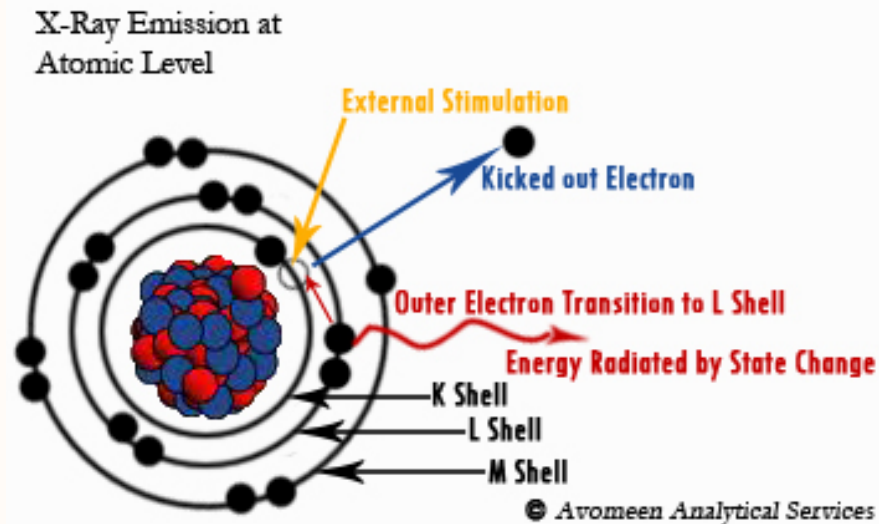


High energy PIXE: measurements for Cu, Ag and Ti K-shell ionization cross sections and comparisons with theoretical model

Q. Mouchard⁽¹⁾, C. Koumeir⁽²⁾, N. Servagent⁽¹⁾,
A. Guertin⁽¹⁾, F. Haddad^(1,2), V. Métivier⁽¹⁾

- (1) Laboratoire SUBATECH, IMT Atlantique, Université de Nantes, CNRS/IN2P3, Nantes, France
- (2) GIP ARRONAX, Saint-Herblain, France
- (3) Université Libanaise, Tripoli, Lebanon

Particle Induced X-ray Emission (PIXE)



- PIXE method :
 - Incident beam energy : <4 MeV
 - Non-destructive multi-elemental method ($Z > 11$)
 - Fast analysis (few minutes)
 - Quantitative analysis
 - Good sensitivity ($\mu\text{g/g}$)
 - Analysis of thin layers close to the surface

High energy PIXE (HE PIXE)

- study of thick and multilayer objects:
 - Energy beam: few MeV
 - Proton range: \sim mm
 - In-depth analysis
 - Adapted for thick archeologic object
 - Detection of elements thanks to their more energetic K line



A. Denker et al, Nucl. Inst. Meth. B 239 (2005) 65–70

Quantitative analysis (PIXE) for the element (Z) in a matrix

Number of detected X-rays Number of atoms Intensity of X-line Ionization cross section Transmission factor

$$N_X^Z = N_p N^Z \omega b \varepsilon \int_{E_f}^{E_0} \frac{\sigma_i(E) \times T(E)}{S(E)} dE$$

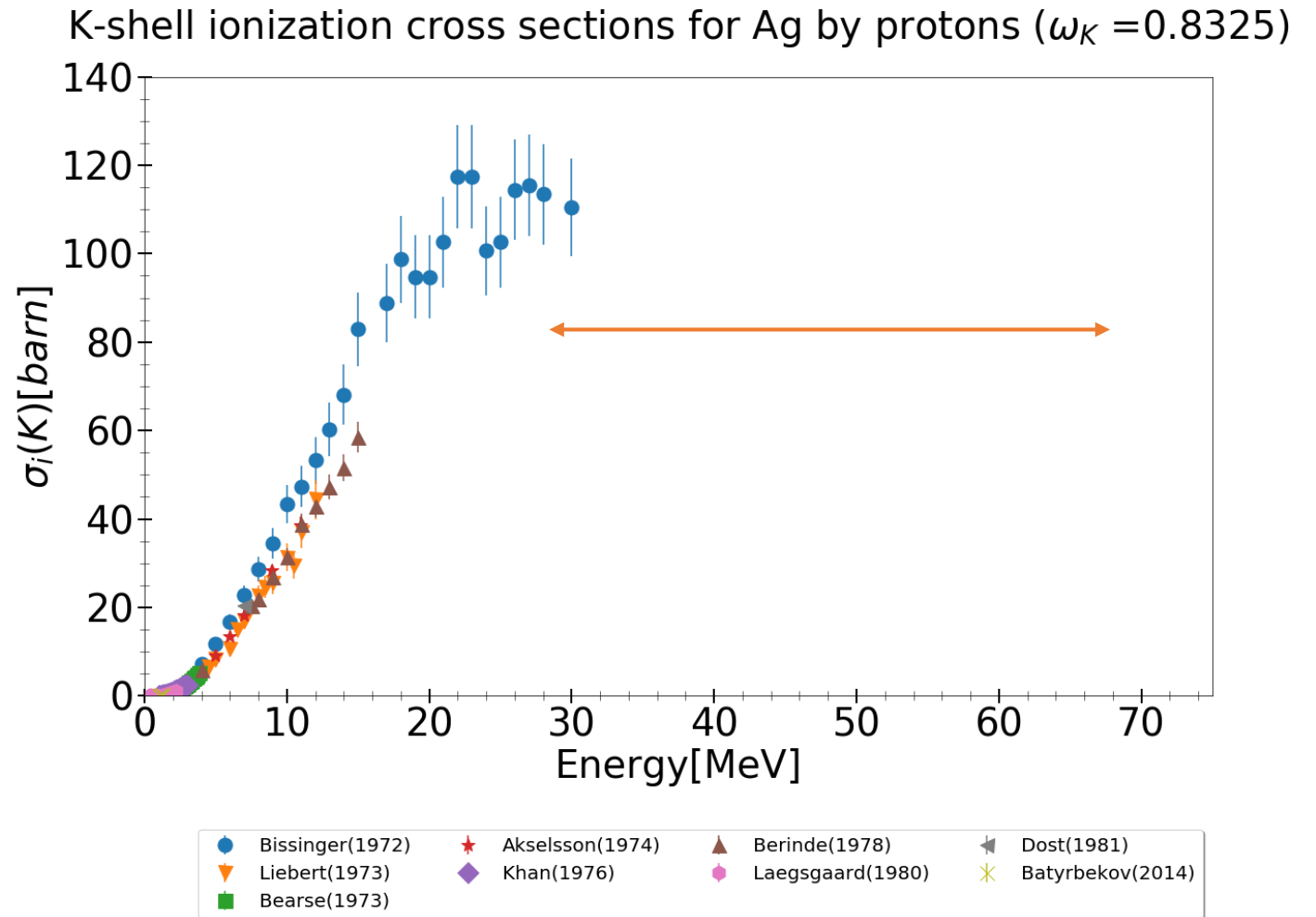
Number of incident particles Fluorescence yields Detection efficiency (intrinsic + geometric) Stopping power

