



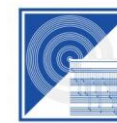
# High energy PIXE: new K-shell ionization cross-section

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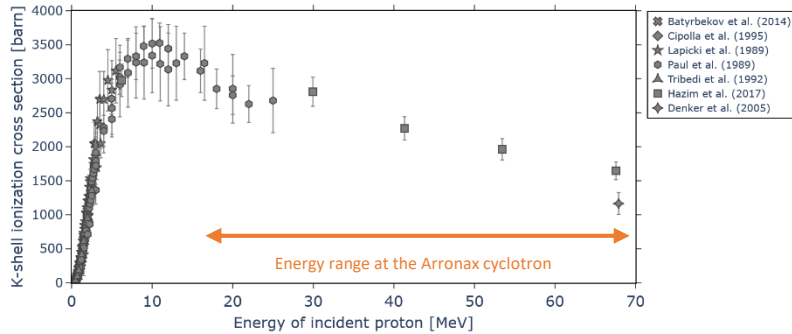
2 – GIP ARRONAX, Saint-Herblain, France

3 – Institut Bergonié, Bordeaux, France

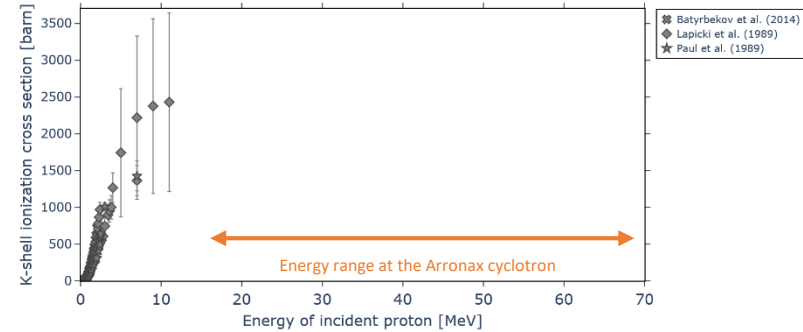


# Why new measures?

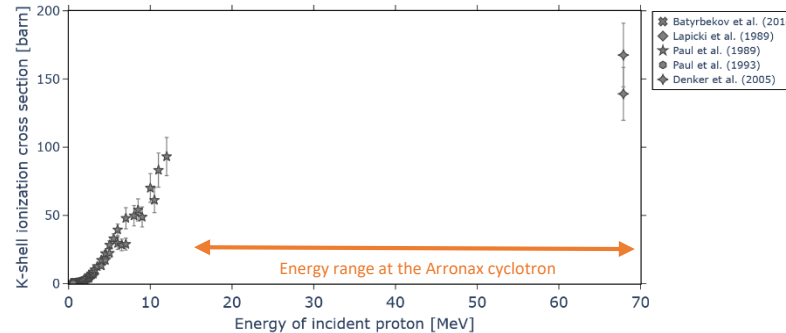
## Titanium



## Chromium



## Molybdenum



Ionization cross-section + medical accelerators → Non-destructive analysis

# HE-PIXE applications with medical accelerators



## ○ Radioisotope production facility:

- Trace elements → tea leaves (post-Fukushima) – protons 20 MeV

K. Ishii et al., Inter. Journal of PIXE, Vol. 28, Nos. 3 & 4 (2018) 93-100

- Trace elements → natural and artificial sodalite – protons 68 MeV

D. Ragheb, J. Radioanal. Nucl. Chem. (2014) 302:895-901

- See new applications at ARRONAX (A. Gillon P3-CH-28 and P3-CH-36)

## ○ Proton Therapy Centre:

- Multi-layer → painting « Judith with the head of Holofernes » – protons 68 MeV

A. Denker et al., Nucl. Instr. Meth. in Phys. Res. A 580 (2007), 457-461

- Depth → Gold Egyptian scarab – protons 68 MeV

A. Denker et al., Nucl. Instr. Meth. in Phys. Res. B 213 (2004), 677-682

- Trace elements → medieval Polish silver coins – protons 68 MeV

M. Hrnjic et al., Archaeometry 63, 3 (2021) 609-626

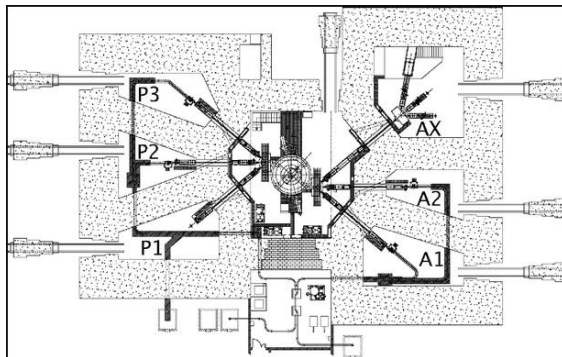
- Imaging (in development) → gold and platinum nanoparticles – protons 220 MeV

Bazalova-Carter et al., Med. Phys. 42 (2) 2015



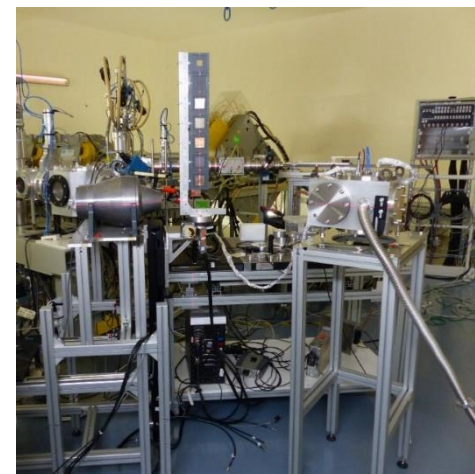
➔ Need to know the ionization cross-section

