Activation cross section measurements of short-lived reaction products on Mo isotopes induced by 16 to 20 MeV neutrons

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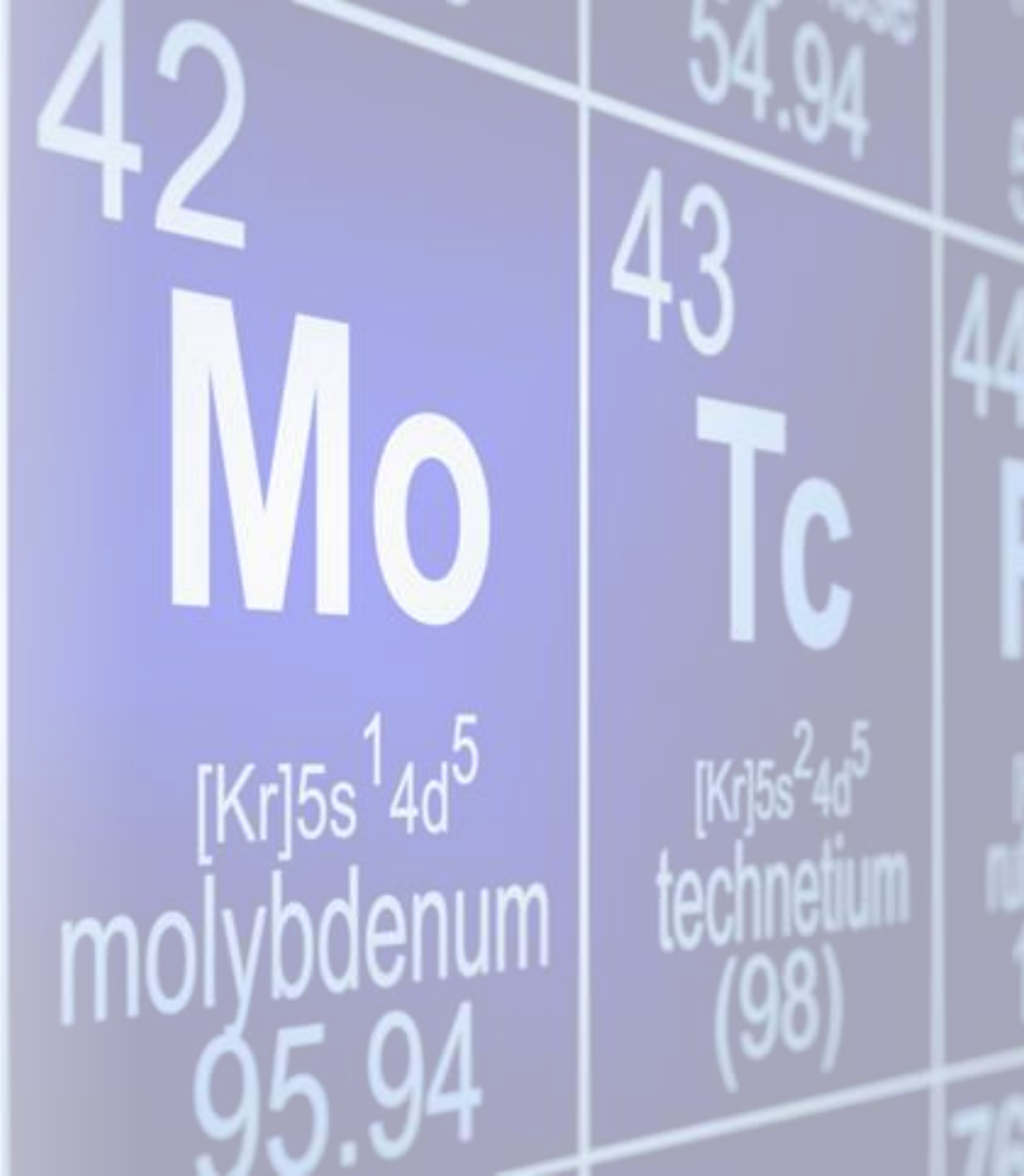


Motivation

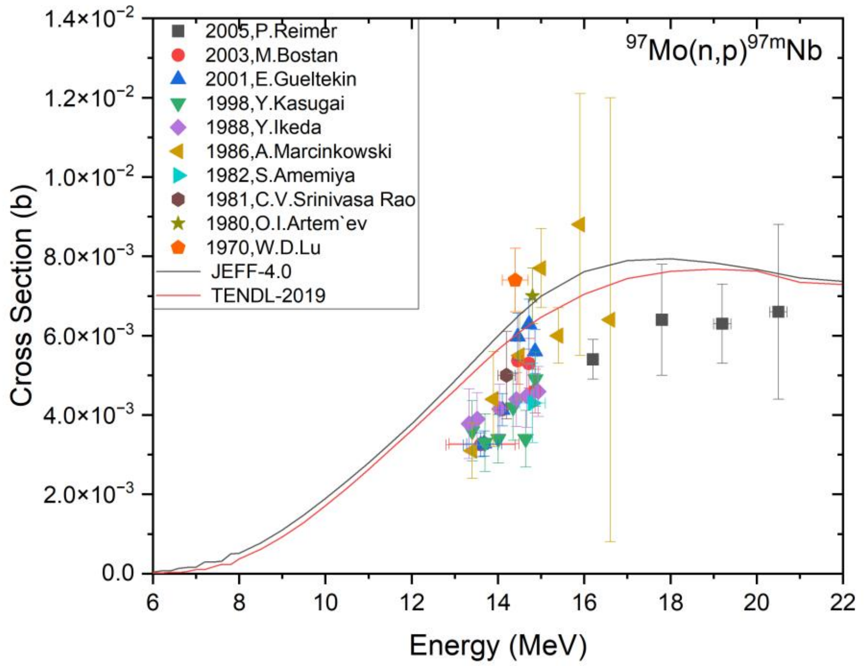
- Accurate cross-section measurements for **short-lived reaction products** are vital for Fundamental Nuclear Physics, Reactor Technology, Astrophysics and Medical Applications