Quantization requires a good knowledge of the ionization cross section :

- Experimental data
- Theoretical values

Ionization cross section: Experimental data available

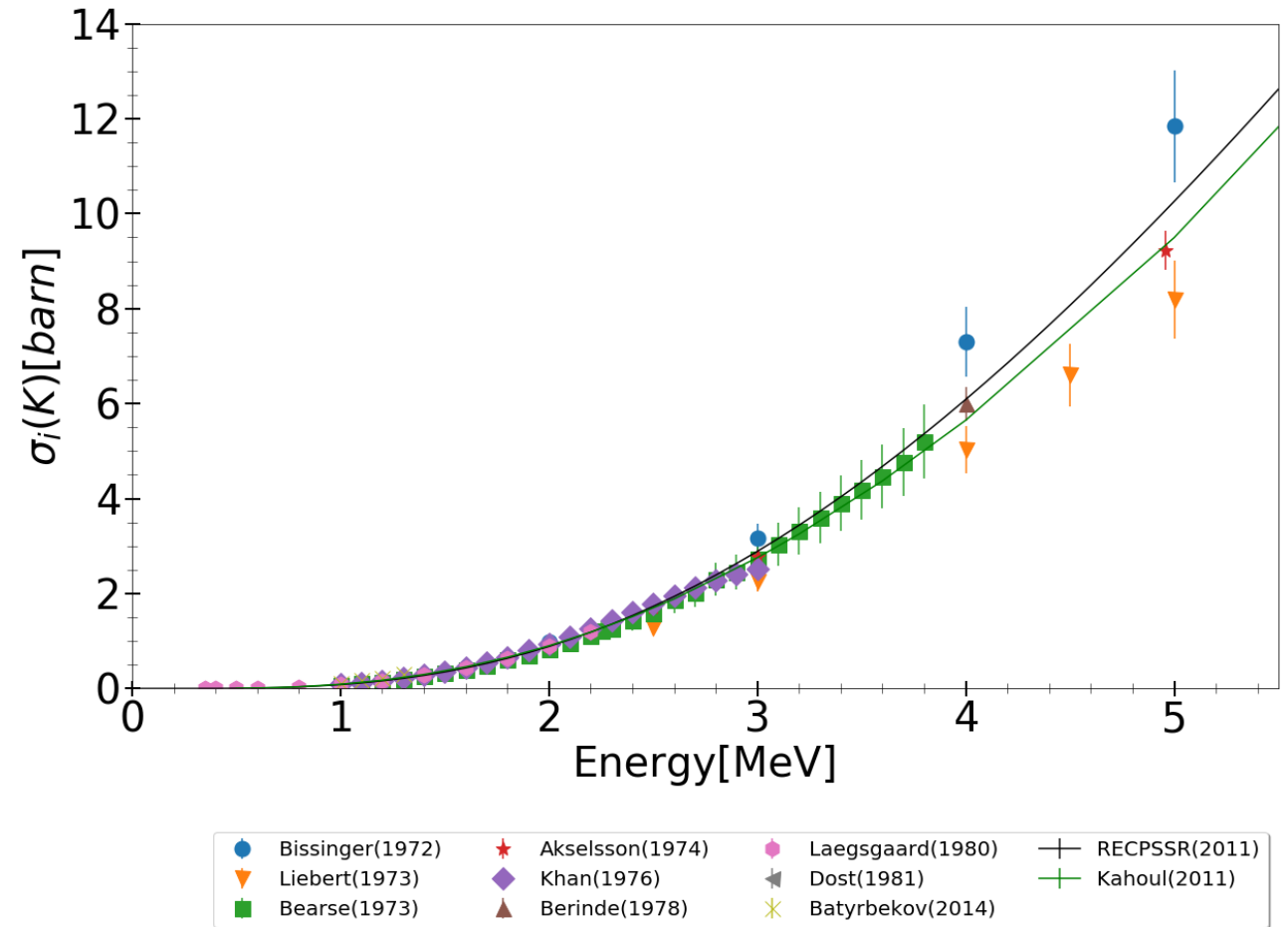
- Experimental data at high energy are scarce



Ionization cross section: Theoretical model (RECPSSR)

- RECPSSR model takes into account the relativistic effect of the projectile

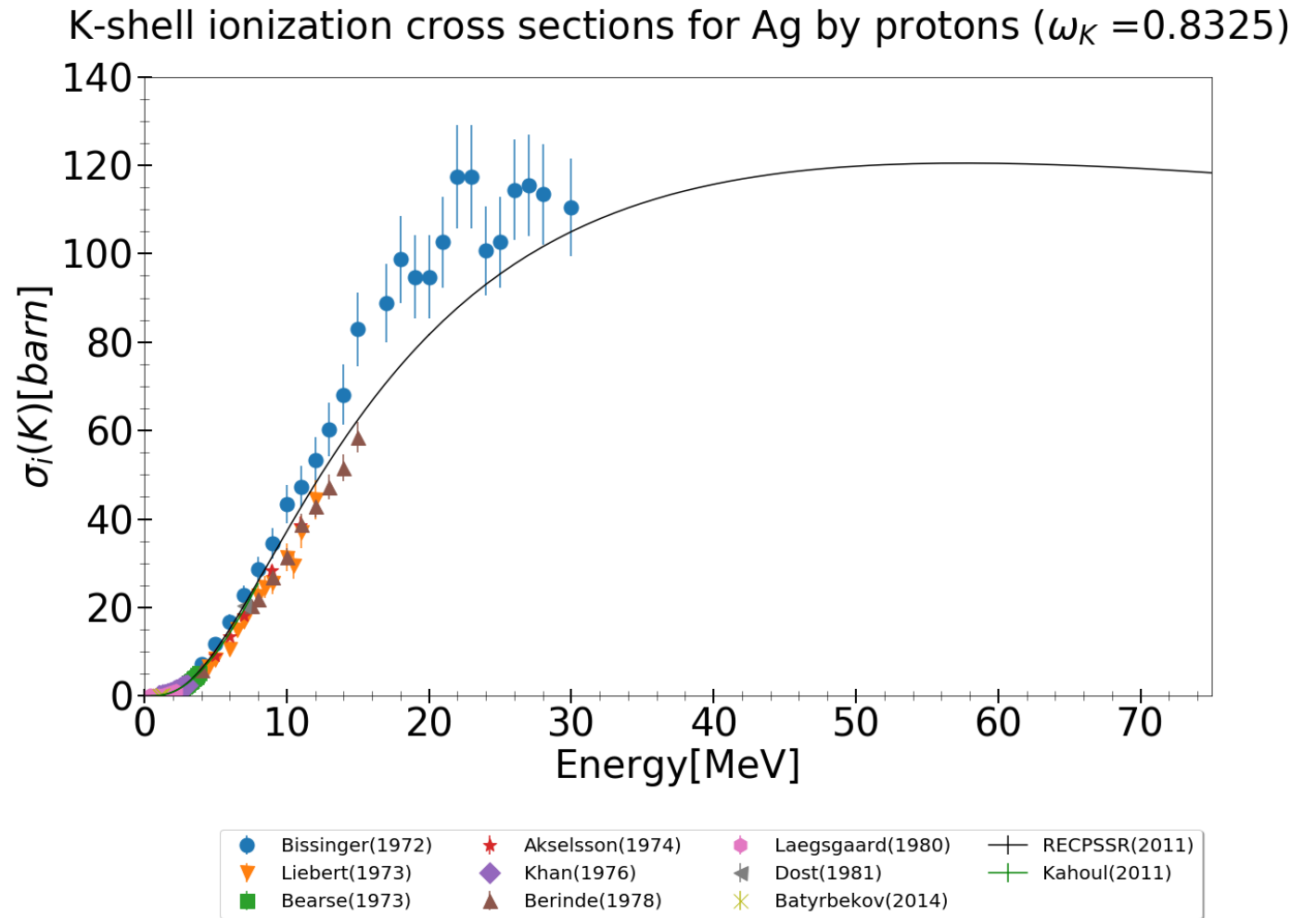
K-shell ionization cross sections for Ag by protons ($\omega_K = 0.8325$)