## Experimental set-up: Arronax Cyclotron

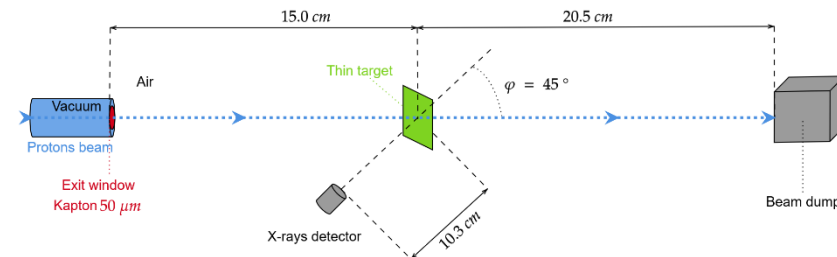


- For translational research in nuclear medicine
- Time dedicated to non-destructive analysis

<https://www.arronax-nantes.fr/>

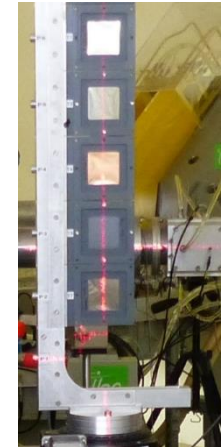
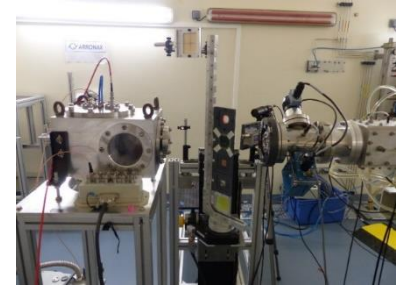
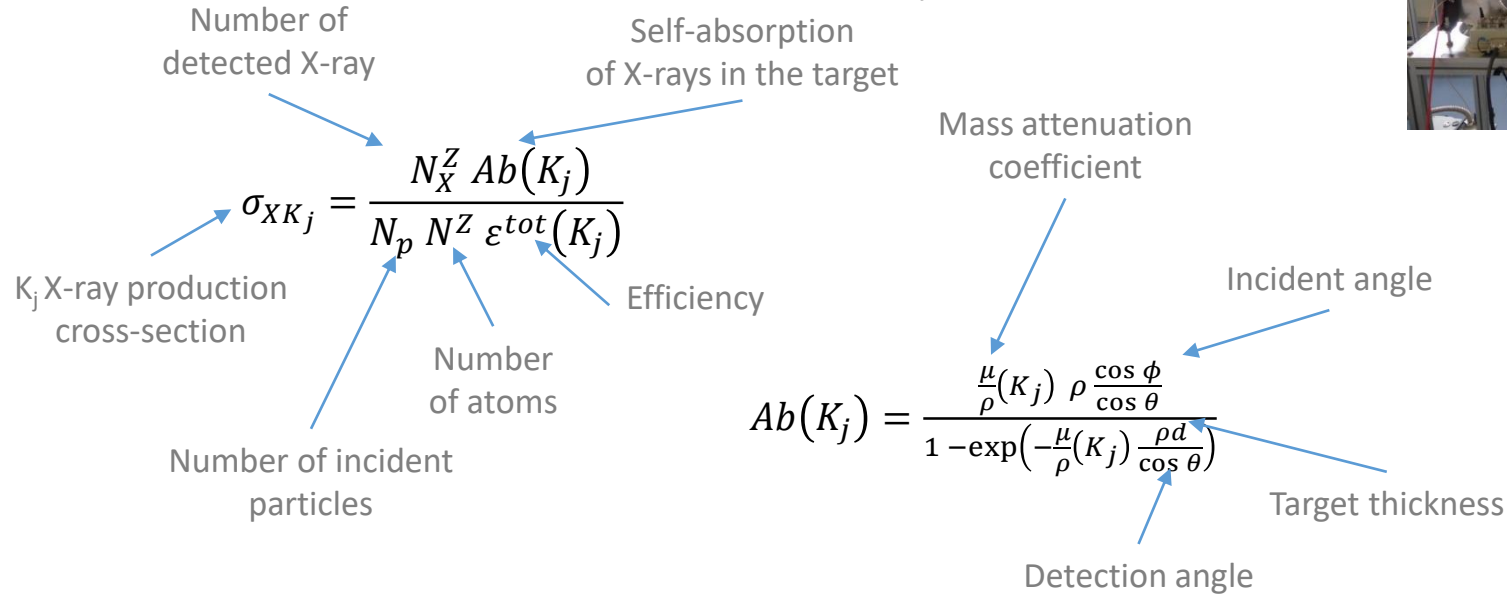


Beams	Accelerated particles	Energy range (MeV)	Current ( $\mu\text{A}$ )
Protons	$\text{H}^-$	30 – 70	1 fA – 350 $\mu\text{A}$ (x2)
	$\text{HH}^+$	17,5	< 50
Deutons	$\text{D}^-$	15 – 35	< 50
$\alpha$ -particles	$\text{He}^{2+}$	70	< 35

