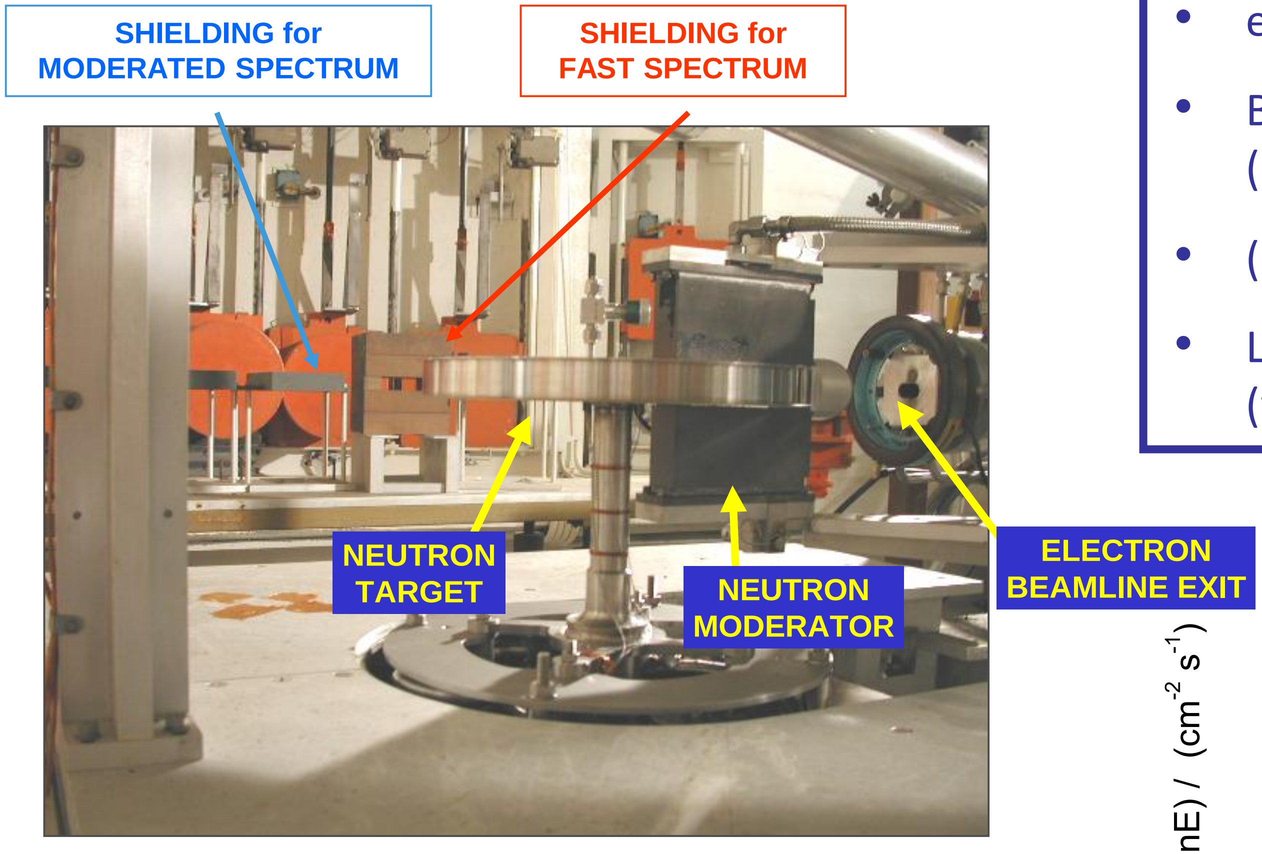
GELINA: **G**eel **E**lectron **LIN**ear **A**ccelerator



Normal Operating Parameters

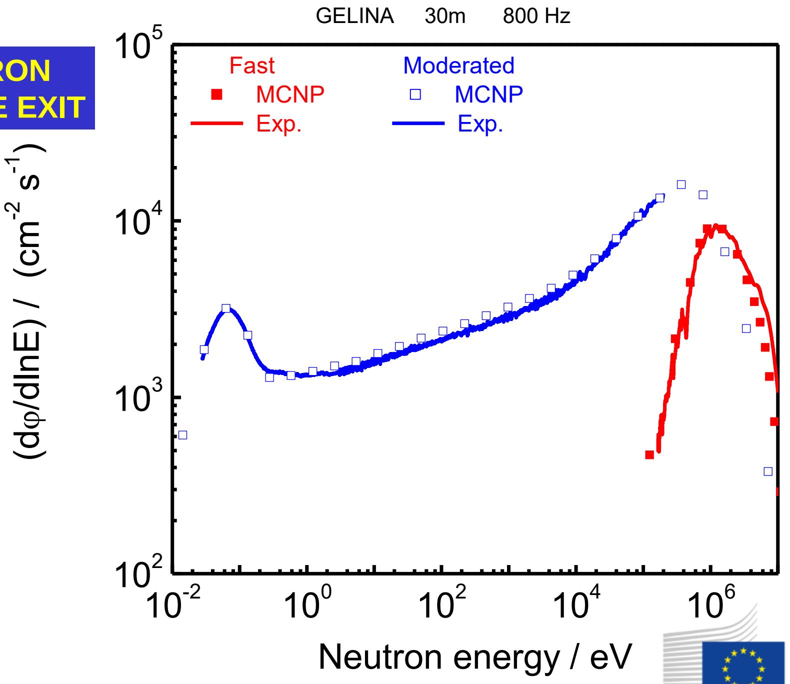
Average Current	: 40 μA	Frequency	: 400 Hz
Average Electron Energy	: 100 MeV	Pulse Width	: 2 ns
Mean Power	: 4.0 kW	Neutron Flux	: 1 x 10^{13} 1/s

GELINA: fast and moderated neutron beam



Flaska et al.,NIM A , 531, 394 (2004)

- e^- accelerated to $E_{e-,max}$ ≈ 140 MeV
- Bremsstrahlung in U-target (rotating & cooled with liquid Hg)
- (γ , n) , (γ , f) in U-target
- Low energy neutrons by moderation (water moderator in Be-canning)