A. Kahoul et al., Rad. Phy. And Chem. 80 (2011) 1300-1311
W. Brandt et al., Phys. Rev. A 23 (1981) 1717

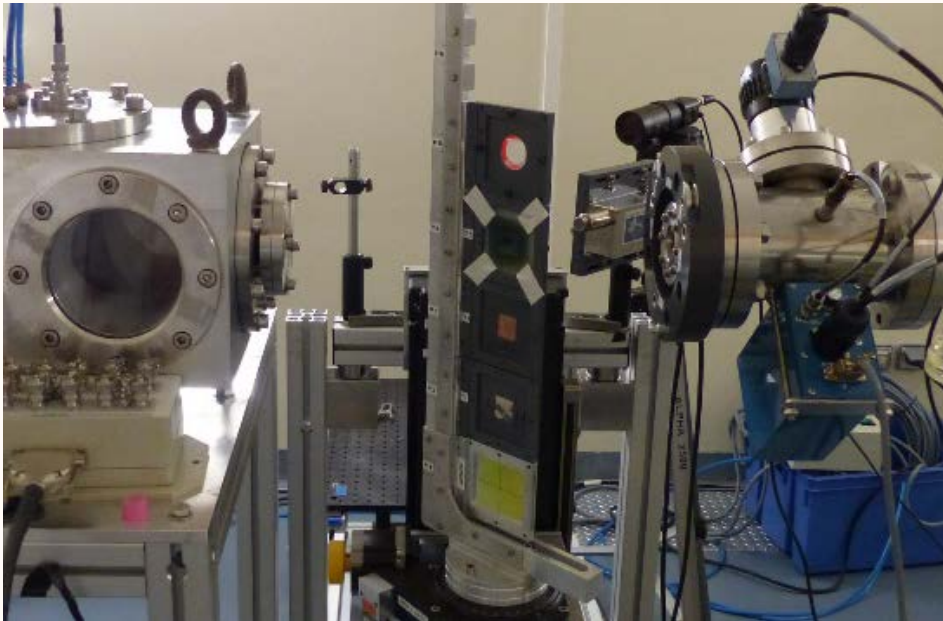
Ionization cross section: Theoretical model (RECPSSR)

- RECPSSR model takes into account the relativistic effect of the projectile
- RECPSSR model have been validated with the bibliographic data at low energy
- The lack of high-energy experimental data does not allow to verify the model over this range in energy (30 – 70 MeV)



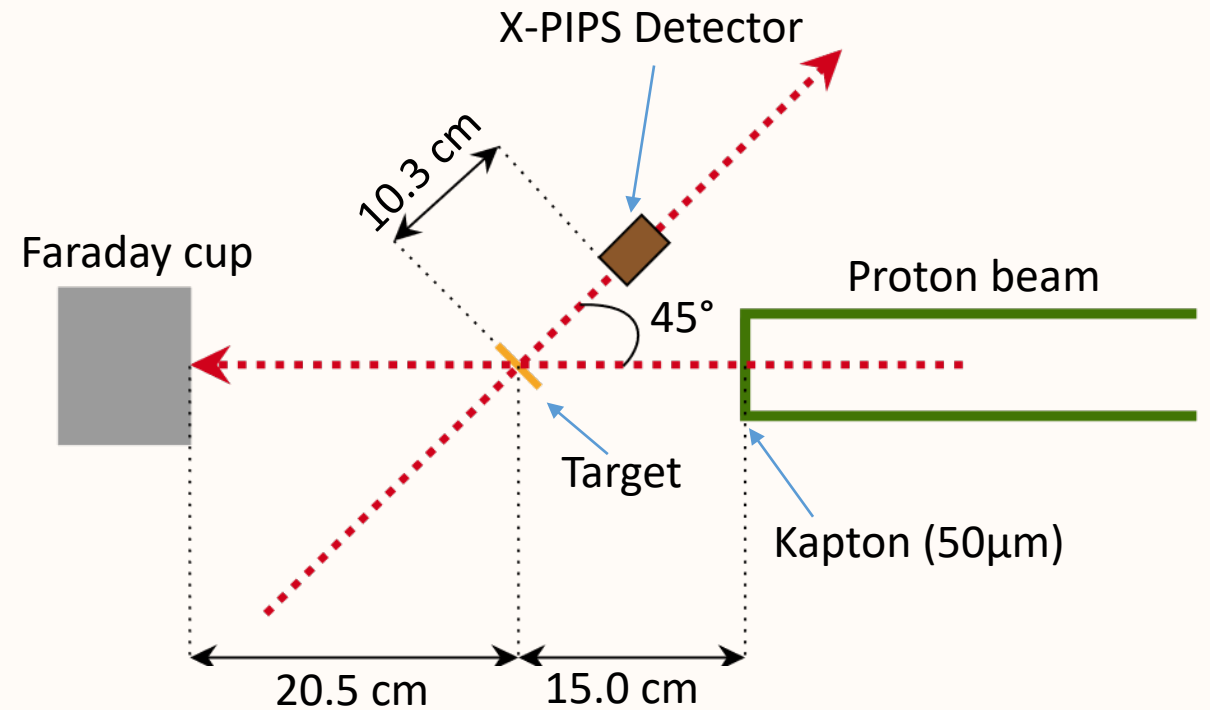
A. Kahoul et al., Rad. Phy. And Chem. 80 (2011) 1300-1311
W. Brandt et al., Phys. Rev. A 23 (1981) 1717