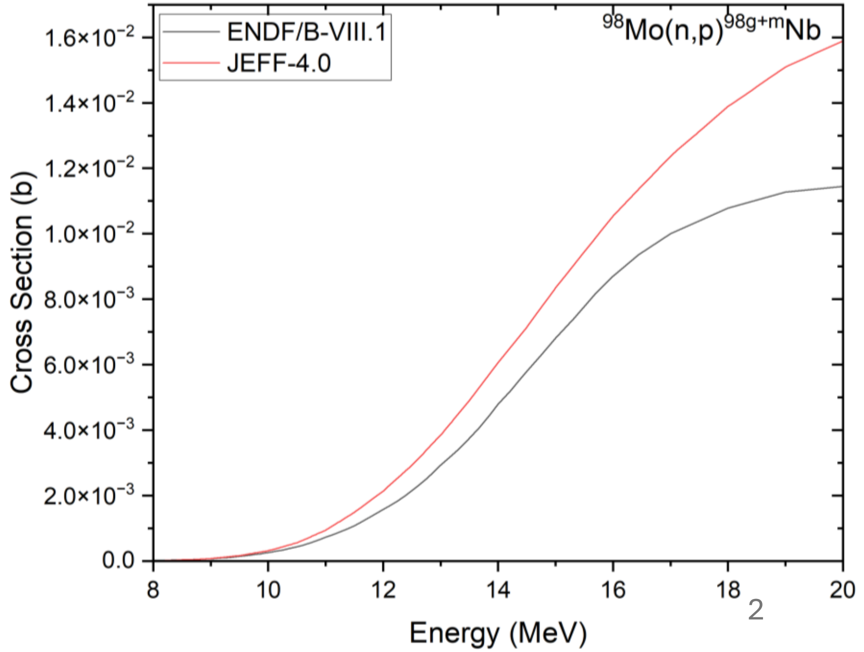
- **The Experimental Challenge :** The rapid decay of the reaction products and interference from neighboring isotopes

- **The Solution :** **1.** Fast Pneumatic "Rabbit" System
  2. Highly Enriched Targets (of Mo)
- **But why Mo?**

Nuclear Technology: Mo is highly resistant to heat, making it an ideal structural material for advanced nuclear reactors like ITER and Accelerator-Driven Systems (ADS)

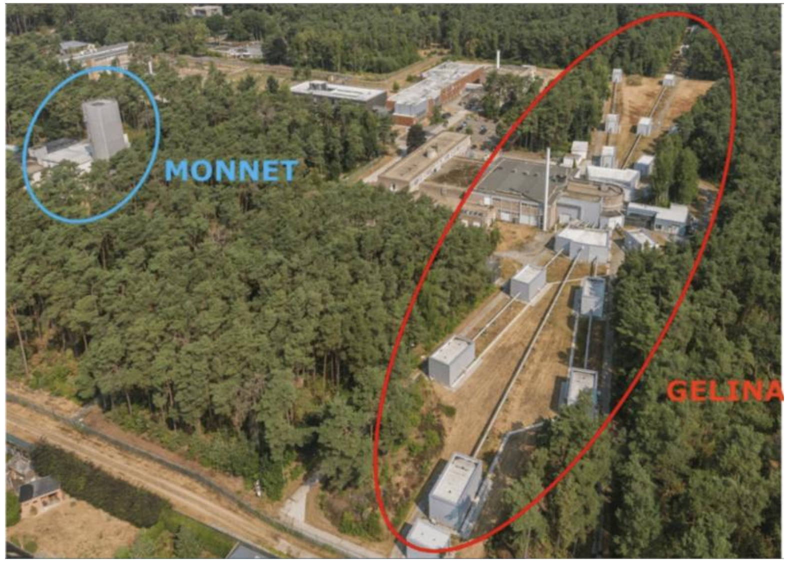
Medical Applications: It is also critical for producing medical isotopes like ^{99m}Tc