GELINA: **G**eel **E**lectron **LIN**ear **A**ccelerator

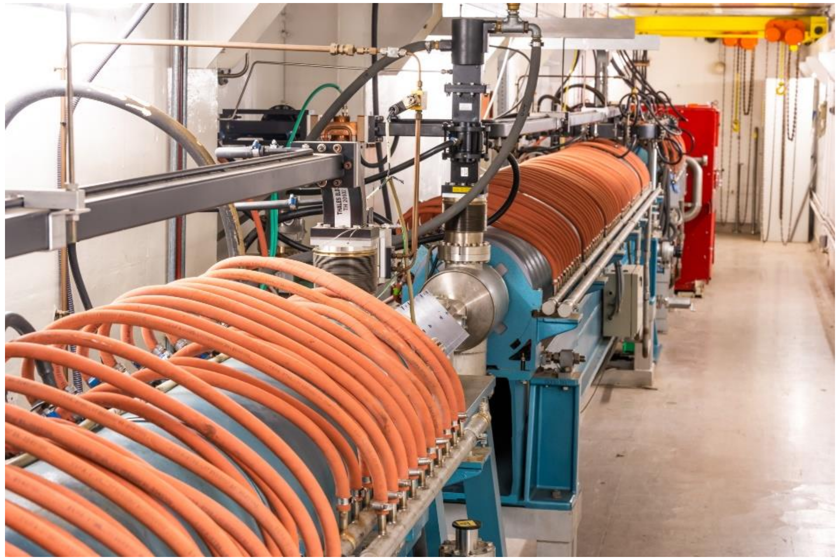
- **Electron linac** driven pulsed white neutron source

  (10 meV < En < 20 MeV)

- Neutron energy : **time – of – flight** (TOF)

- **Multi-user facility**: 12 flight paths (10 m – 400 m)

- Measurement stations with **special equipment**:
  - Total cross section measurements
  - Partial cross section measurements



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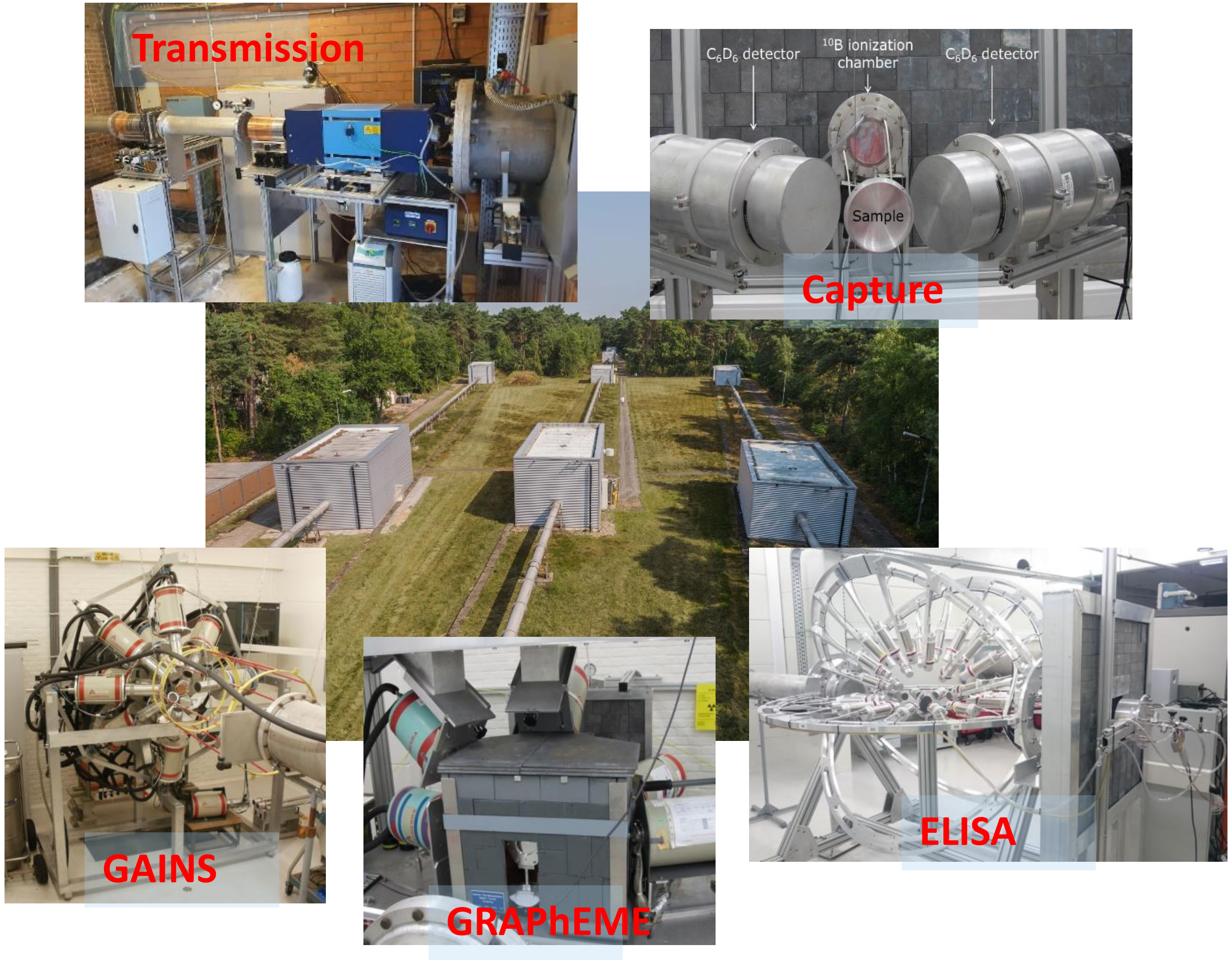
GELINA: Experimental set-ups



- Transmission

  FP13-10 m, FP12-30 m, FP4-50 m

- Capture

  FP5-10 m, FP15-30m, FP14-60 m

- Fission, (n,p), (n,α), …

  FP2-10 m

- *Elastic, in-elastic scattering*

  FP1-30 m

- *In-elastic scattering (n,n’γ)*

  FP16-30 m, FP3-100 m

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Past contribution to Nuclear Astrophysics

- Intensive JRC contribution between 1990 and 2010 on neutron capture (leaded by F. Corvi) and neutron-induced charge particle reactions (leaded by C. Wagemans).

Nuclear Astrophysics was part of the work programme at that time!