Experimental measurements for ionization cross section:



Cyclotron C70 ARRONAX, Nantes, France

Thin targets ($10\ \mu\text{m}$):
Titanium (Ti), Copper (Cu) and Silver (Ag)



Particles: Protons
Energies: 35, 40, 50 and 68 MeV

$$N_X^Z = N_p N^Z \omega b \varepsilon \int_{E_f}^{E_0} \frac{\sigma_i(E) \times T(E)}{S(E)} dE$$

Experimental set-up

K X-rays production cross section

- Thin target → constant production cross section
- Production cross section → Independent of the fluorescence yield
 - For each K-lines $\sigma_P^T(K) = \sum_i \sigma_P(K_i)$ → Independent of the intensity of a given transition b

Diagram illustrating the production cross section $\sigma_P(K_i)$ for K_i X-rays:

$$\sigma_P(K_i) = \frac{N_X(K_i) \times M \times \frac{\mu}{\rho}(K_i) \times \rho \times \cos(45)}{N_P \times \varepsilon_{tot}(K_i) \times N_A \times \rho \times \left(1 - \exp\left(-\frac{\mu}{\rho}(K_i) \times \rho \times d\right)\right)}$$

Labels and arrows in the diagram:

- Number of X-rays detected (X-PIPS detector) → $N_X(K_i)$
- Atomic mass → M
- Mass attenuation coefficient → $\frac{\mu}{\rho}(K_i)$
- Number of incident particles (Faraday cup) → N_P
- Detection efficiency → $\varepsilon_{tot}(K_i)$
- Avogadro number → N_A

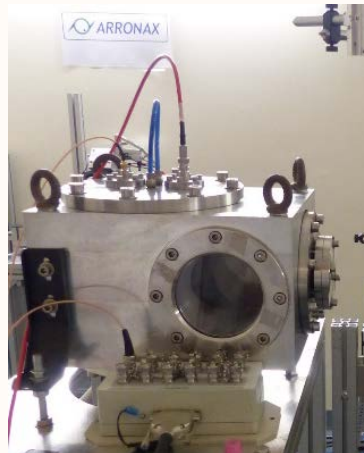
Experimental set-up

$$\sigma_p(K_i) = \frac{N_X(K_i) \times M \times \frac{\mu}{\rho}(K_i) \times \rho \times \cos(45)}{N_p \times \varepsilon_{tot}(K_i) \times N_A \times \rho \times \left(1 - \exp\left(-\frac{\mu}{\rho}(K_i) \times \rho \times d\right)\right)}$$

Current load measurement

- Use of an faraday cup equipped with a guard ring
- Uncertainty : 0.5%
- For our measurements, all incident particles reach the faraday cup

→ Number of incident particles N_p



Thin targets

- Determination of the thickness:
 - Mass with a precision of 10^{-5} g
 - Surface with a high-precision scanner
- Titanium: $9.95 \pm 0.09 \mu\text{m}$
- Copper: $10.38 \pm 0.09 \mu\text{m}$
- Silver: $10.11 \pm 0.09 \mu\text{m}$

→ Thickness of the target d

Experimental set-up

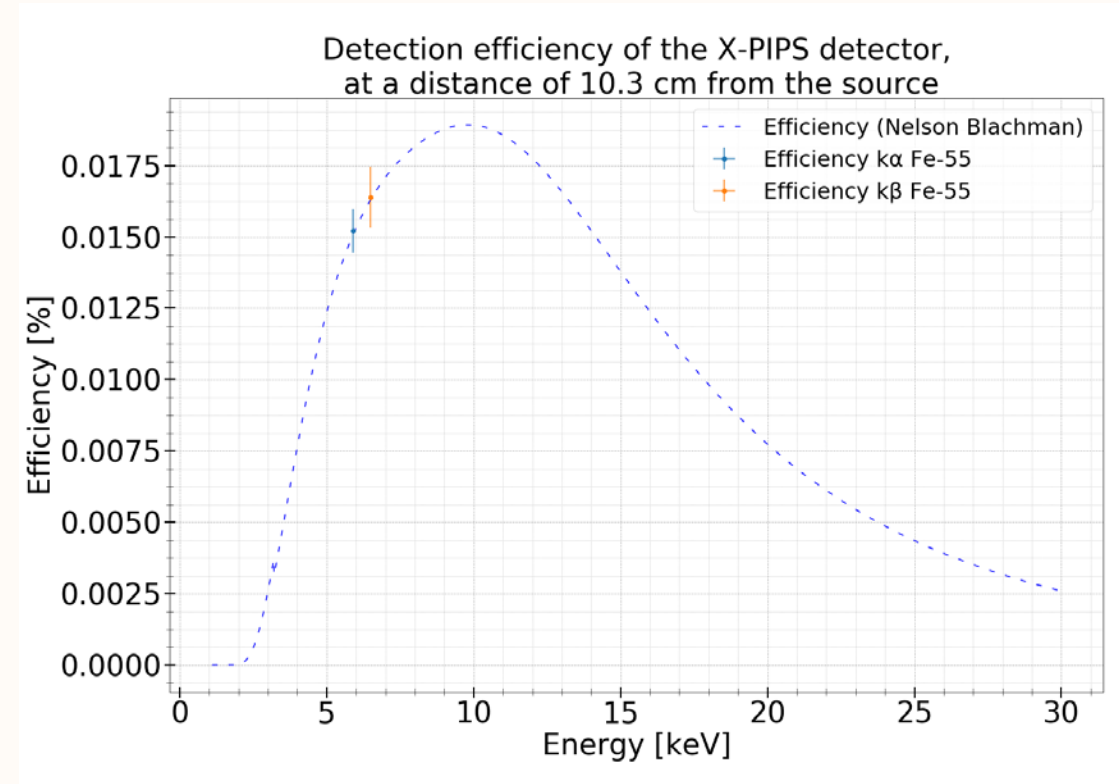
$$\sigma_p(K_i) = \frac{N_X(K_i) \times M \times \frac{\mu}{\rho}(K_i) \times \rho \times \cos(45)}{N_p \times \varepsilon_{tot}(K_i) \times N_A \times \rho \times \left(1 - \exp\left(-\frac{\mu}{\rho}(K_i) \times \rho \times d\right)\right)}$$

Detection efficiency $\varepsilon_{tot}(K_i)$

- Use of an Fe-55 source for calibration and validation of theoretical efficiency model (Nelson-Blachmann) A.H. Jaffrey, Rev. Sci. Instrum 25 (1954) 349
H.R.V. Carrillo, Nucl. Instr. And Meth. A 371 (1996) 353
- Uncertainty : 5%
- X-PIPS detector : SDD (500 μ m, 30mm²)