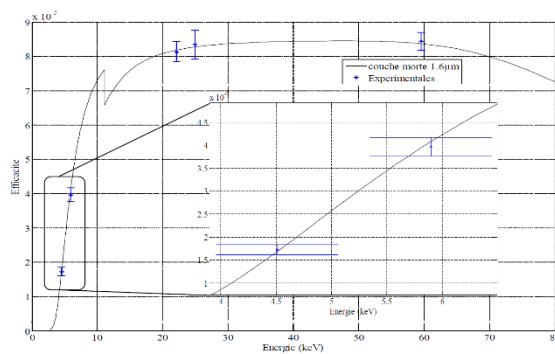
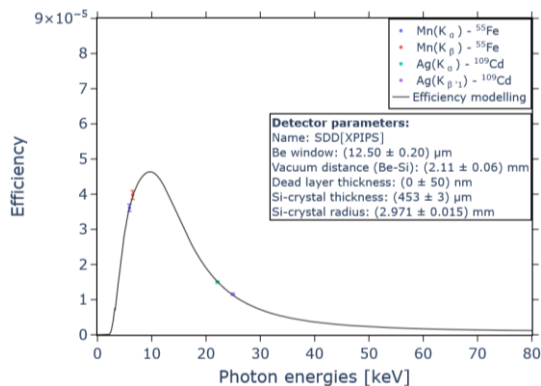
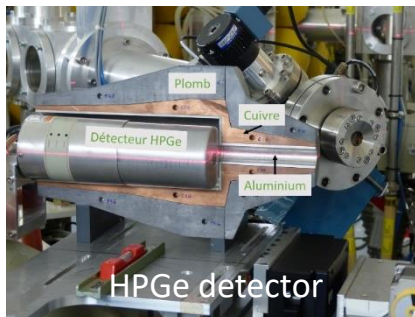


# X-ray production cross-section

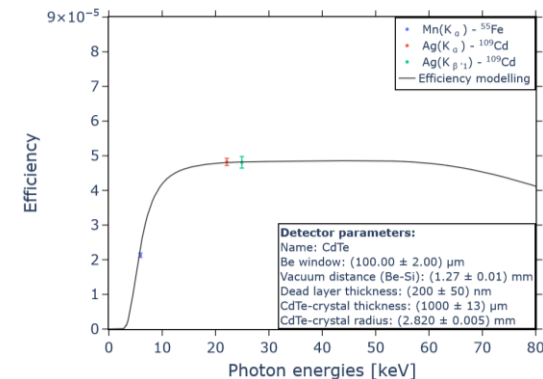
- Thin targets → X-ray production cross-section ~ constant
- Total production cross-section:  $\sigma_{XX}^{tot} = \sum_j \sigma_{XK_j} = \frac{\sigma_{XK_j}}{b(K_j)}$



# Experimental set-up: X-ray detectors

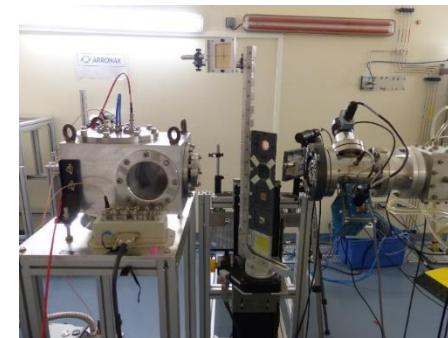
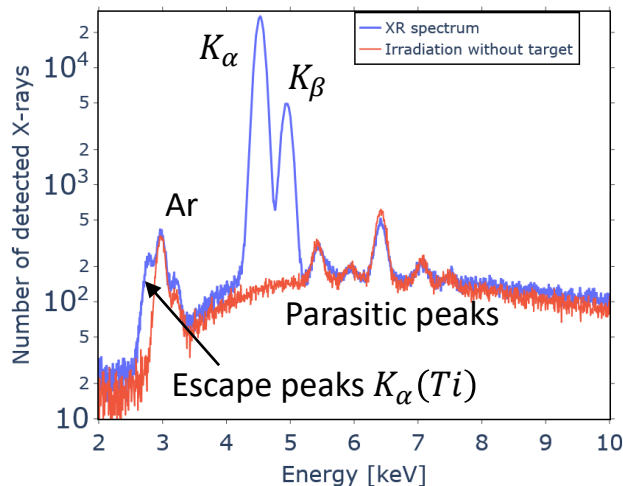


M. Hazim thesis, <http://www.theses.fr/2017NANT4100>



Experimental set-up:

# Measurement of the number of X-rays detected



Acquisition of a spectrum without the target:

- Eliminate parasitic peaks

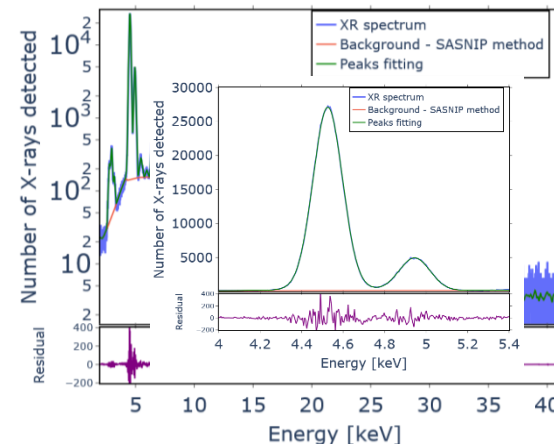
Background noise (area under the peaks):

- Iterative method (step-approx. SNIP)

R. Shi et al., Nucl. Instr. Meth. in Phys. Res. A 885 (2018), 60-66

Number of X-ray:

- Fitting with a gaussian function



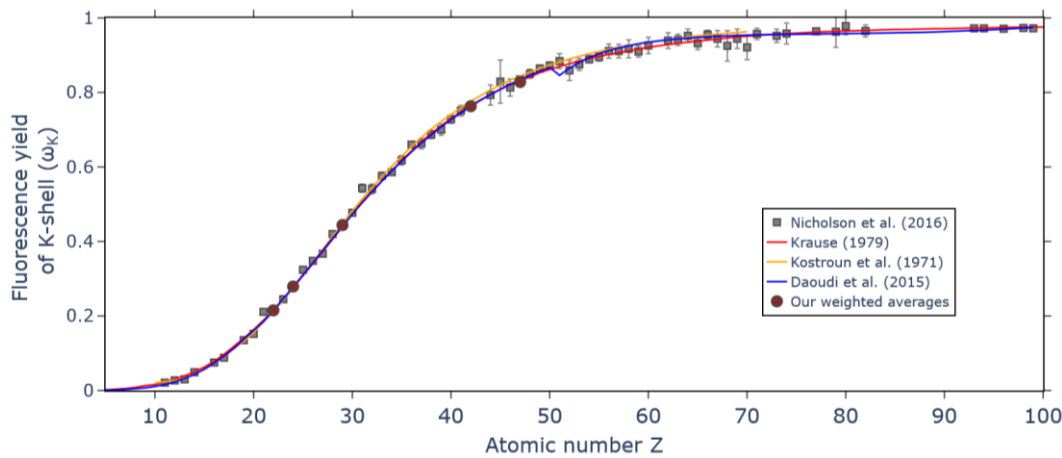
# Ionization / X-ray production cross-section

Ionisation cross-section

Production cross-section of the shell

$$\sigma_I(K) = \frac{\sigma_P^T(K)}{\omega_Z}$$

Fluorescence yield



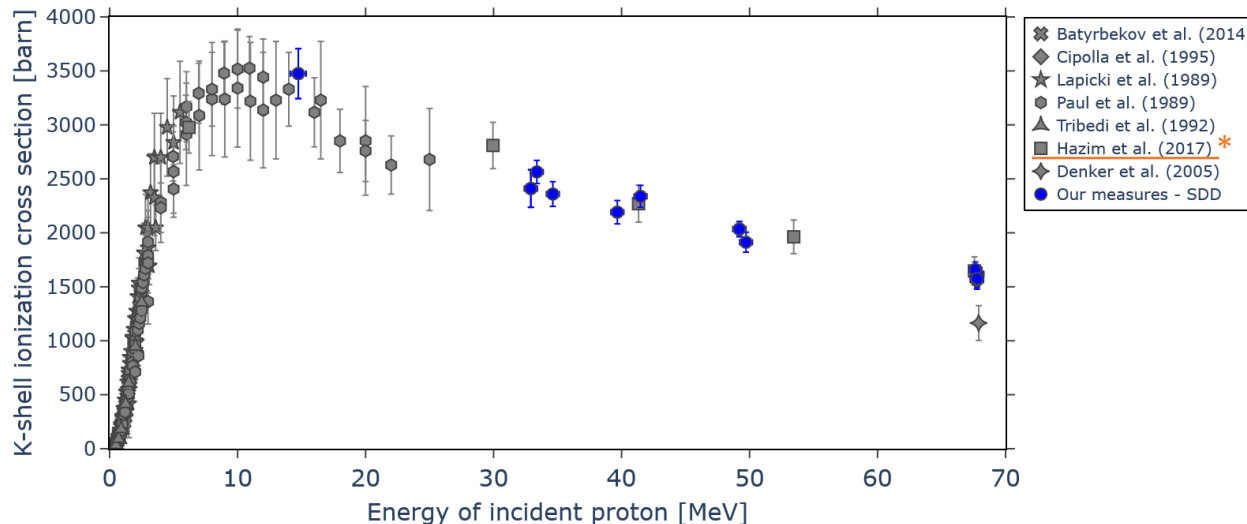
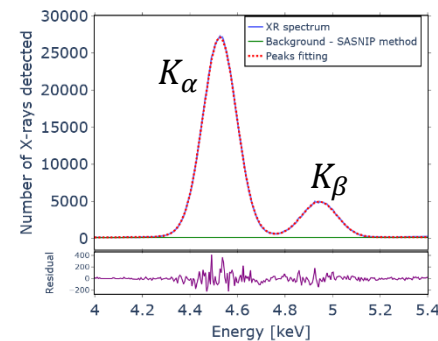
## Fluorescence yield

- Average of literature data weighted by their uncertainties

$$\omega_K = \frac{1}{\sum_{i=1}^N \left(\frac{1}{\Delta\omega_i}\right)^2} \sum_{i=1}^N \left(\frac{\omega_i}{(\Delta\omega_i)^2}\right)$$