Conference	(n,γ)	(n,α), (n,p)
NIC-II (92)	^{138}Ba	$^{32,33}S$, ^{14}N
NIC-III(94)	^{208}Pb	$^{35,36}Cl$, ^{41}Ca
NIC-IV(96)	^{136}Ba	
NIC-V(98)	^{84}Kr, ^{207}Pb, ^{209}Bi	^{37}Ar
NIC-VI(00)	^{99}Tc	^{37}Ar, ^{39}Ar
NIC-VIII&ND2004	$^{80,82,83,84}Kr$	^{26}Al, ^{36}Cl
NIC-IX&ND2007	$^{128,129,130,132}Xe$	^{41}Ca

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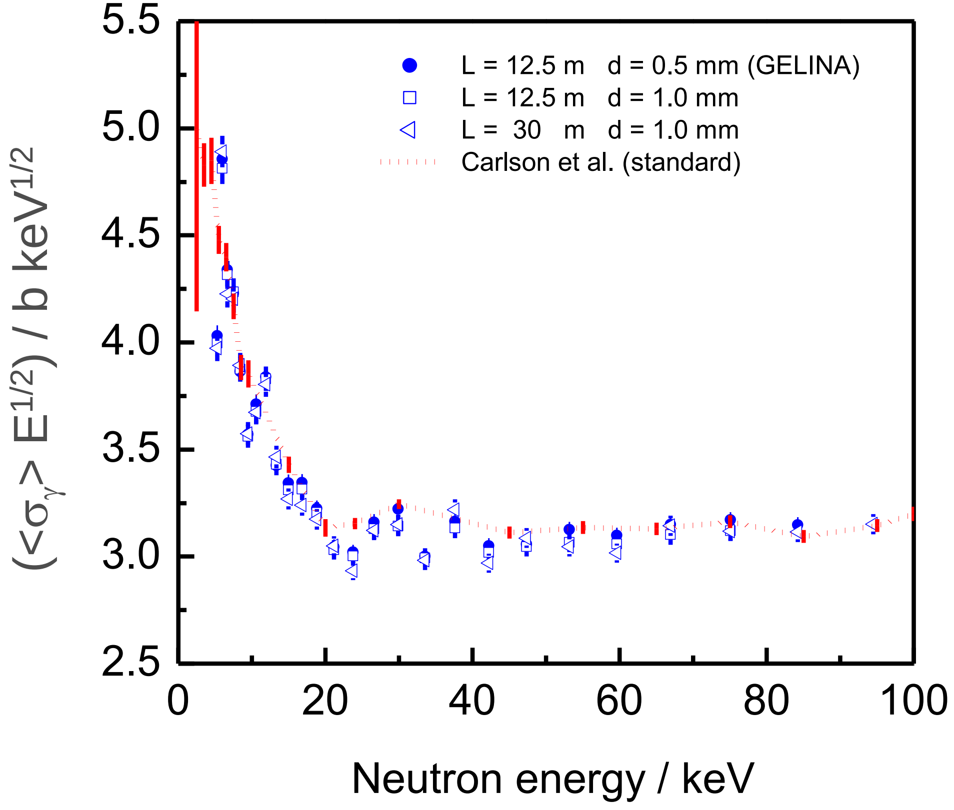
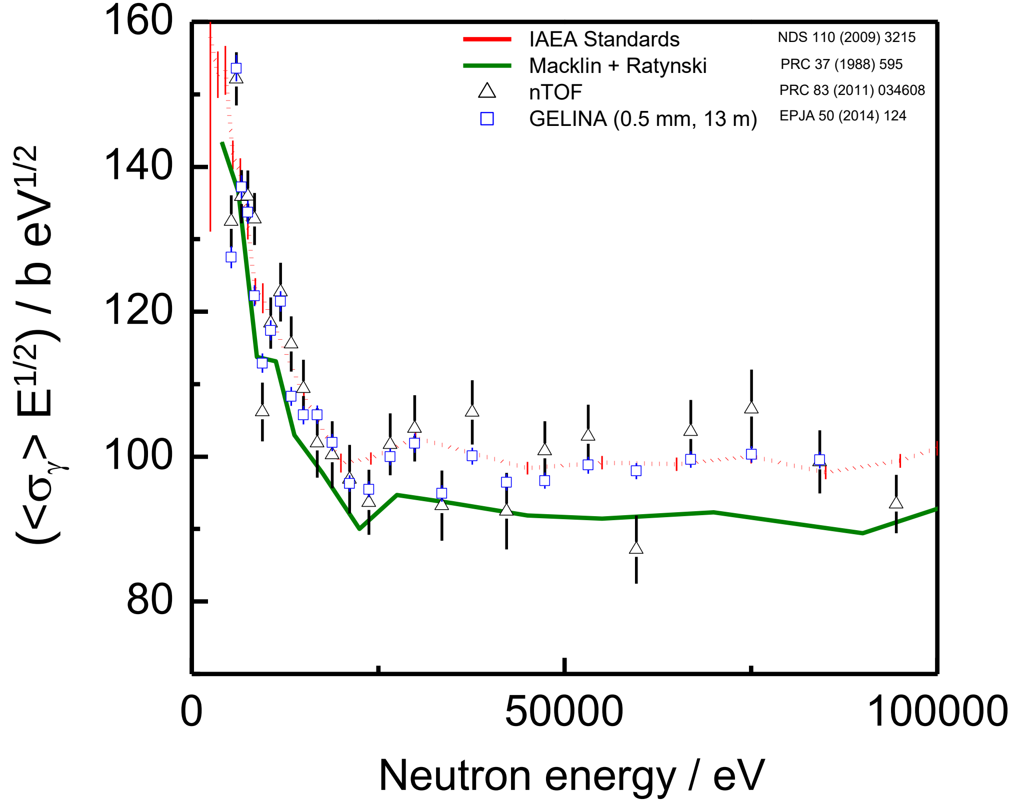
Past IRMM contribution to Nuclear Astrophysics

Au(n,γ) cross section studied in a systematic way:

- Different FP lengths and sample thicknesses
- Self-shielding and multiple interaction corrections





Massimi et al., Eur. Phys. J. A **50** (2014) 124

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Recent contributions relevant for Nuclear Astrophysics

- **Since 2013 contributions through Open Access projects, proposed by external users, in particular n_TOF collaboration**
  - **^{92}Zr(n,γ) and (n,tot)** in collaboration with INFN-Bari *Phys. Rev. C 105, 025805 (2022)*
  - **^{89}Y(n,γ) and (n,tot)** proposed by INFN-Bari, *in preparation*
  - **^{154,}**^{155,157}Gd(n,tot) proposed by INFN-Bologna with n_TOF samples *Phys. Lett. B 804, 135405 (2020)*
  - ^{nat,142}Ce(n, γ) and (n,tot) in collaboration with ORNL (Nuclear Criticality Safety Program)
  - ^{94,95,96,nat}Mo(n,tot) proposed by INFN-Bologna, *accepted by NIMB*
  - ^{26}Al(n,α) with University of Edinburgh *Phys. Rev. C 104, 032803 (2021)*
  - **^{16}O(n, α)** proposed by HZDR, *submitted to Phys. Rev. C*

Experiments carried out with in-house detection setups or with detectors provided by external users.