Tomography scan of X-PIPS detector

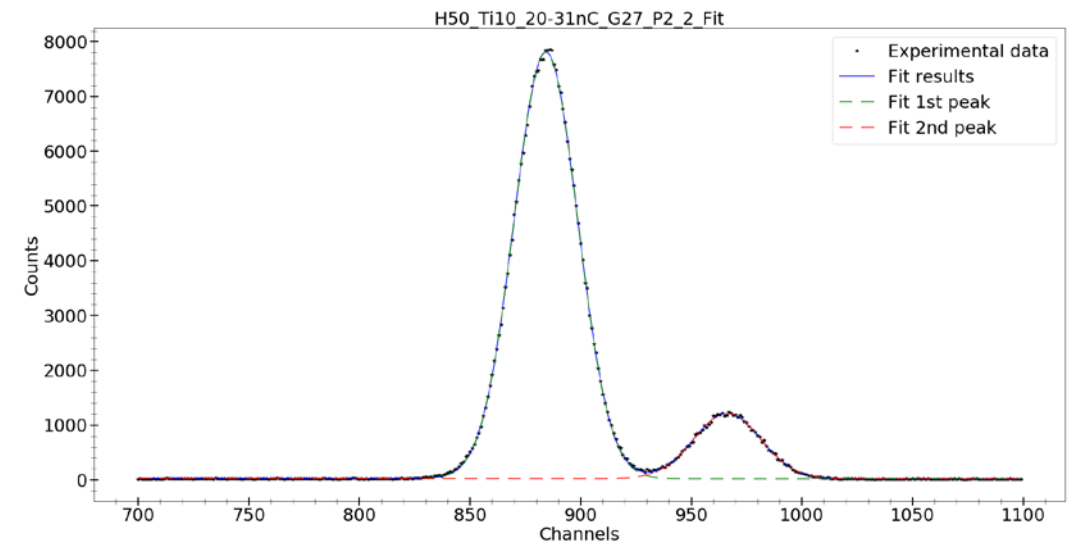


Experimental set-up

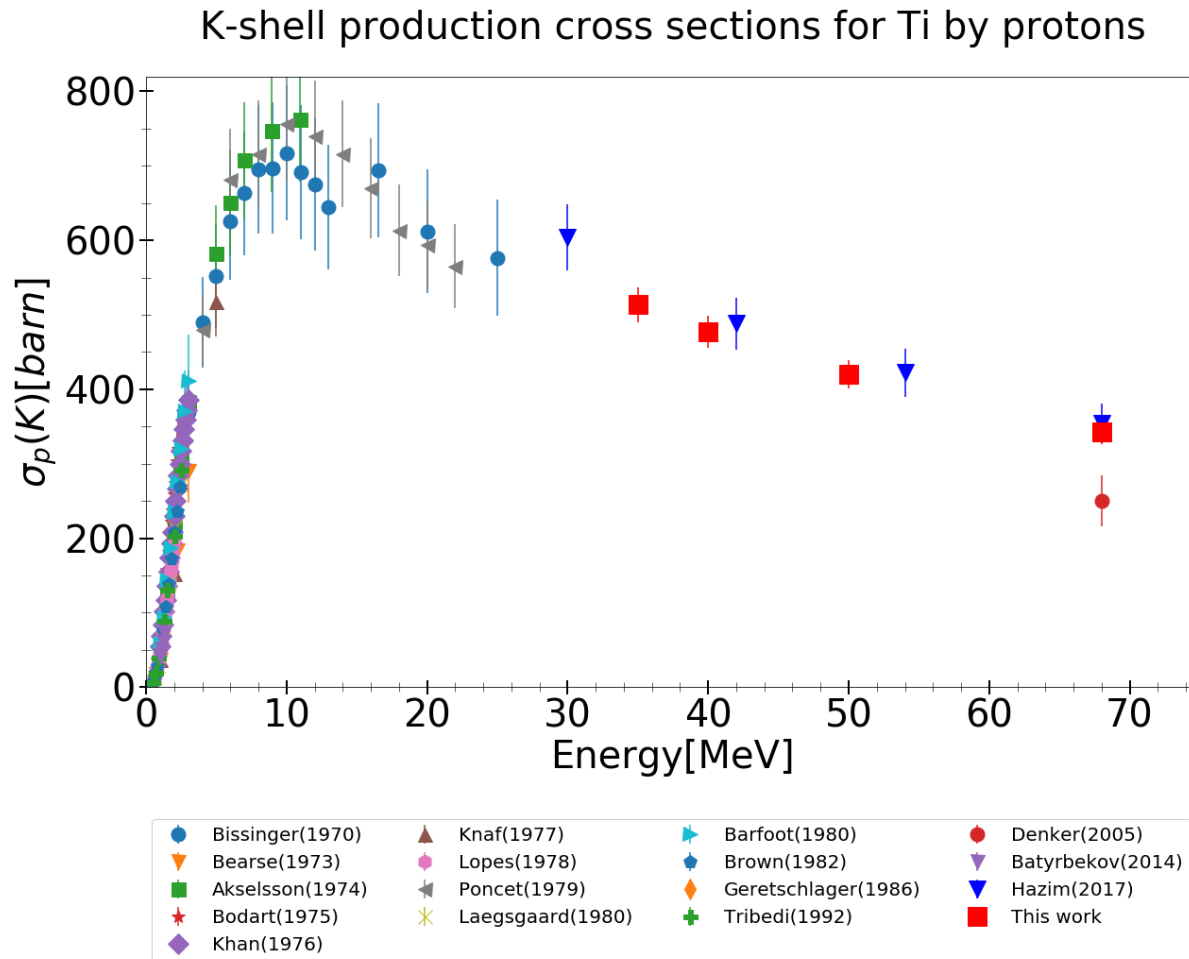
$$\sigma_p(K_i) = \frac{N_X(K_i) \times M \times \frac{\mu}{\rho}(K_i) \times \rho \times \cos(45)}{N_p \times \varepsilon_{tot}(K_i) \times N_A \times \rho \times \left(1 - \exp\left(-\frac{\mu}{\rho}(K_i) \times \rho \times d\right)\right)}$$

Measurement of the number of X-rays $N_X(K_i)$

- Use of the X-PIPS detector
- Number of X-rays obtained after :
 - fitting of the characteristic peaks of the K layers.
 - integration on fitting curve
 - Correction dead time of detector
- Uncertainty : ~1%
 - (statistic and fitting)