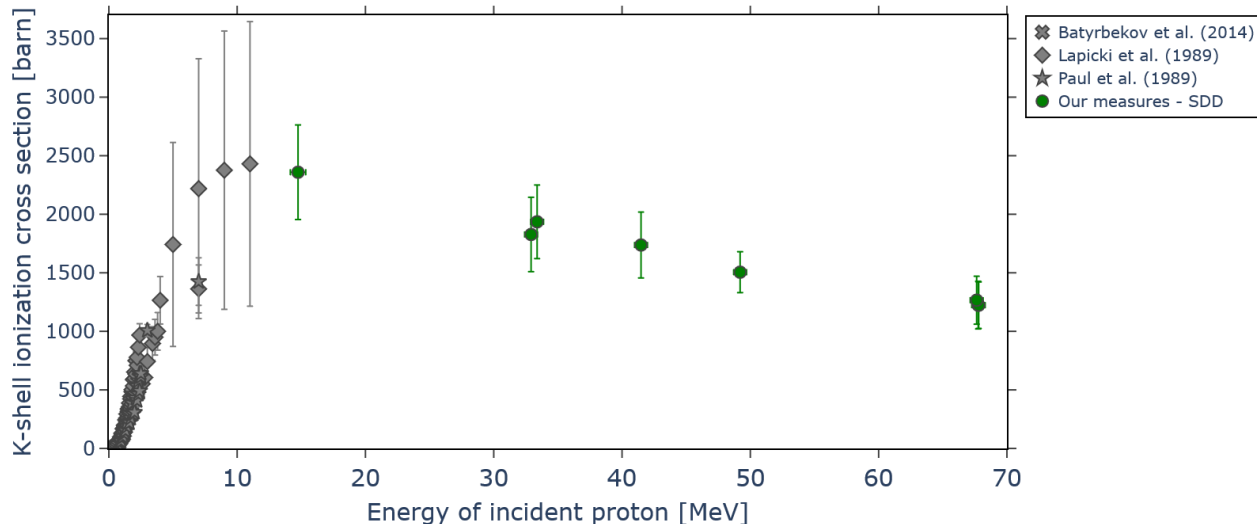
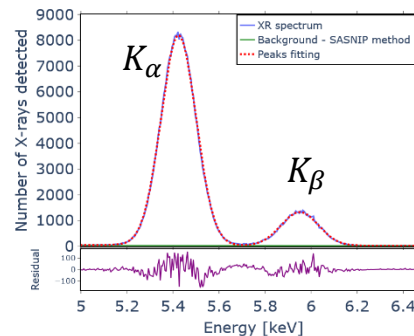
Experimental results:  
**Titanium target** ( $Z = 22$ )



- ✓ Good agreement with 2 detectors (SDD and HPGe)
- ✓ Good agreement with 2 different targets
- ✓ Compatibility with other experimental data

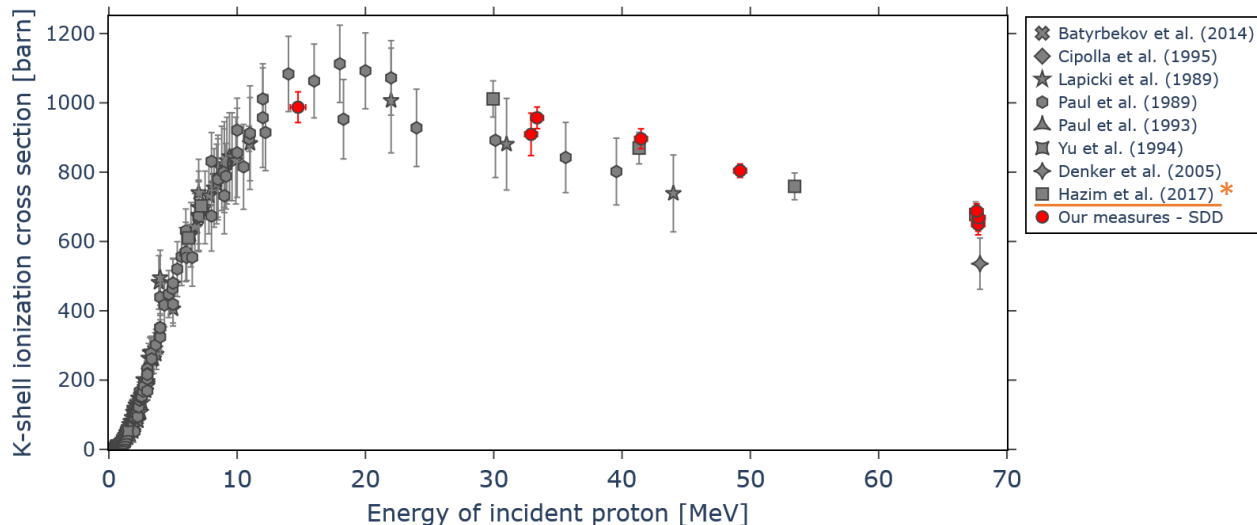
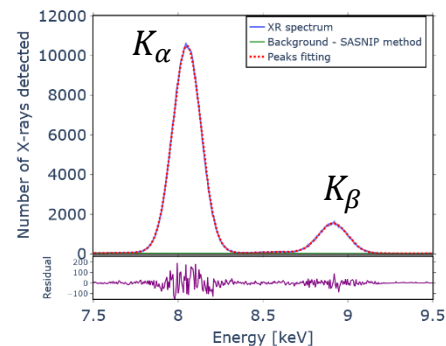
\*Realized at the Arronax cyclotron with an HPGe detector

Experimental results:  
**Chromium target** ( $Z = 24$ )