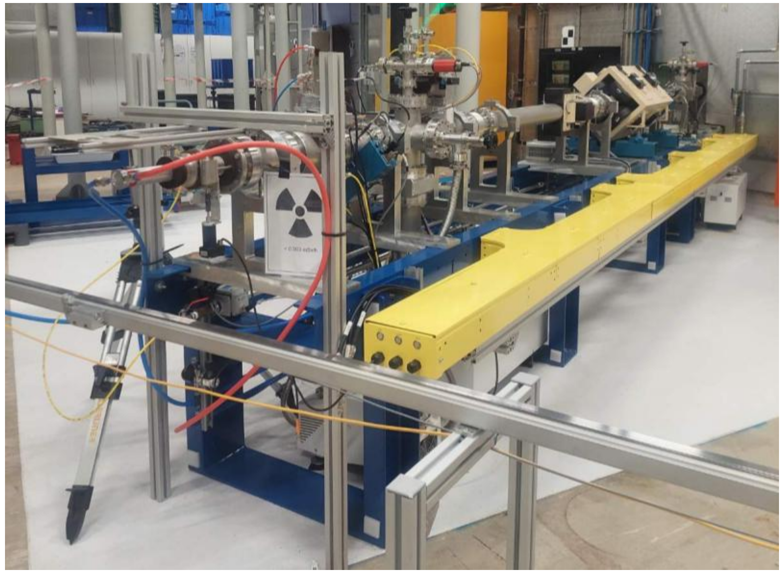




The MONNET Facility at JRC-Geel

- The facility operates under the **Joint Research Centre**'s nuclear research center in **Geel, Belgium**
- **Neutron Source:** A high-intensity, quasi-monoenergetic fast neutron facility (up to 24 MeV)
- **Accelerator:** Van De Graff 3.5 MV accelerator
- **Beam Flexibility:** Continuous and pulsed proton, deuteron, and helium ion beams
- **Applications**: Nuclear data research for activation, fission and scattering experiments, complementing the GELINA time-of-flight facility



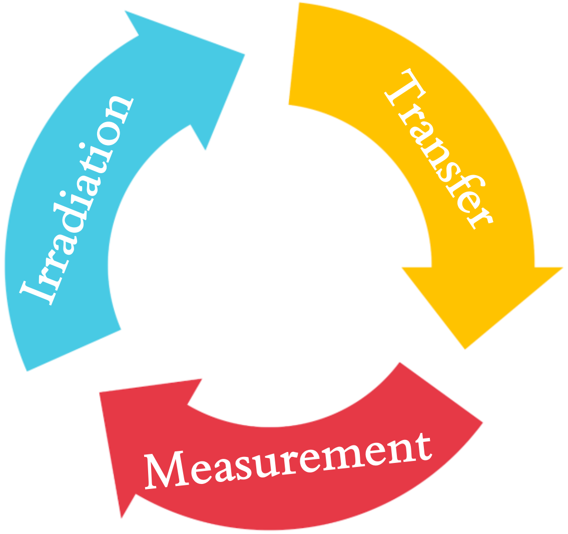


Experimental Set-up

- **Neutron Production:** Quasi-monoenergetic fast neutrons produced via the **$^{3}H(d,n)^{4}He$** reaction (E_n = 16-20 MeV)
- **Flux Monitor:** A De Pangher Proportional Long Counter (PLC) equipped with a 10 Hz pulser to continuously monitor neutron flux and system dead-time
- **HPGe Detector:** HPGe detector of 48.2% relative efficiency
- **Shielding:** consisting of Pb, Cu and a custom-made wall of Pb and concrete
- **The Pneumatic "Rabbit“ System:** High-speed transport system (FESTO)

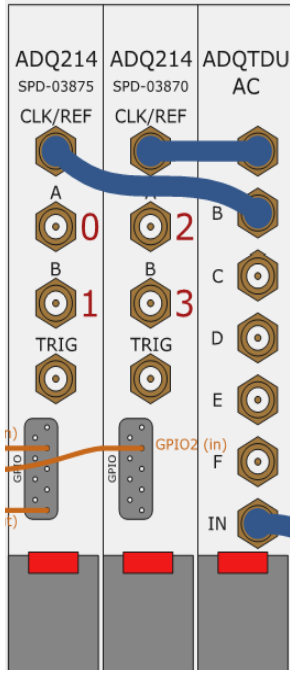
Methodology: Neutron Activation Technique

- **Neutron energies**: **16.1, 17.3, 18.2 and 19.6 MeV**
- **Reference reaction**: **^{27}Al(n,p)^{27}Mg, $t_{1/2}$= 9.58 min**
- **Target**: Highly enriched **^{97}Mo (98.2%)** and **^{98}Mo (98.67%)** targets, provided by the **CERN n_TOF** collaboration
- **Configuration:** Sequential irradiation (Al foil & Mo targets) at the exact same position (~9 cm away from T target)
- **Cyclic Activation:** Multiple irradiation-measurement cycles applied to Mo isotopes to build sufficient counting statistics for short-lived products.



Sample	Reaction	Half-life	Irradiation time	Transfer time (sec)	Measurement time	Number of cycles
Al	^{27}Al(n,p)^{27}Mg	9.458 min	15 min	~ 3	30 min	1-2
Background			15 min	~ 3	30 min	1
^{97}Mo	^{97}Mo(n,p)^{97m1}Nb	58.7s	5 min	~ 3	8 min	2-9
^{98}Mo	^{98}Mo(n,p)^{98}Nb	2.86 s	15 s	~ 3	30 s	15