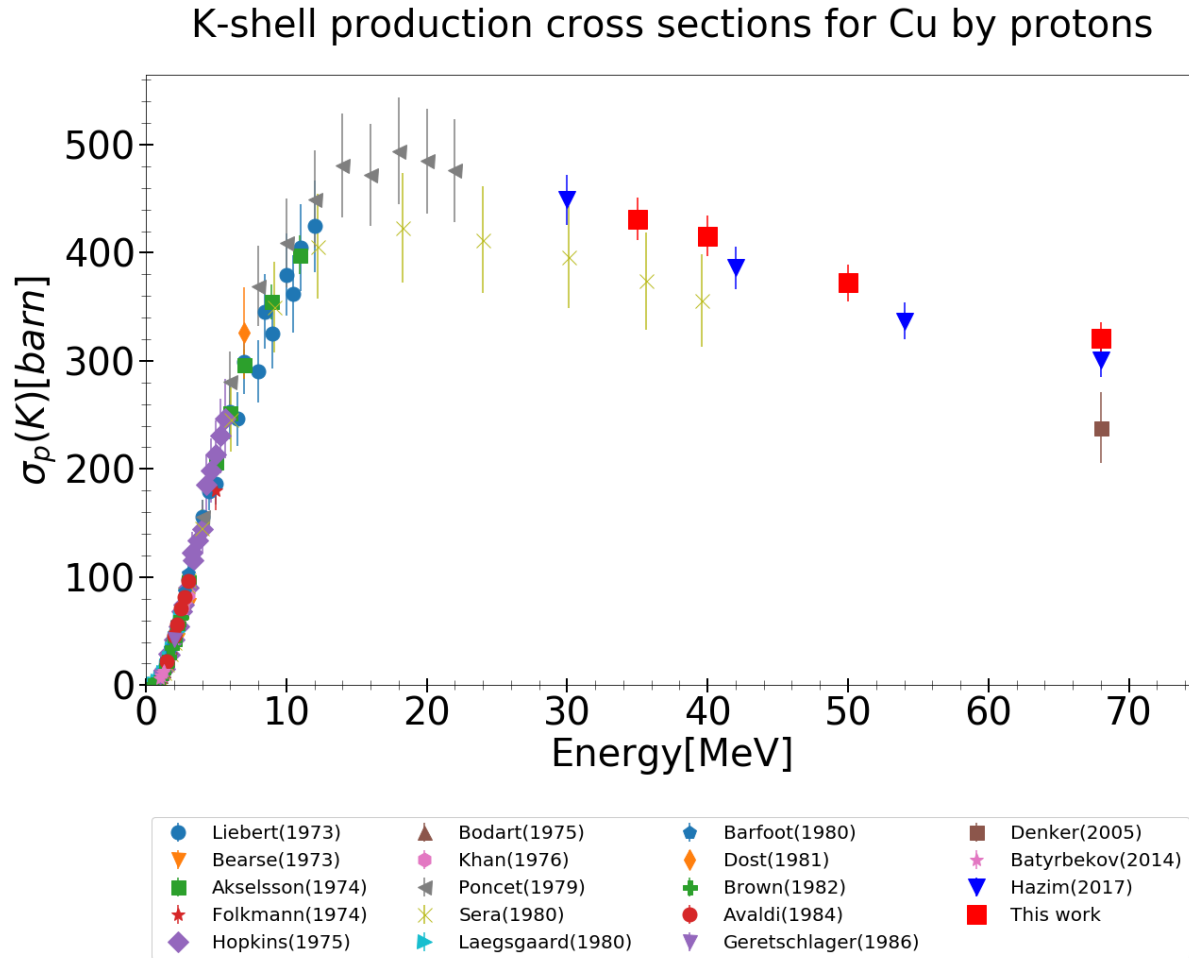
Experimental results: K X-rays production cross sections for Titanium



- Our measurements (red square) are
 - consistent with the low-energy trend
 - above the experimental point at 68 MeV
 - Good matching with previous data acquired with a Ge detector (blue triangle)

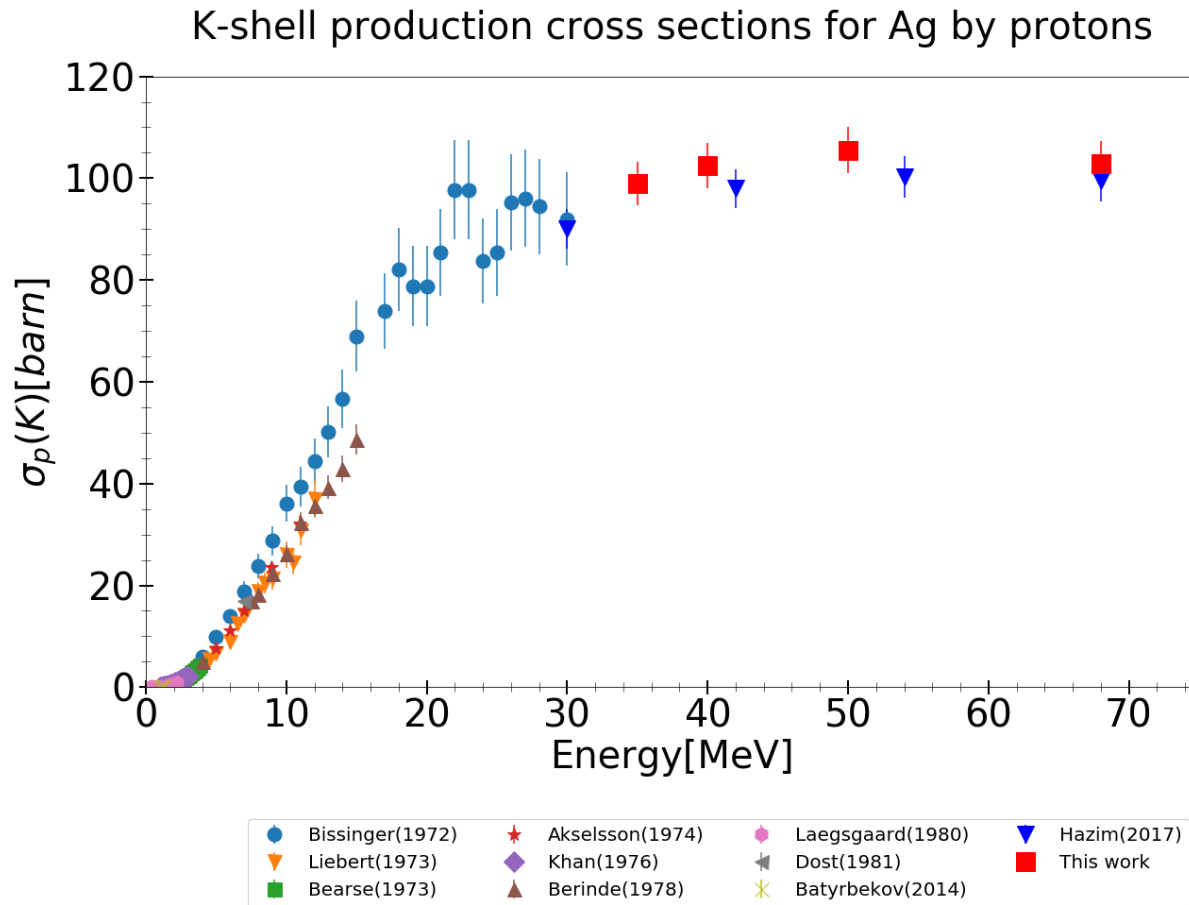
M. Hazim, PhD thesis, Université de Nantes, march 2017

Experimental results: K X-rays production cross sections for Copper



- Our measurements (red square) are
 - consistent with the low-energy trend
 - above the experimental point at 68 MeV
 - Good matching with previous data acquired with a Ge detector (blue triangle)

Experimental results: K X-rays production cross sections for Silver



- Our measurements (red square) are
 - consistent with the low-energy trend
 - Good matching with previous data acquired with a Ge detector (blue triangle)

What about models ?