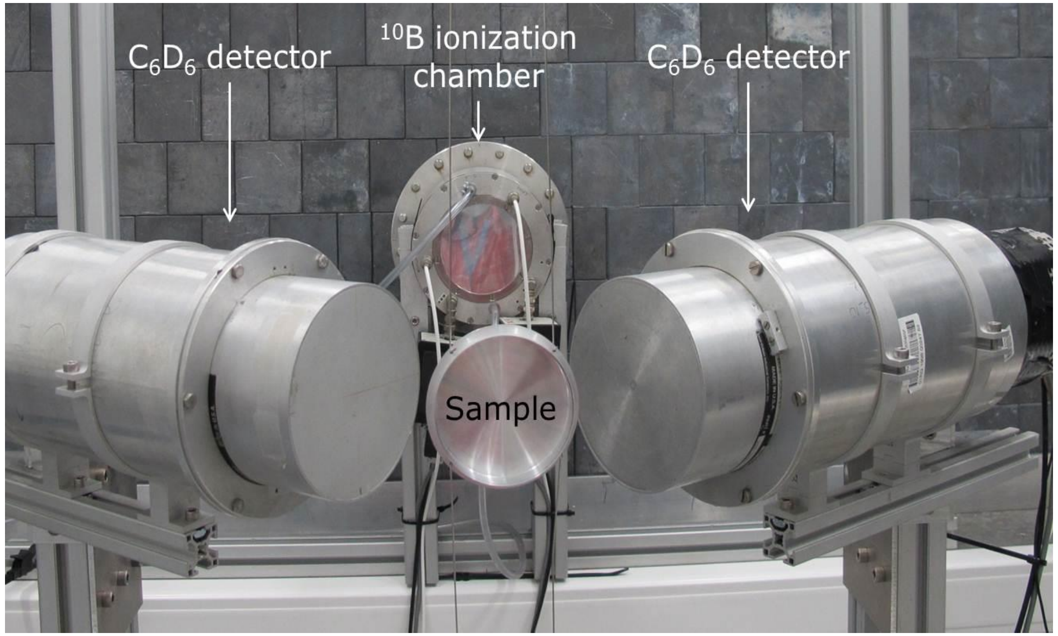
GELINA – (n,γ) at 12.5 m, 30 m and 60 m

- Total energy detection principle
  - C_6D_6 liquid scintillators
    (Boron free quartz window!)
  - 125°
  - Pulse Height Weighting Technique

$$C_w = \int C_c(E_d)\, WF(E_d)\, dE_d$$

$$\varepsilon_\gamma \propto E_\gamma \quad \Rightarrow \quad \varepsilon_c \propto S_n + E_n \frac{A}{1+A}$$

- Fluence rate measurements (IC)
  - **$^{10}B(n,\alpha)$**
  - $^{235}U(n,f)$



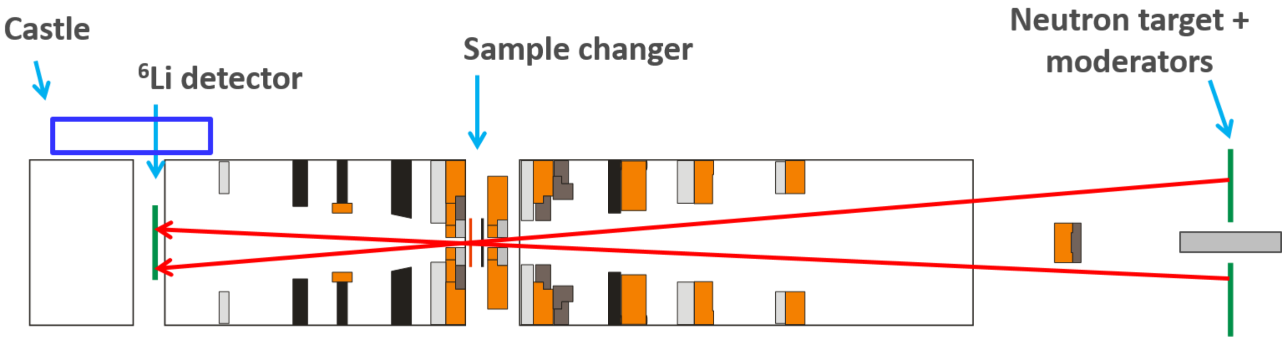
$$Y_{exp} = N \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$

GELINA – (n,tot) at 10 m, 30 m and 50 m

- Transmission: direct relation between T_{exp} and σ_{tot}

$$T_{exp} = \frac{C_{in}}{C_{out}} \propto e^{-n\sigma_{tot}}$$

- Incoming neutron flux cancels
- Detection efficiency cancels
- Li-glass scintillator ^{6}Li(n,t)α



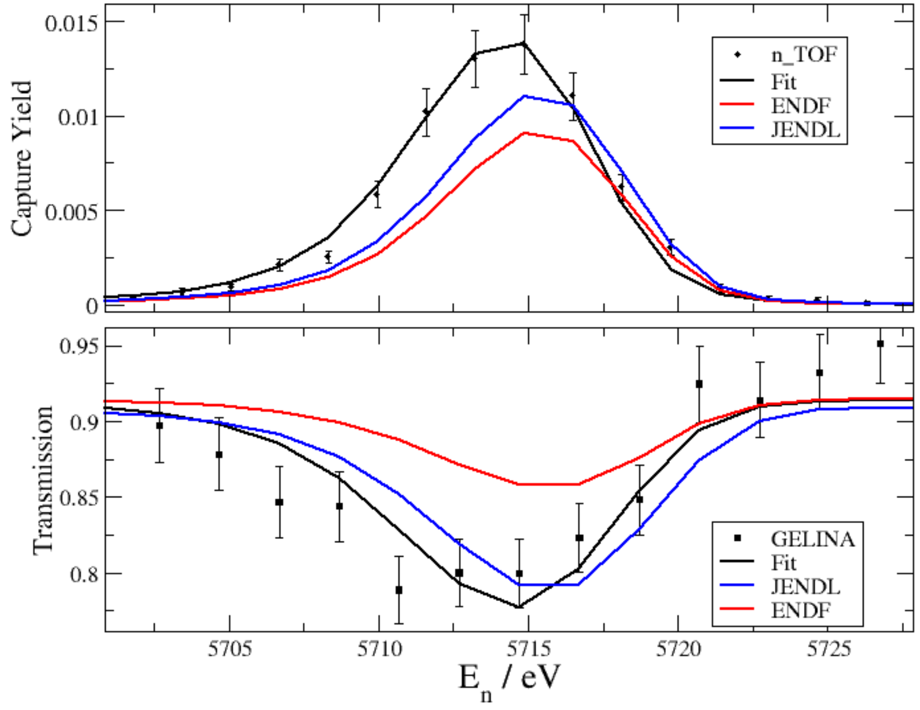
^{89}Y(n,tot) (n,γ) cross section measurement