High-Precision transfer time

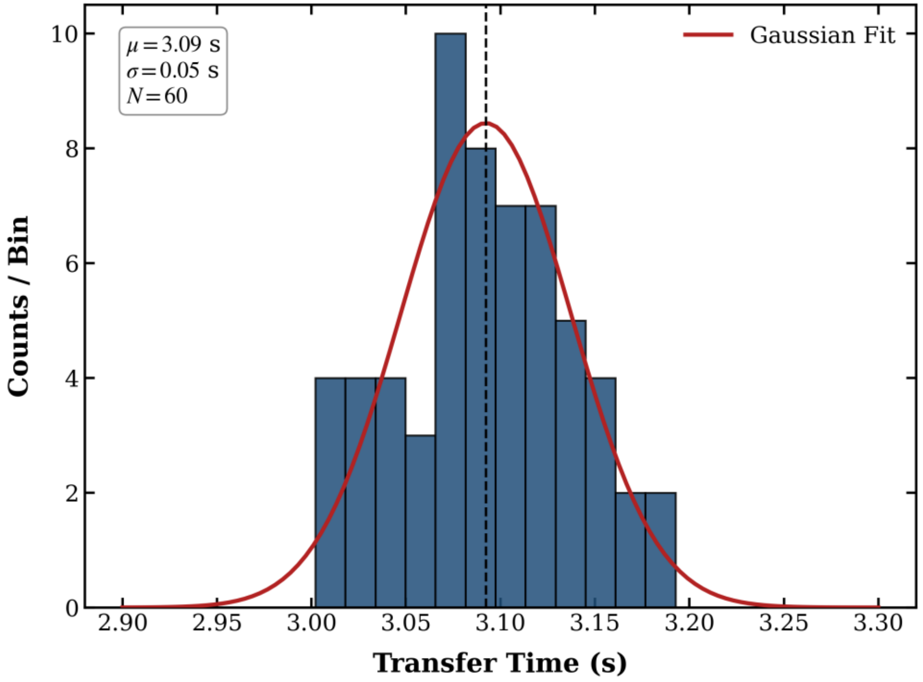


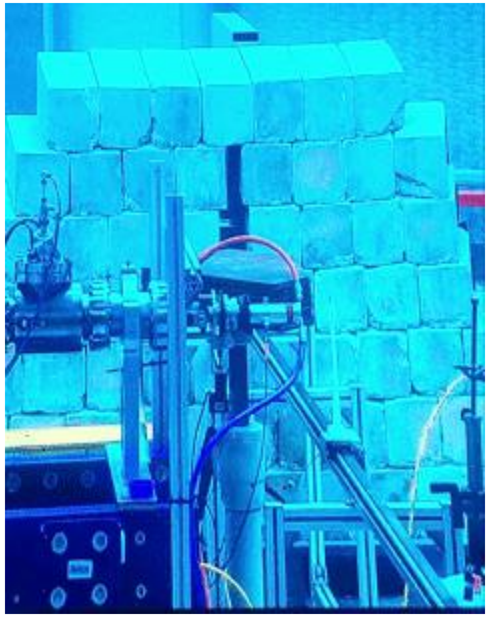
Timing Calculation Signals:

- **Signal 1 (Start):** The accelerator pulse **(DAQ Ch3)** marking the end of the irradiation (NEPTUNE).
- **Signal 2 (Stop):** The Rabbit optical sensor **(DAQ Ch1)** detecting the sample's arrival inside the lead castle.

The time interval between the signals was precisely captured using synchronized 50 MHz digitizers.

Result: Transfer time of **(3.09 ± 0.05) s** over 60 cycles.





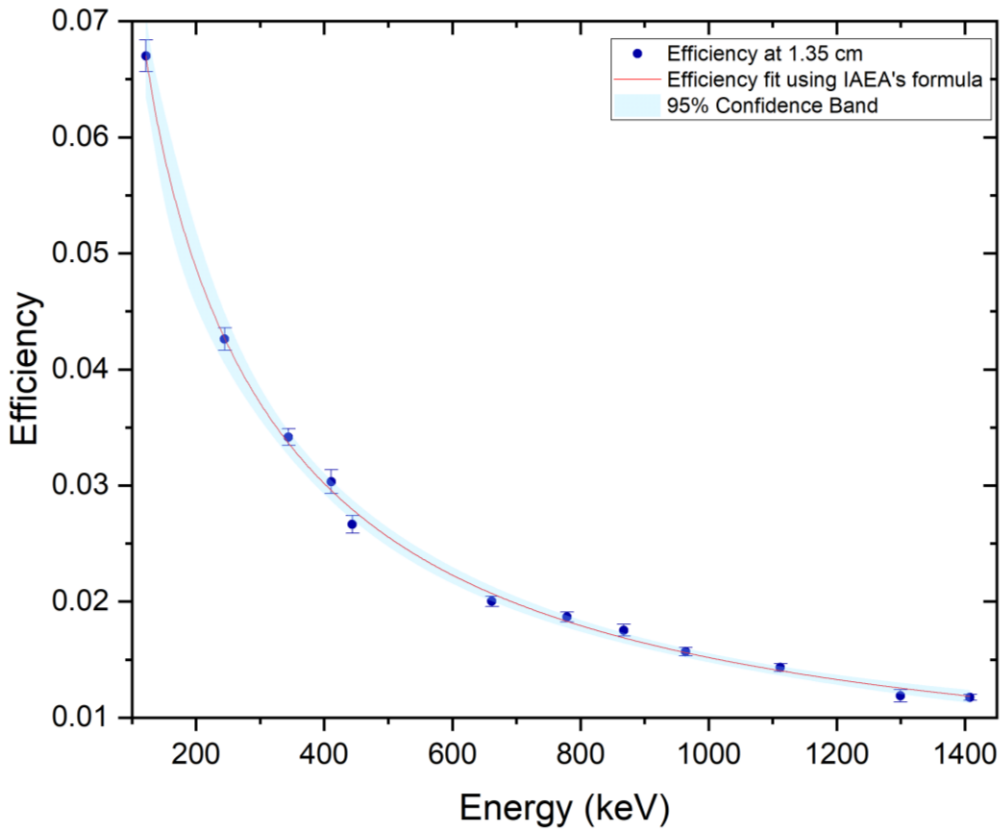
HPGe detector & Efficiency Measurement

Detector Specifications:

- **Model:** Canberra HPGe GR4520 (48.2% relative efficiency).
- **Calibration Sources:** ^{152}Eu and ^{137}Cs point sources

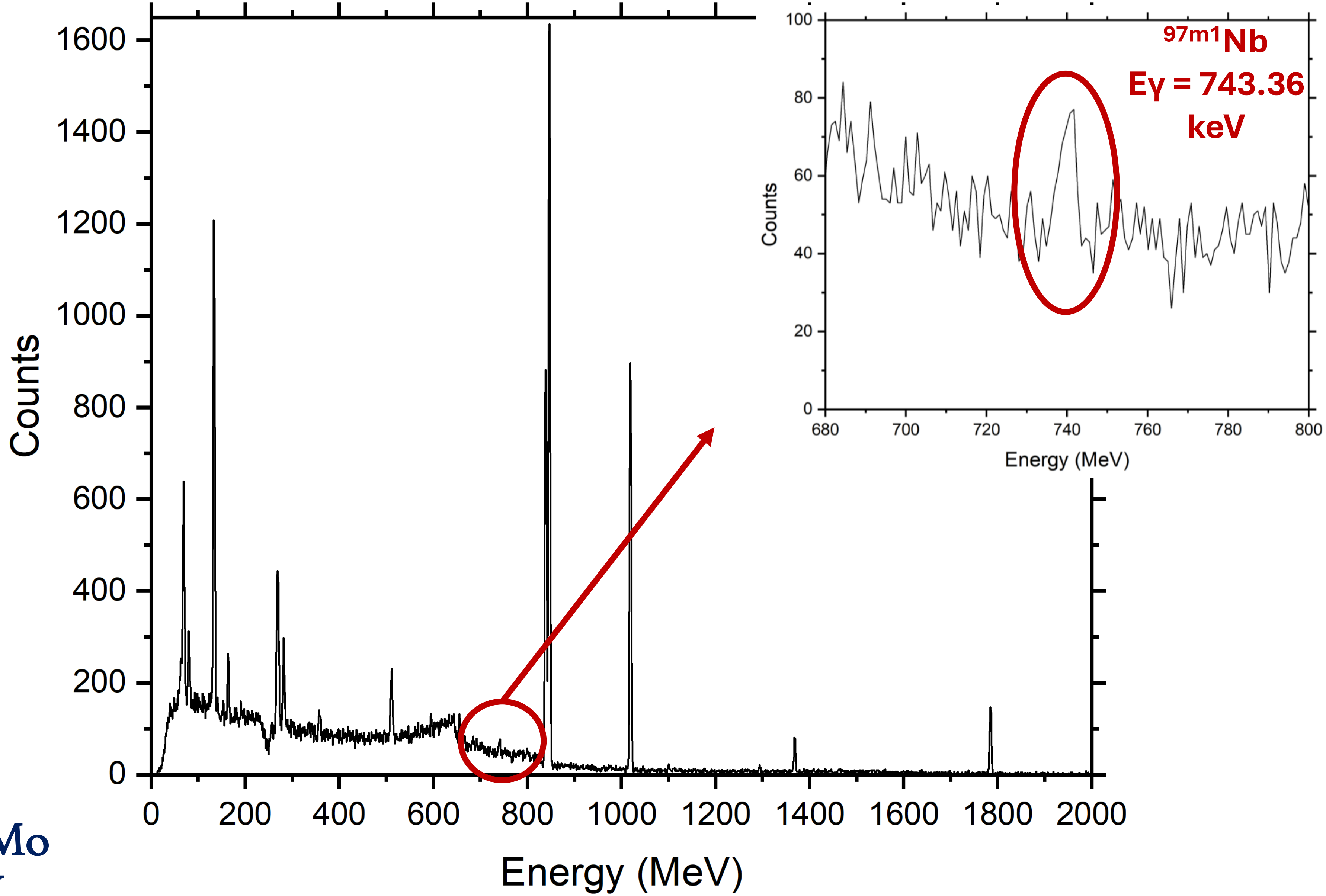
Efficiency & Geometry Corrections:

- **Distance Mapping:** Measured at 13, 9, 5, 4, 3, 2, and 1.35 cm to study True Coincidence Summing (TCS) effects.
- **Current Methodology:** Efficiency at 1.35 cm derived by applying a geometrical scaling factor to the 13 cm reference position.
- **TCS Corrections:** Ongoing **MCNP-CP** simulations to correct for cascading γ-rays.