- ✓ Compatibility with other experimental data
- ☐ Lack of data

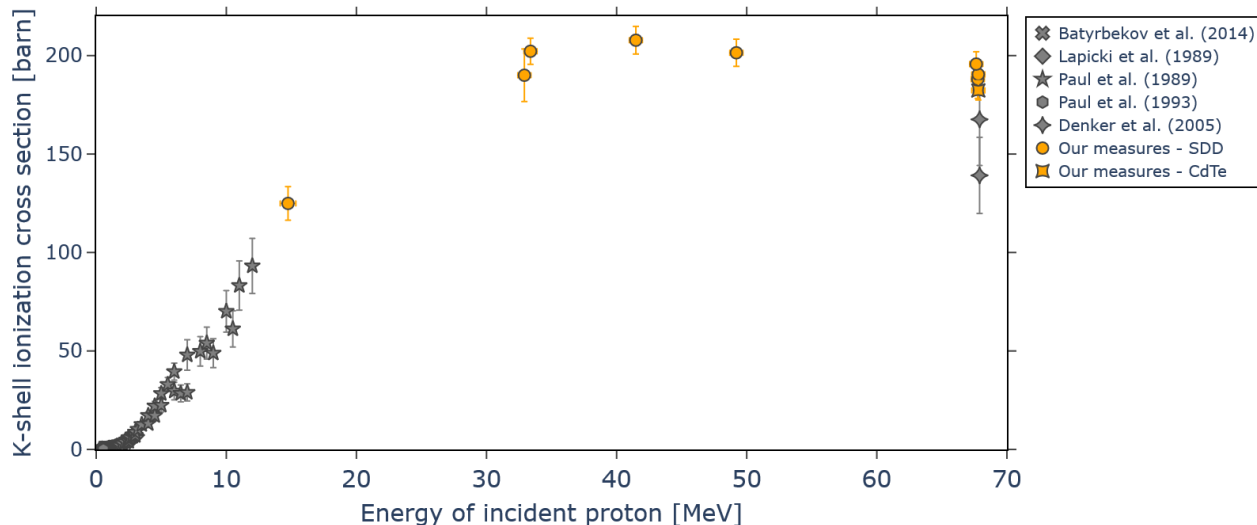
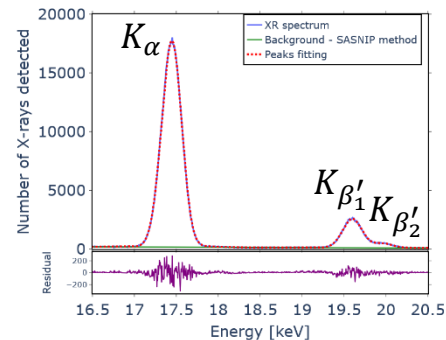
Experimental results:  
**Copper target (z = 29)**



- ✓ Good agreement with 2 detectors (SDD and HPGe)
- ✓ Good agreement with 2 different targets
- ✓ Compatibility with other experimental data

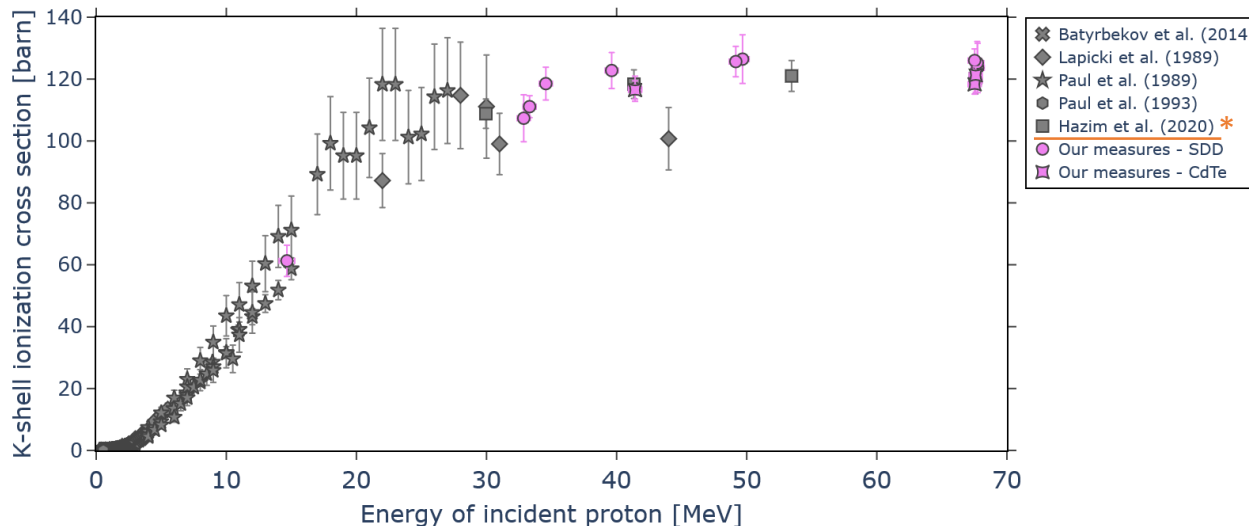
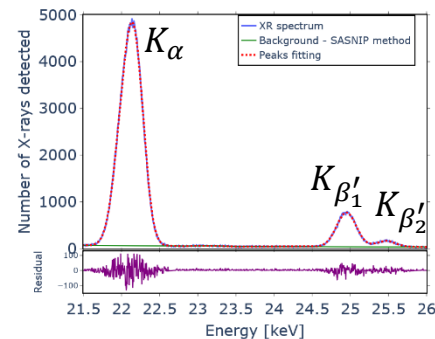
\*Realized at the Arronax cyclotron with an HPGe detector

Experimental results:  
**Molybdenum target (z = 42)**



- ✓ Good agreement with 2 detectors (SDD and CdTe)
- ✓ Compatibility with other experimental data