Production/Ionization cross section

K-shell ionization cross section

K-shell production cross section

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

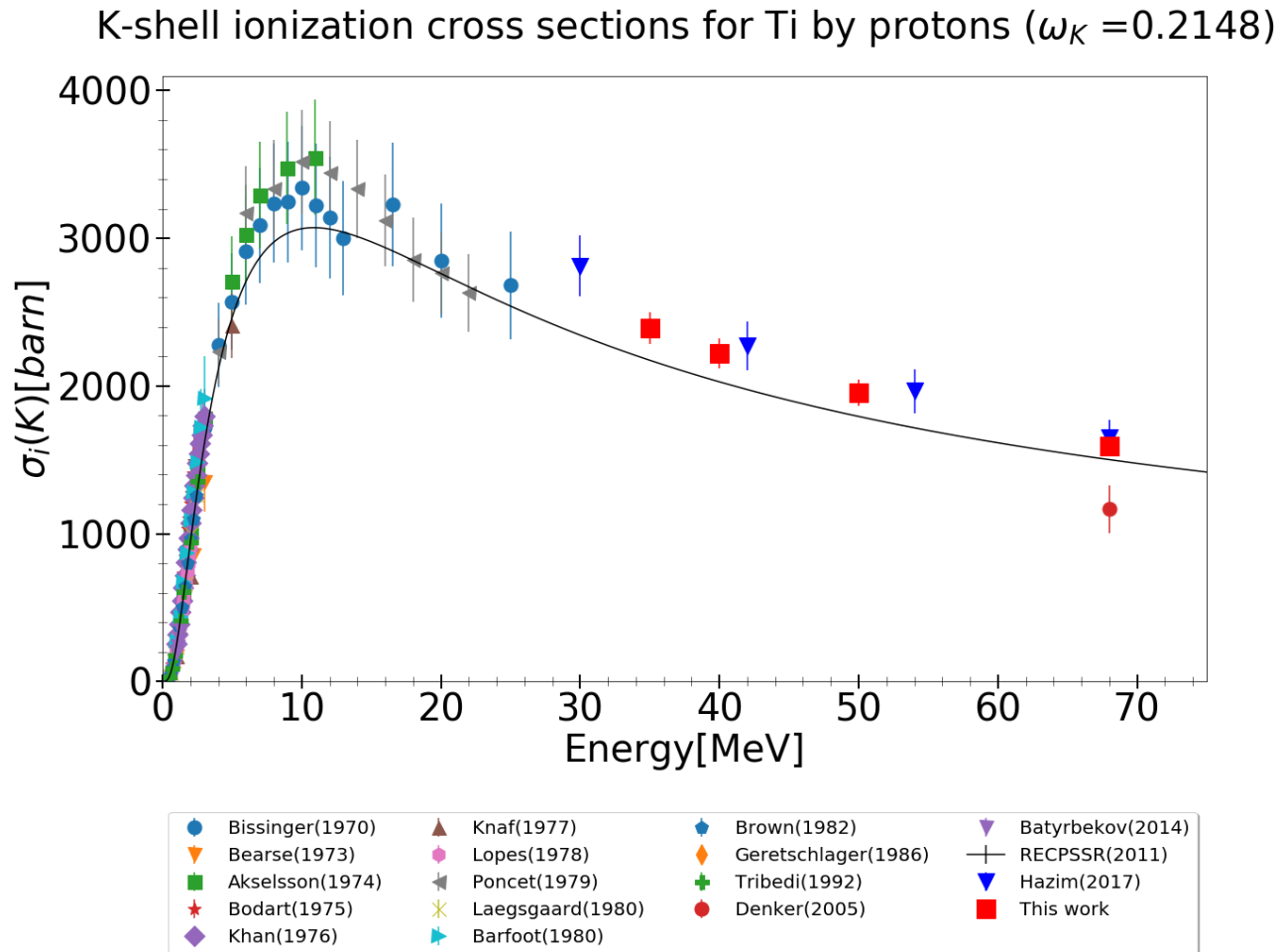
Florescence yield

The fluorescence yield used is an average of the bibliographic data weighted by the errors