Reaction	Half-life (sec)	E_γ (keV)
^{27}Al(n,p)^{27}Mg	567.48	1014.52 (28.2 %)
^{97}Mo(n,p)^{97m}Nb	58.7	743.36 (97.9%)
^{98}Mo(n,p)^{98}Nb	2.6	787.4 (13%)

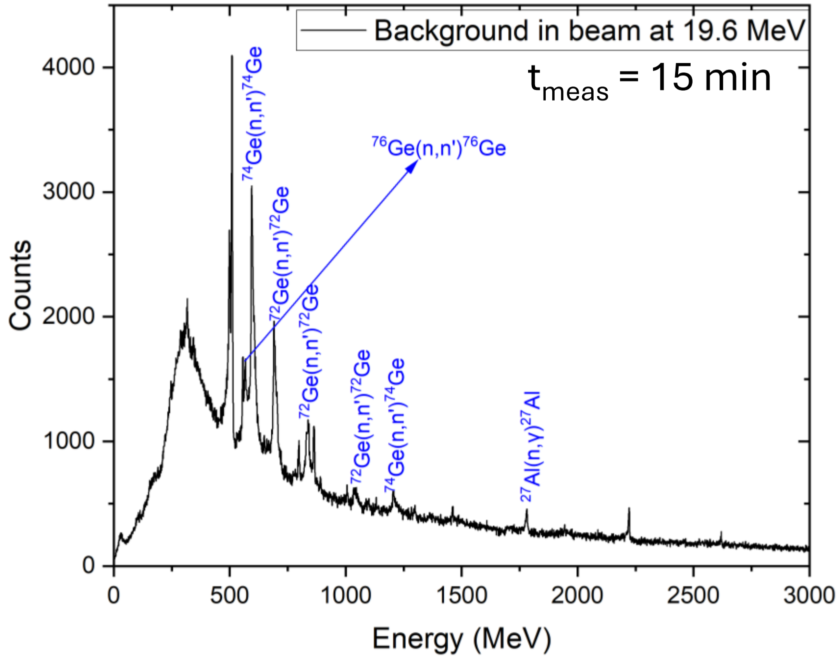
Typical spectrum



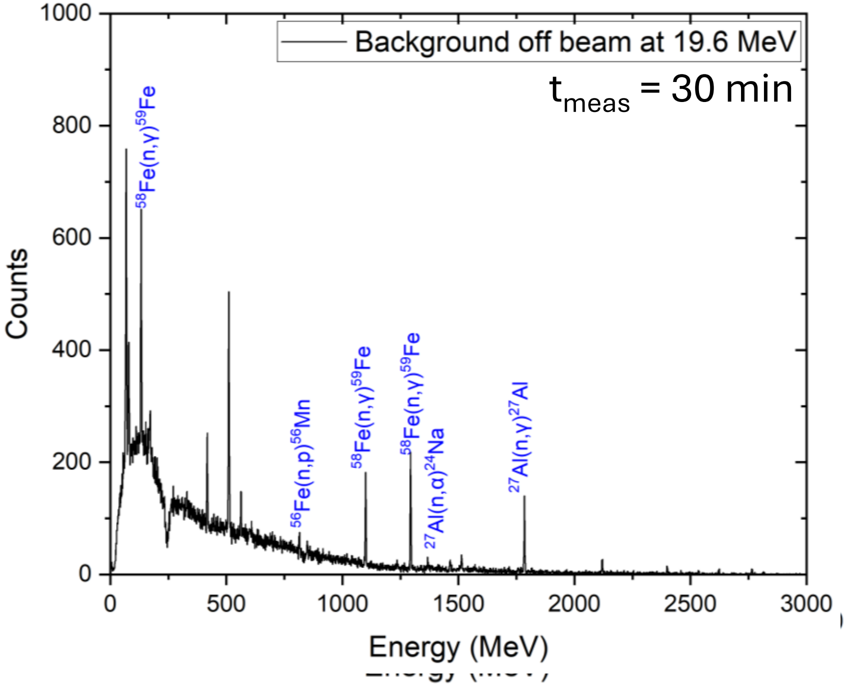
HPGe spectrum from the irradiation of ^{97}Mo at E_n = 16.1 MeV

Background measurements

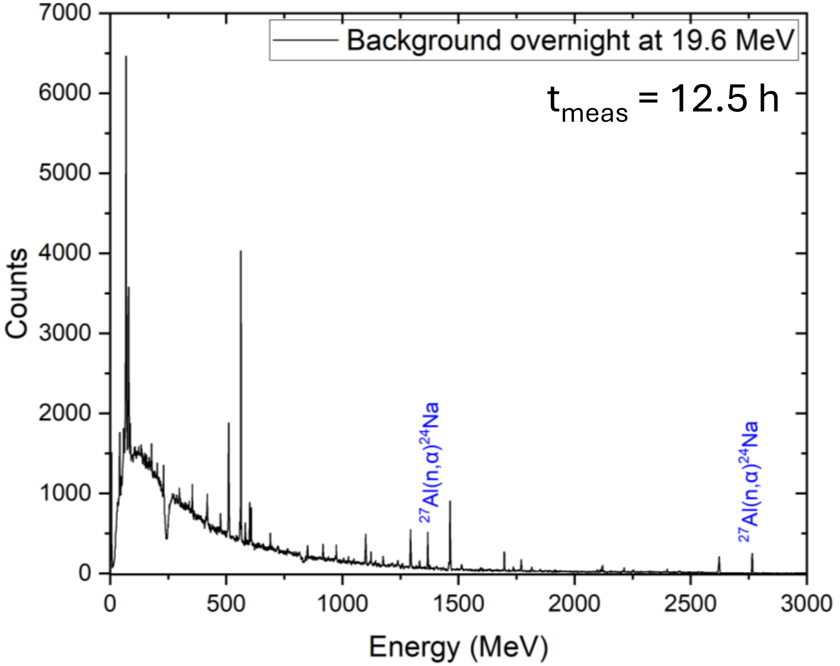
During Irradiation



Immediately After



Overnight



Cross Section

Cross Section formula:

$$\sigma = \frac{N_\gamma}{N_T \cdot \Phi \cdot \varepsilon \cdot I_\gamma \cdot D \cdot F \cdot f_c}$$

Correction factors:

F: γ-ray self-absorption within the sample, calculated via MCNP6.0 simulations.