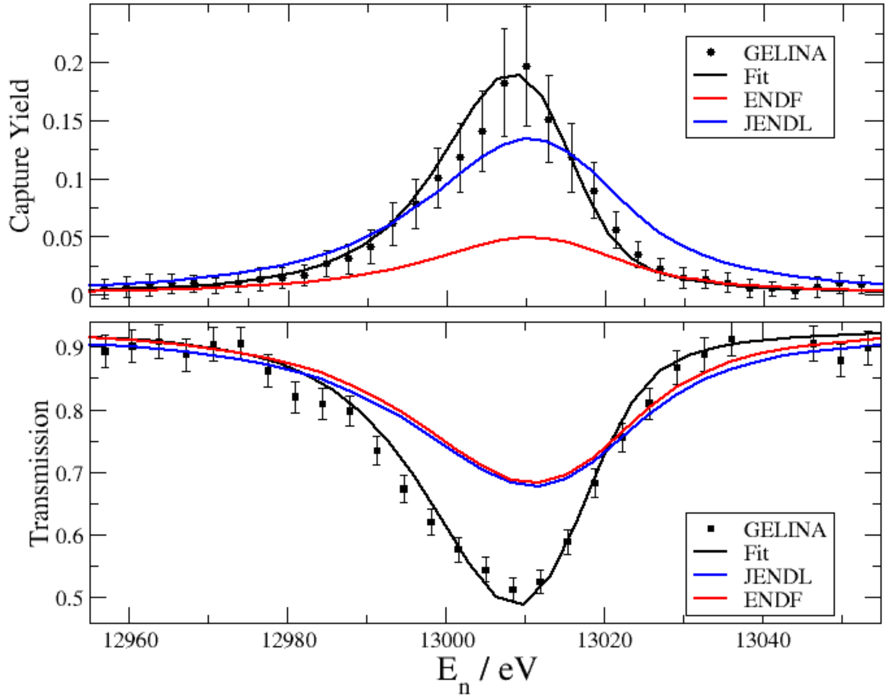
❑ n_TOF

- (n,γ) at 185 m
- 1 sample of 1 mm thickness (30 mm ∅)

❑ GELINA

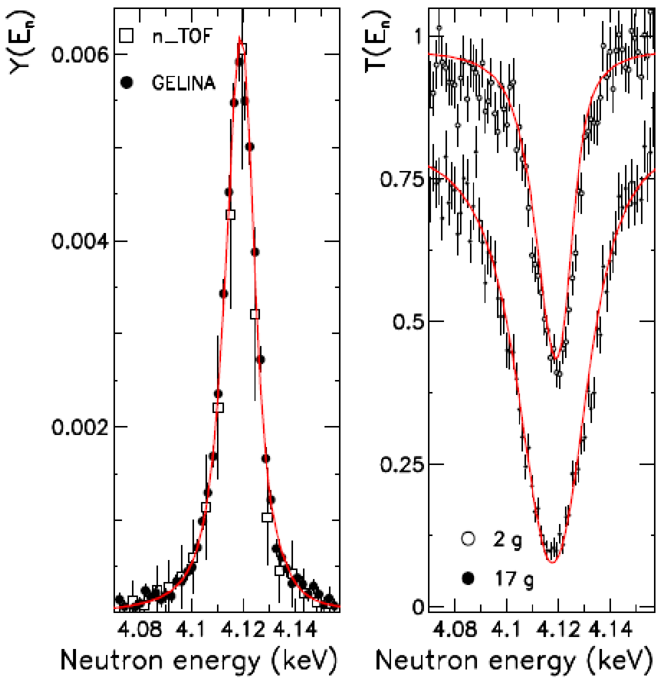
- (n,γ) at 60 m and 2 mm thick sample (80 mm ∅)
- (n,tot) at 50 m and 3 sample thicknesses: 1.28, 2 and 4.48 mm



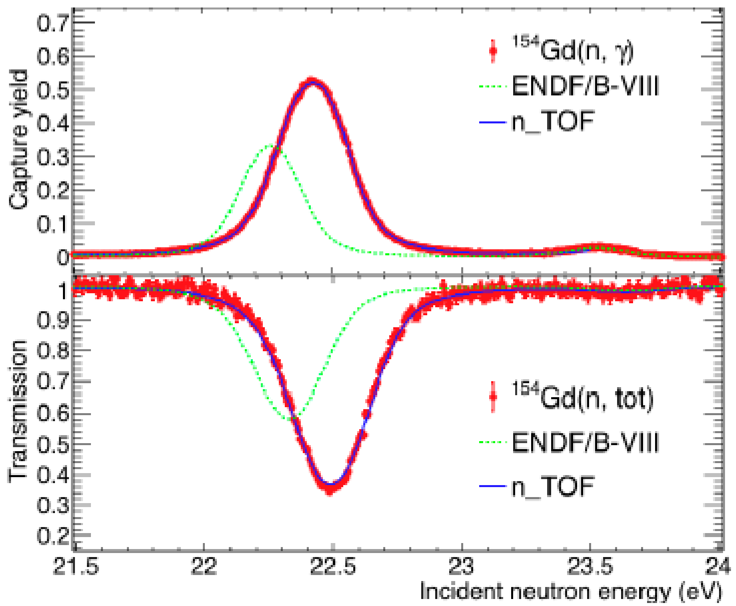


GELINA + n_TOF: other examples

- ^{92}Zr + n
  - n_TOF : (n,γ) at 185 m
  - GELINA:
    ^{92}Zr(n,γ) at 30 m
    ^{92}Zr(n,tot) at 50 m



- ^{154,155,156,157,158,160}Gd + n
  - n_TOF : ^{154,155,157}Gd(n,γ) at 185 m
  - GELINA:
    ^{155,156,157,158,160}Gd(n,γ) at 30 m
    ^{154,155,157,nat}Gd(n,tot) at 10 and 50 m