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

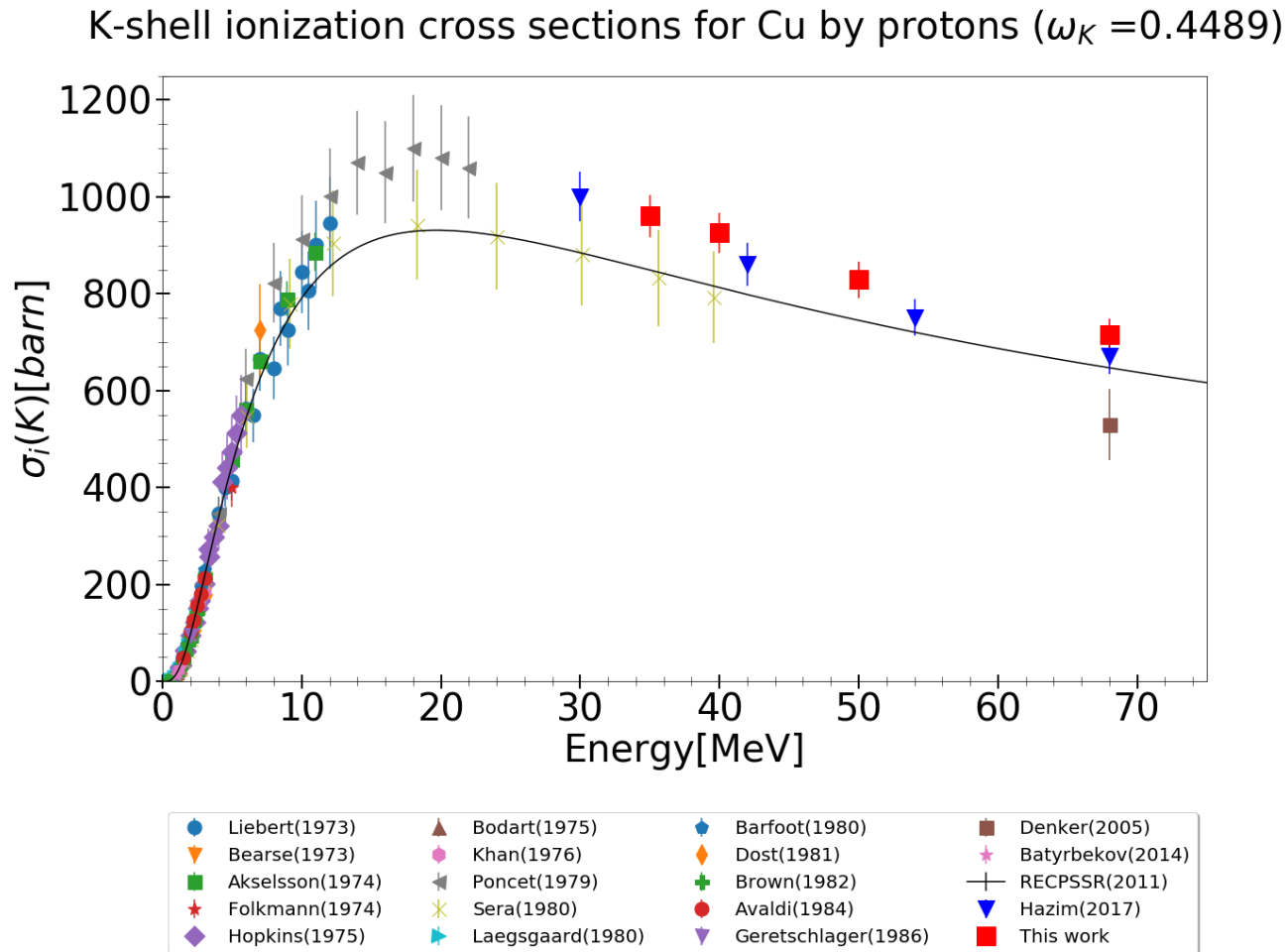
Target	ω_K
Ti	0,2148 ± 0,0050
Cu	0,4489 ± 0,0060
Ag	0,8320 ± 0,0102

Comparison with the theory (RECPSSR): K X-rays ionization cross sections for Titanium



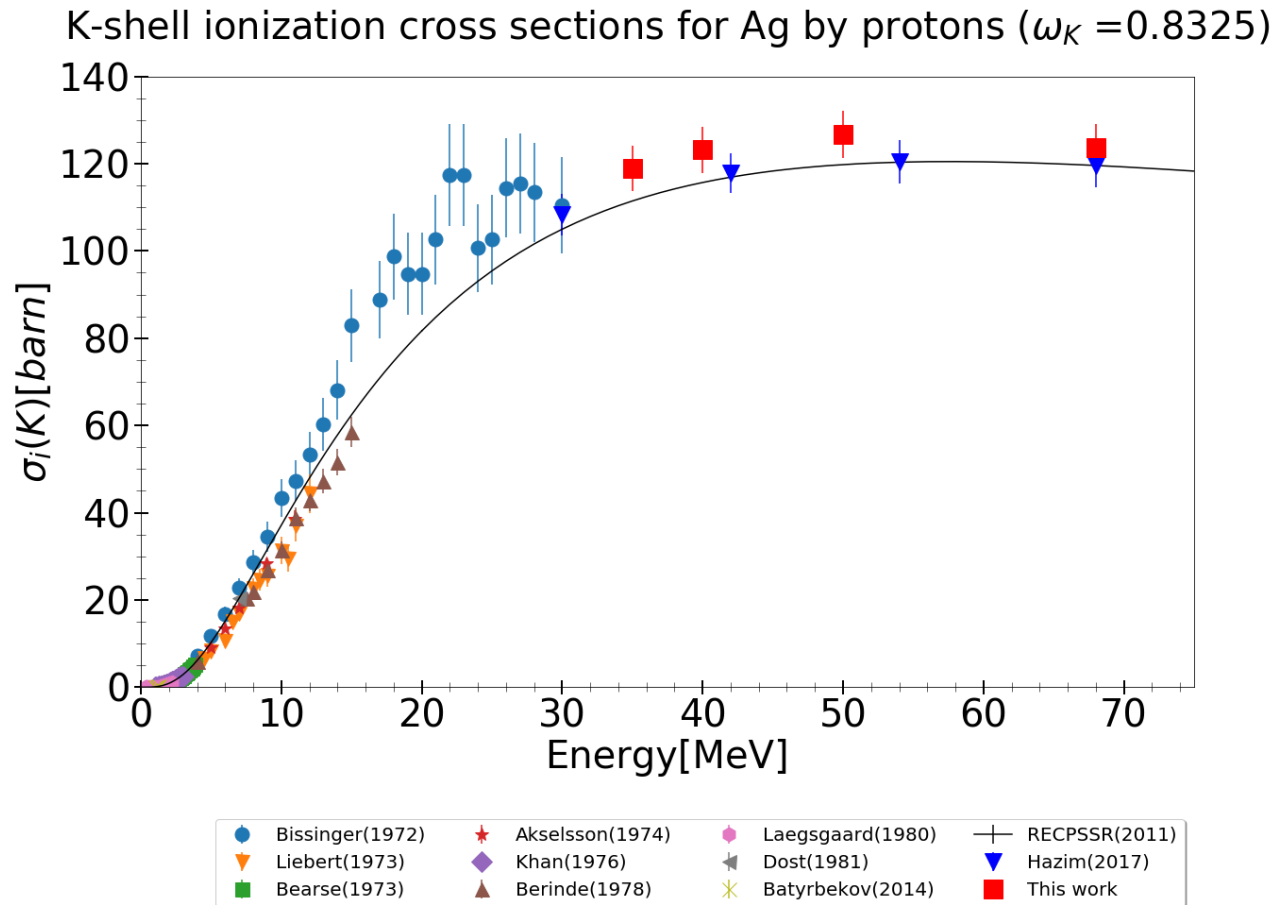
- The model correctly reproduces the trend of the experimental points
- But slightly lower than our experimental data

Comparison with the theory (RECPSSR): K X-rays ionization cross sections for Copper



- The model correctly reproduces the trend of the experimental points
- But lower than our experimental data

Comparison with the theory (RECPSSR): K X-rays ionization cross sections for Silver



- The model correctly reproduces the trend of the experimental points
- But slightly lower than our experimental data

Conclusions:

- We have measured ionization cross section with high-energy protons (30 – 68 MeV)
- It completes the lack of experimental data in this energy region

- We have compared our measurements with a theoretical model
 - At high-energy, there is an underestimation of the ionization cross section

- what remains to be done:
 - acquire new experimental data with other targets and energies
 - understand the difference between our experimental points and the theoretical model
 - to develop HE PIXE applications at the ARRONAX cyclotron.

Thanks for your attention

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