D: Decay during the transfer and measurement intervals. $D = e^{-\lambda t_{tr}} - e^{-\lambda(t_{tr}+t_{meas})}$

f_c: Decay during irradiation and neutron beam instabilities (integrated via the De Pangher monitor).

N_T: Total number of target nuclei

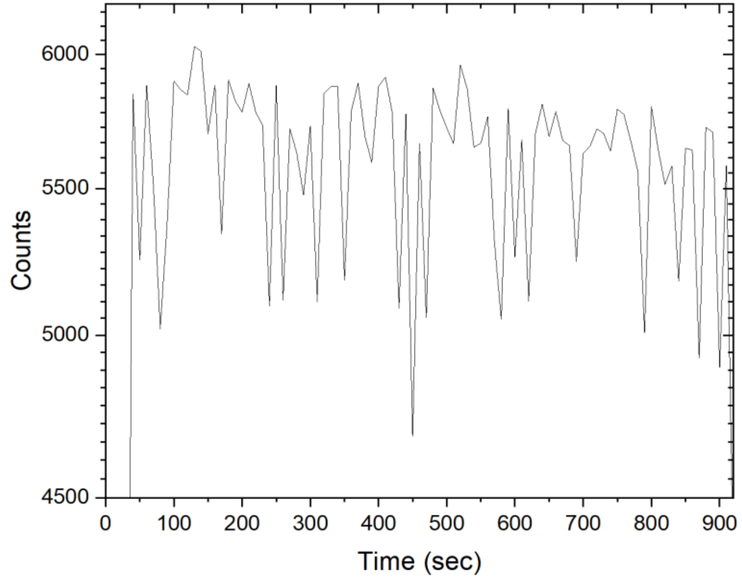
N_γ: Integral of the γ-ray peak of interest

I_γ: Characteristic γ-ray intensity

ε: Absolute efficiency of the HPGe detector

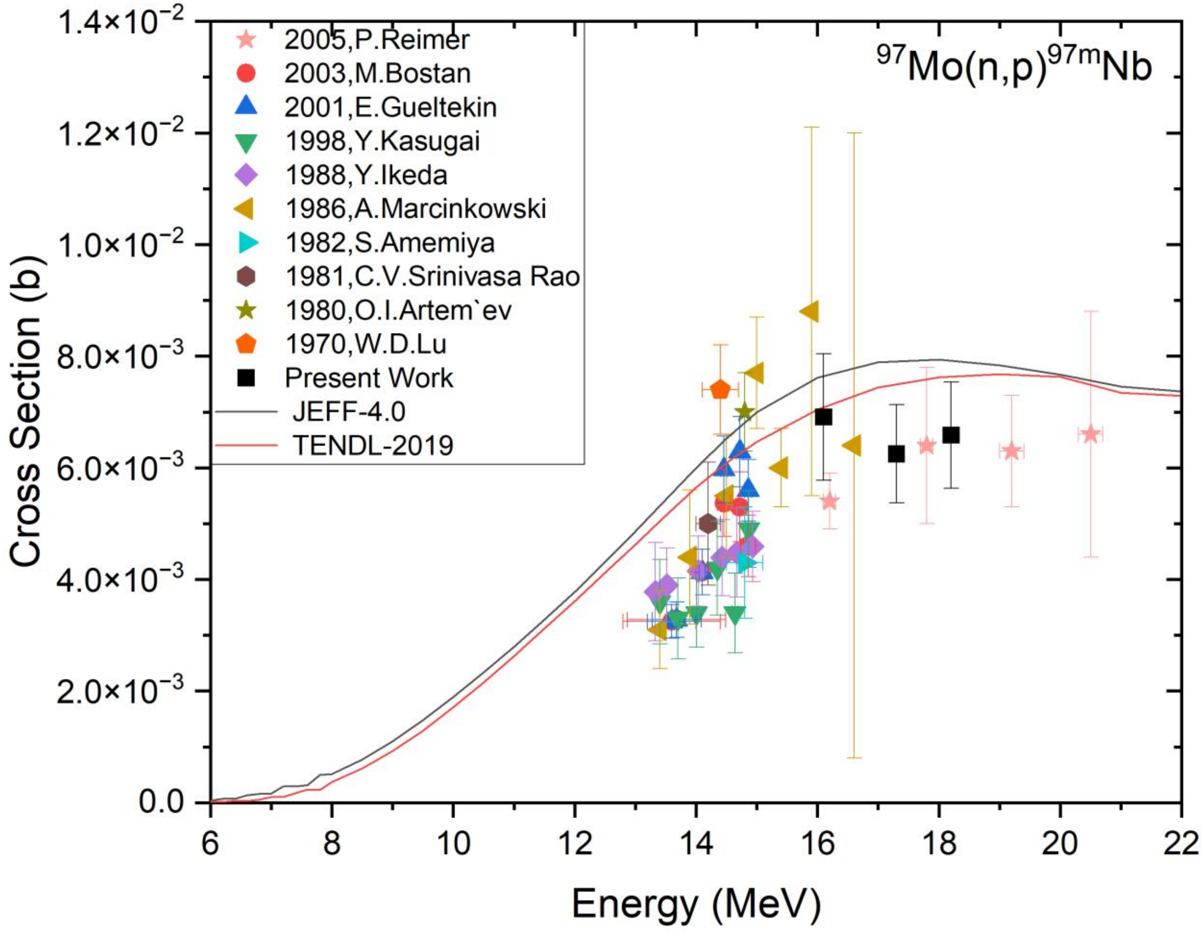
Φ: Neutron flux is derived from the reference reaction **$^{27}Al(n,p)^{27}Mg$**.