Experimental results:  
**Silver target (z = 47)**

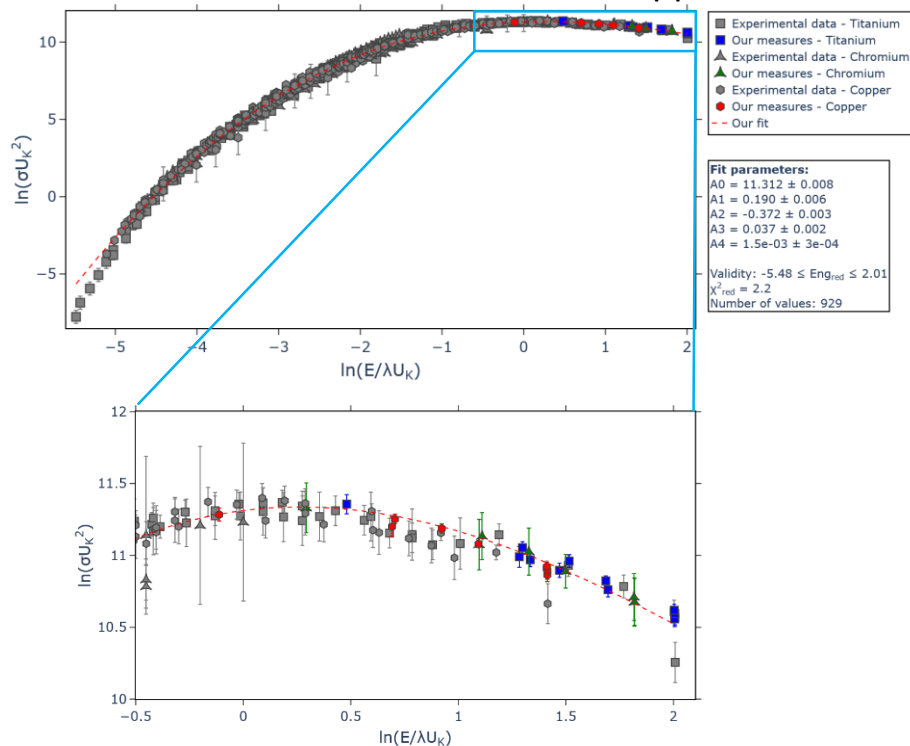


- ✓ Good agreement with 3 detectors (SDD, CdTe and HPGe)
- ✓ Good agreement with 2 different targets
- ✓ Compatibility with other experimental data

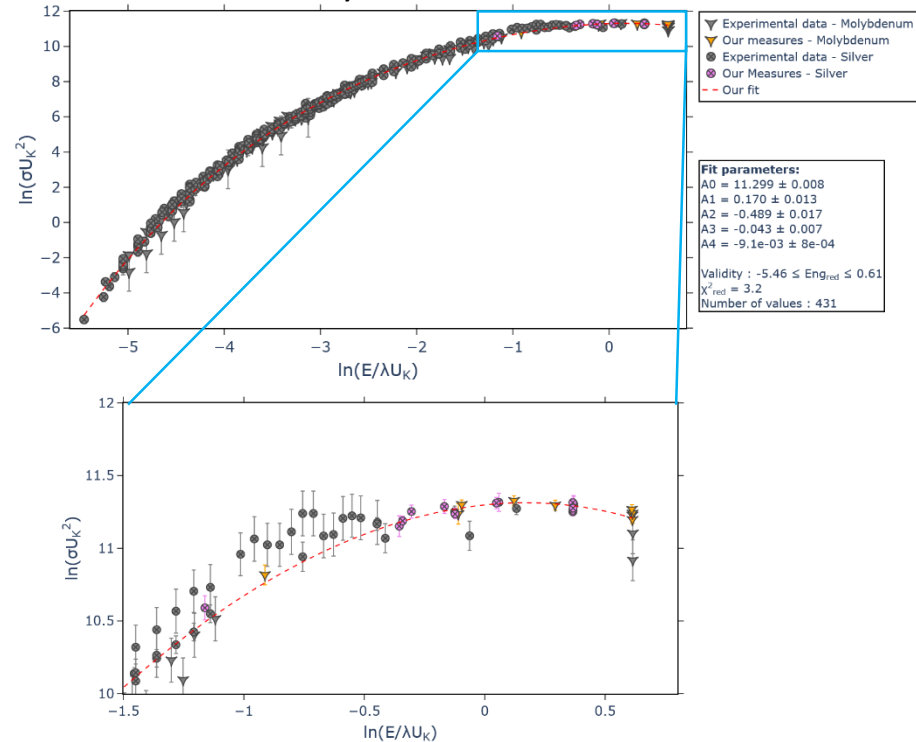
\*Realized at the Arronax cyclotron with an HPGe detector