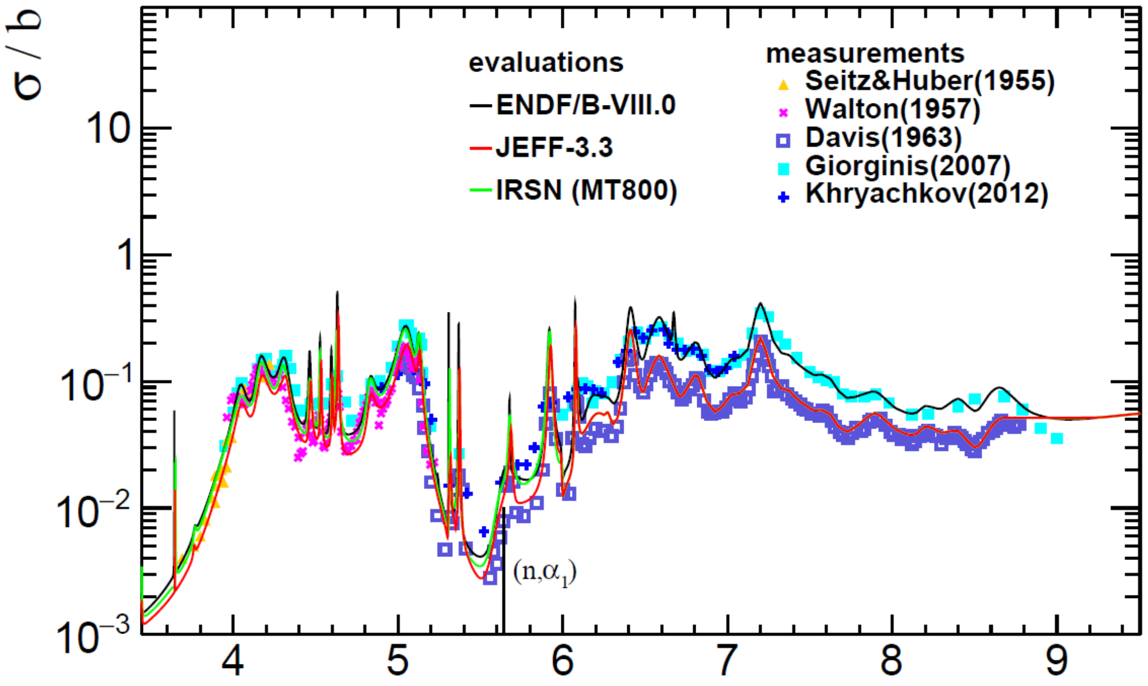


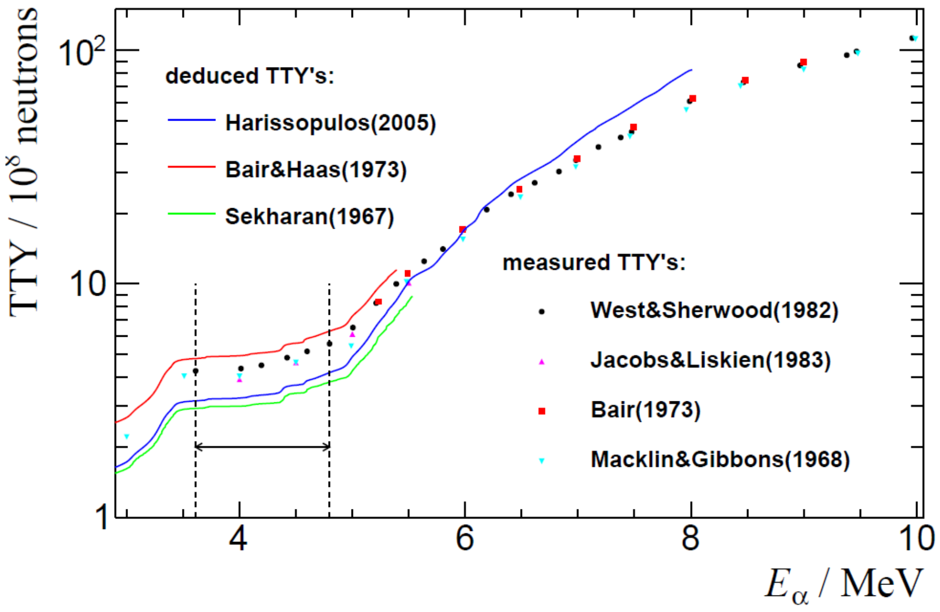
Kye et al. Eur. Phys. J. A (2020)56:30
Mazzone et al. Phys. Lett. B 804 (2020) 1354

$^{16}O(n,\alpha)$ cross section

- Impact for s-process: $^{13}C(\alpha,n)^{16}O$ inverse reaction
- Large discrepancies among experiments and evaluations of $^{16}O(n,\alpha)$

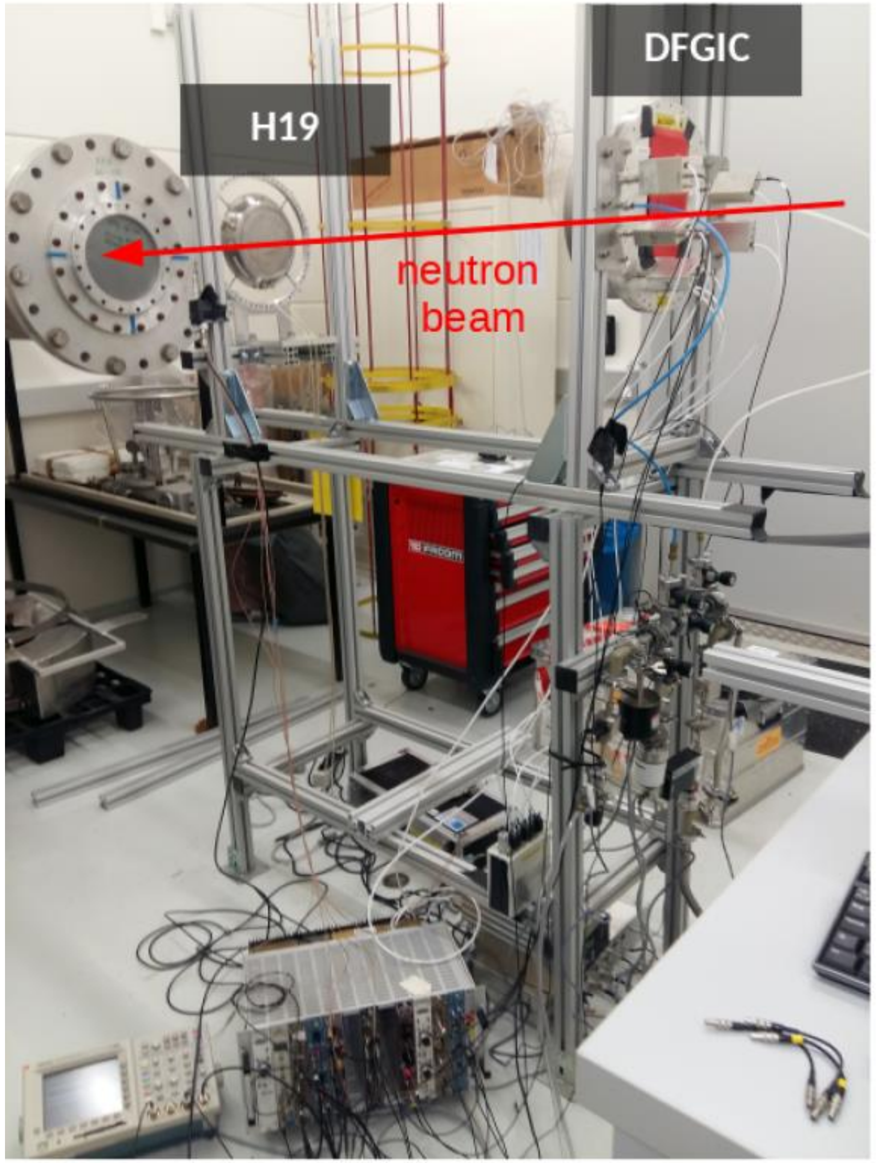
- $^{13}C(\alpha,n)$ thin target experiments show discrepancies
- Consistency of thick target experiments