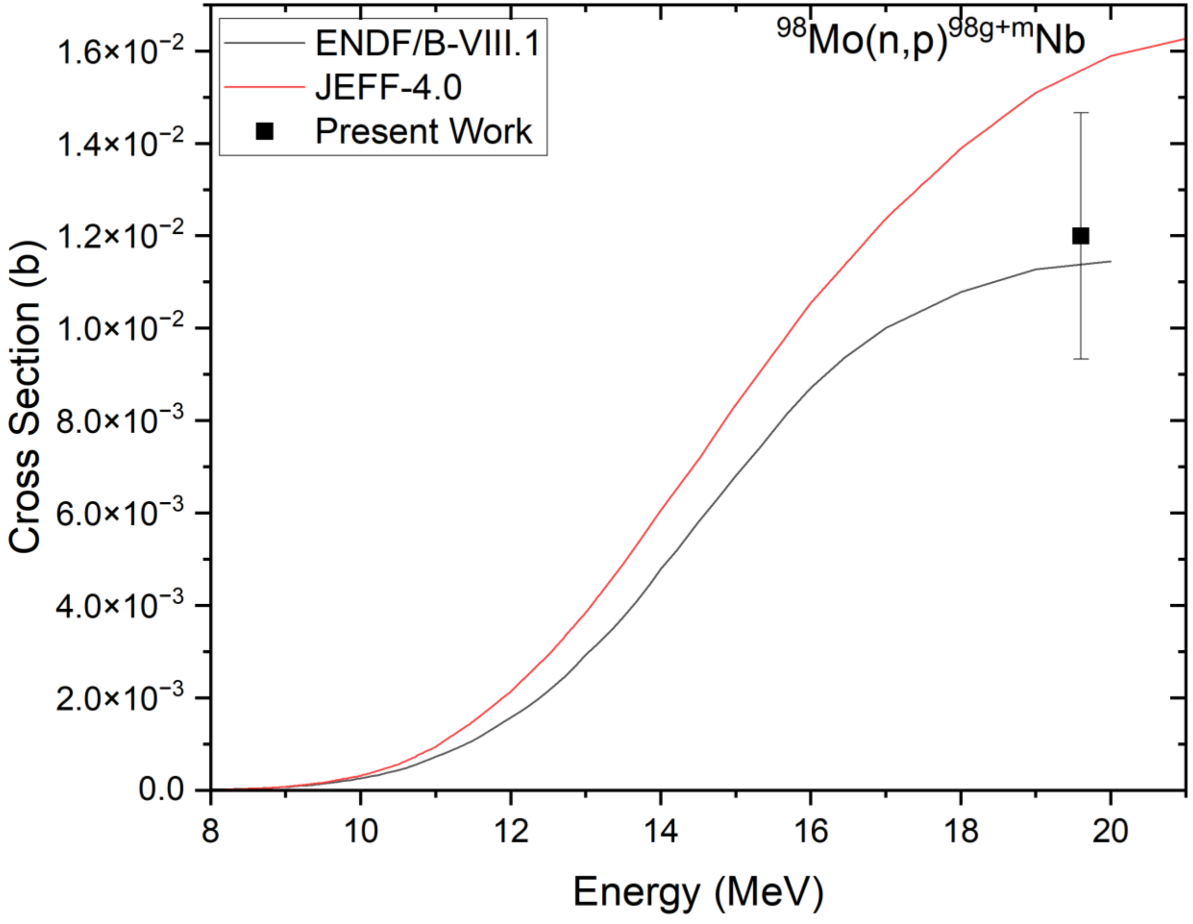
Normalization: The integrated flux is normalized to the target's beam current and specific irradiation time to yield the neutron flux for the target samples.



Al irradiation at 18.2 MeV, t_{irr} = 900 sec

Preliminary Cross Section Results





Conclusions & Future Perspectives

- Cross-section measurements of the **$^{97}Mo(n,p)^{97m1}Nb$ ($t_{1/2}$ = 58.7 s)** and **$^{98}Mo(n,p)^{98g+m}Nb$ ($t_{1/2}$ = 2.8 s)** reactions successfully performed in the **16–20 MeV** neutron energy range

- The reaction **$^{98}Mo(n,p)^{98g+m}Nb$** has been measured for the first time

- **Preliminary results** show **good agreement** with existing experimental data and the libraries

- Complete the **MCNP-CP** simulations to fully correct for True Coincidence Summing (TCS) effects

- Measure **additional neutron energies** across the 16–20 MeV range, with a specific focus on **^{98}Mo**

- Investigate the **remaining highly enriched Mo isotopes (^{92}Mo, ^{100}Mo)** and other materials (Ge, Au)

Thank you for your attention!!