# Universal ionization cross-section

Titanium, chromium and Copper

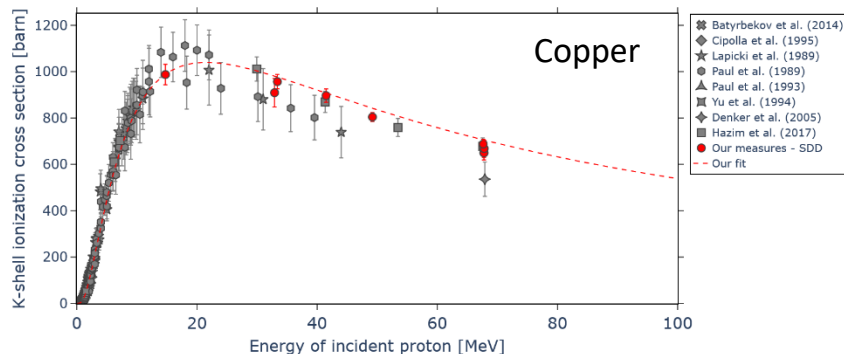
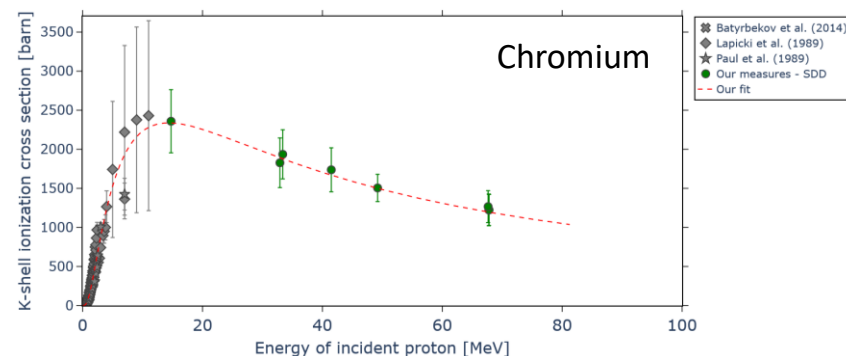
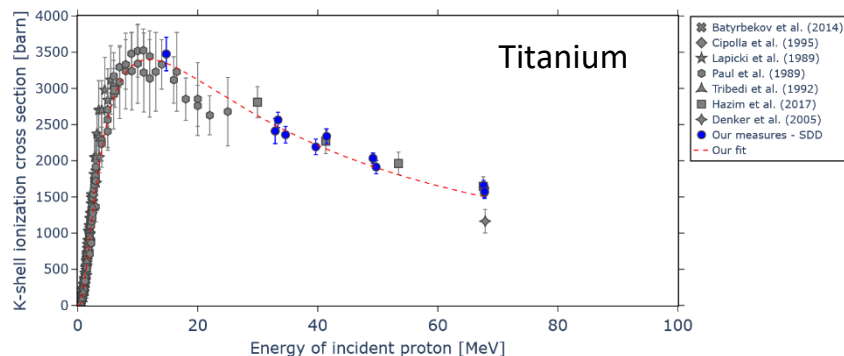


Molybdenum and Silver



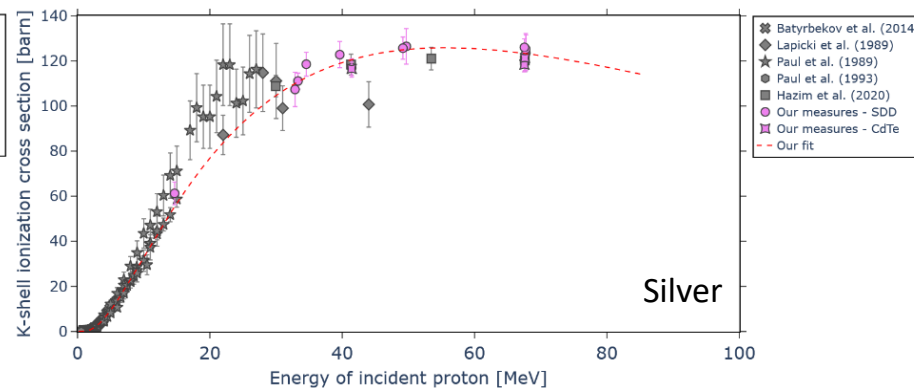
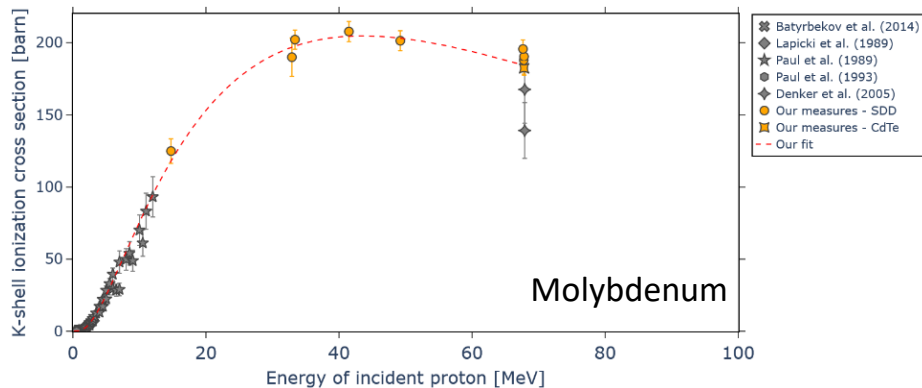
$$\lambda = \frac{\text{proton mass}}{\text{electron mass}}, U_K: \text{K-shell binding energy}$$

# Comparison with the empirical fit



- Titanium and chromium:
  - Good agreement with the experimental data
- Copper:
  - Lack of data (around the maximum ionisation cross-section and at high energy) → improved fit

# Comparison with the empirical fit



- Fit in accordance with the experimental data
- Lack of data (10 – 30 MeV and high energy) → improved fit





## Conclusion and outlook

- new measurements at Arronax energies (15 to 68 MeV) for Ti, Cr, Cu, Mo and Ag
  - ✓ Agreement between the **different detectors** (SDD, CdTe and HPGe)
  - ✓ Agreement between the **different targets**
  - ✓ Consistent with other available data
  
- Fitting using the universal ionisation cross section:
  - ✓ Validated for **titanium and chromium** at energies **up to 70 MeV**
  
- ☐ New measures → constrain the empirical model:
  - **between 10 and 30 MeV**
  - **at more than 70 MeV**
  - for **other elements**

Thank you !