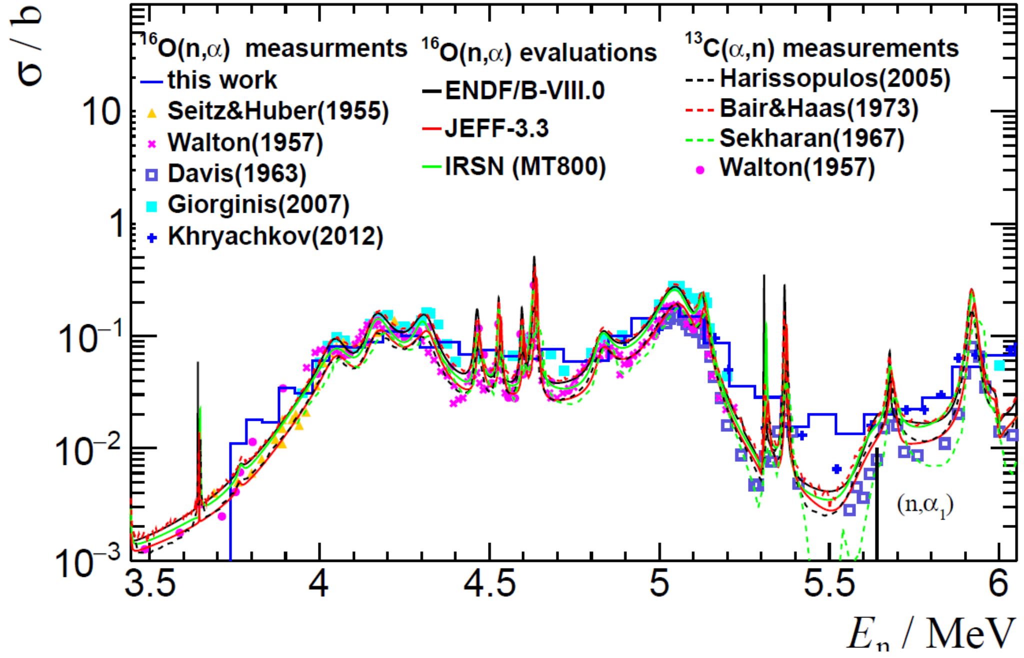
$^{16}O(n,\alpha)$ measurement at GELINA

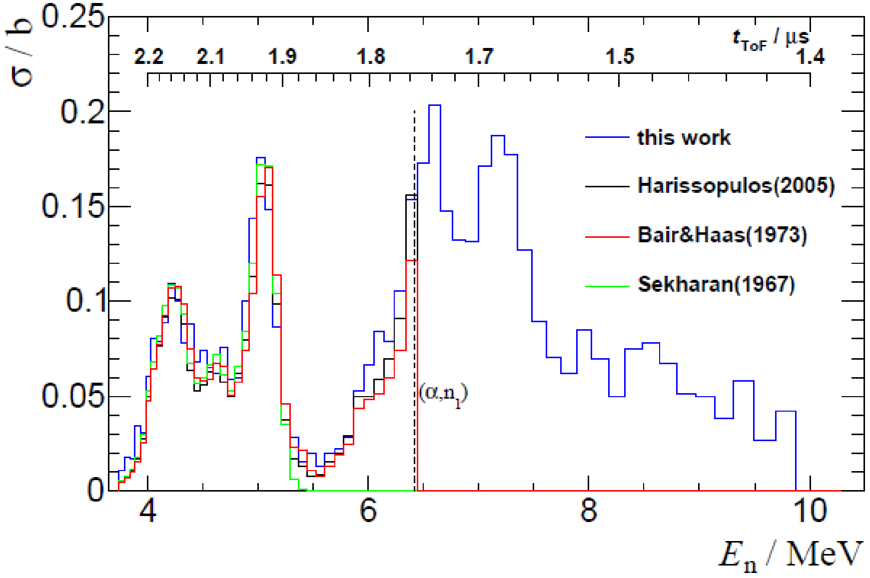
- Proposed by HZDR
- ^{16}O(n,alpha) reaction measured with a FGIC at 2 bar 95% Kr + 5% CO2
- Incoming neutron flux monitored by ^{235}U(n,f) H19 chamber from PTB (10 ^{235}U layers)
- FP16-60m during 2 weeks



$^{16}O(n,\alpha)$ measurement at GELINA

- Reduced TOF resolution (27 ns)
- Discrimination only for (n,α_0)
- Absolute measurement
  - Careful determination of areal density
  - Validation by C(n,n) reactions
- Comparison to converted data from $^{13}C(\alpha,n)\,^{16}O$





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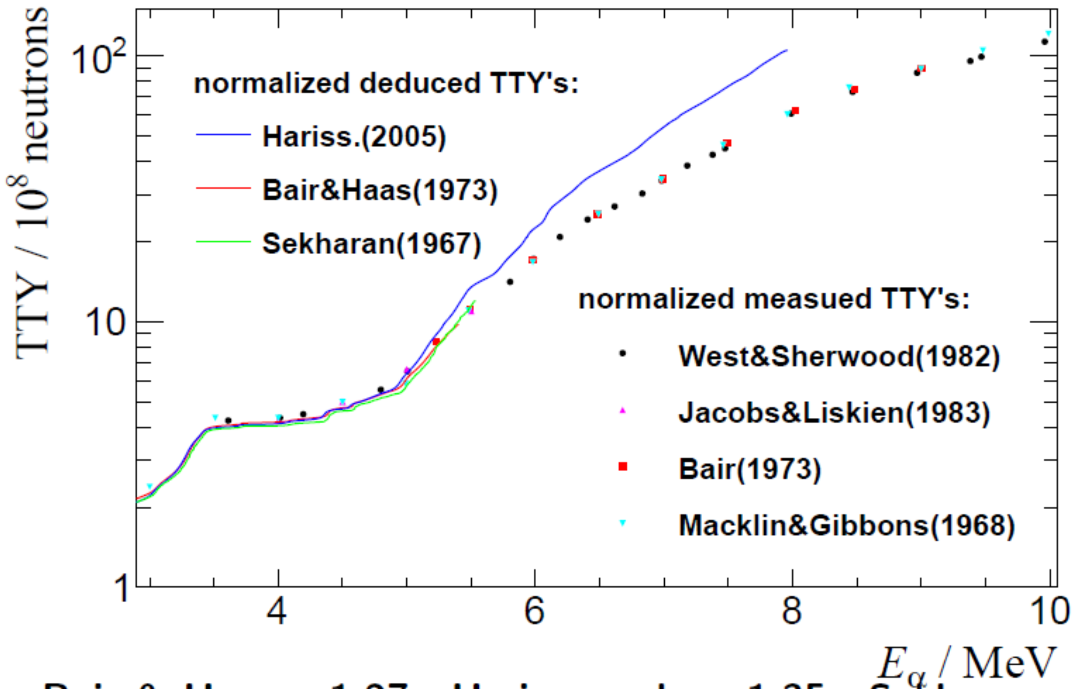
^{16}O(n,alpha) cross section measurement

The result agrees with Thick Target Yield (TTY) renormalization



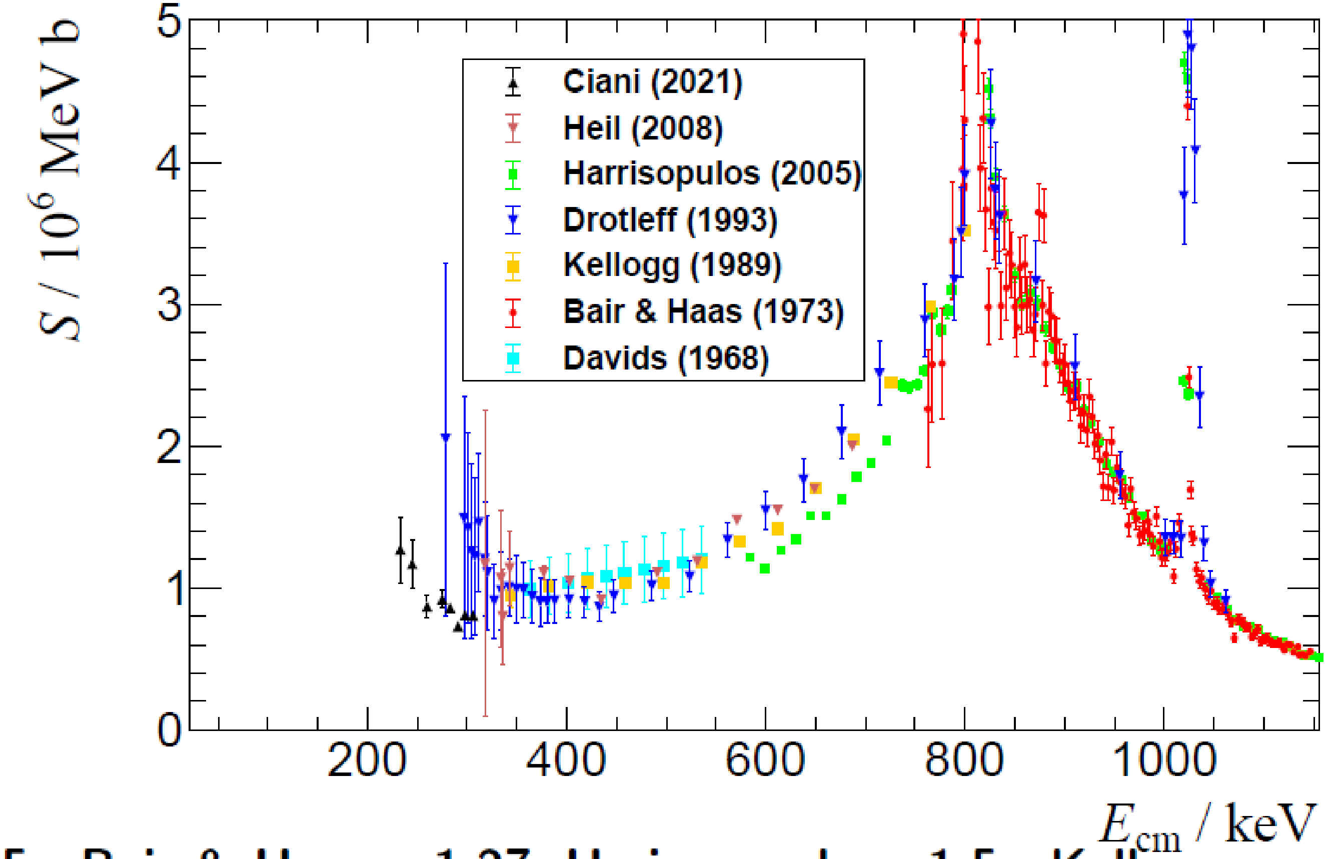
0.85 · Bair & Haas , 1.27 · Harissopoulos, 1.35 · Sekharan

	$^{16}O(n,\alpha_0)$ data (this work)	West and Sherwood TTY [3]	Pigni and Croft [4]	Ciani et al. [5]
main uncertainty	5% N_T^{16O} (^{16}O target)	8% ^{13}C abundance	8% ^{13}C abundance	8% detection efficiency
Bair and Haas [6]	0.87	0.85	0.8	
Harissopoulos [7]	1.30	1.27	1.15	1.37
Sekharan [8]	1.37	1.35		
IRSN [9]	1.02	1.00		
ENDF/B-VIII.0	0.92	0.89		
JEFF-3.3	1.26	1.25		

^{16}O(n,alpha) cross section measurement

Implication for s-process stellar nucleosynthesis

- 800-1000 keV: agreement of Drotleff with Bair&Haas and Harissopoulus (renorm.)
- 300-800 keV: Drotleff, Heil, Davids



0.85 · Bair & Haas , 1.27· Harissopoulos, 1.5 · Kellogg

Summary

- GELINA: High-resolution TOF measurements for (n,γ), (n,tot) and (n,α)

- Multi-user facility: 11 flight paths in use (10 m – 400 m)
  - Adaptability in energy range
  - Beam time availability

- In-house detectors and acquisition system or/and equipment provided by external users

- Complementarity with other facilities like n_TOF
  - Combination of transmission and capture data for different isotopes

- Open to proposals on neutron cross sections relevant for astrophysics.
  - 2022 call deadline on 9th September
  - Proposal on Sr-88 cross sections from INFN

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