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Muonic Atom X-ray Emission Spectroscopy: implementation and benchmark of Monte Carlo simulation codes for non-destructive measurements

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XIX INFN Seminar on Software for Nuclear, Subnuclear and Applied Physics – Alghero, 9/06/2022

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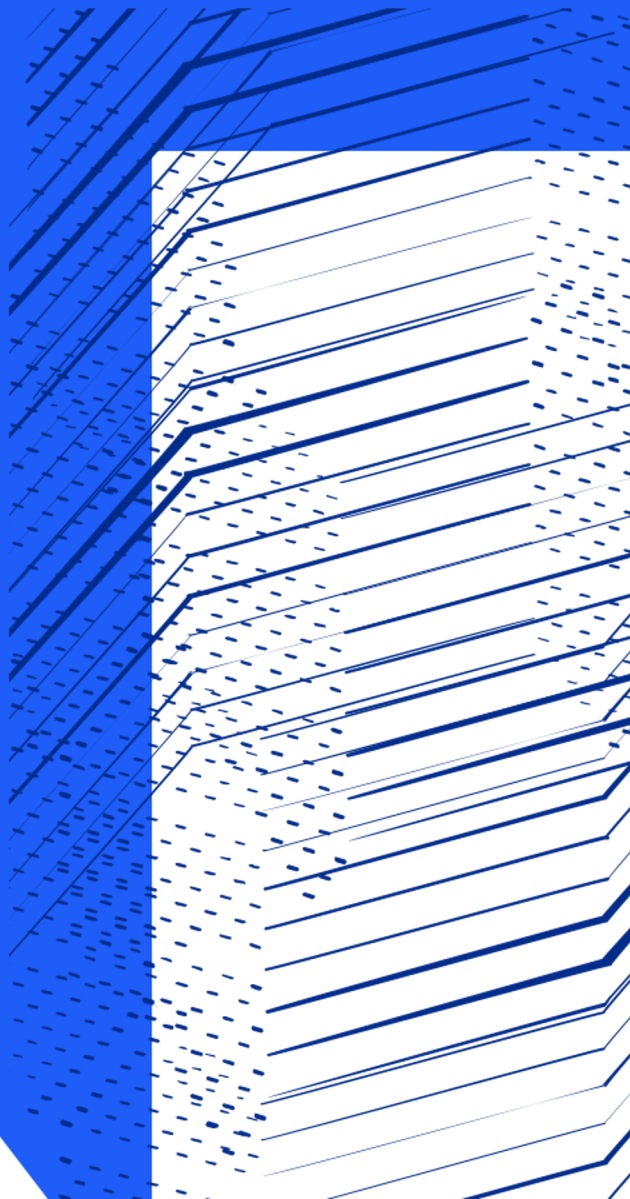
INFN CHNet
Istituto Nazionale di Fisica Nucleare
Cultural Heritage Network



Outline

1. Phd Project overview

2. Current work

3. Application in Cultural Heritage science

4. Final remarks

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University of Milano Bicocca -INFN

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Background: Master degree in Science and conservation for cultural heritage at the University of Florence

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1. PhD project overview

Framework: CHNET_TANDEM (R&D Gruppo V INFN) project for the implementation and development of techniques in the field of Archaeometry;

Collaboration with the ISIS Neutron and Muon Source (Didcot, UK, fig.1) development the RIKEN-RAL muon facility, especially for the **Muonic Atom X-ray Emission Spectroscopy (μ-XES) technique**. The PhD is co-founded by Bicocca and ISIS.

The ISIS Neutron and Muon source

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1. PhD project overview - Background

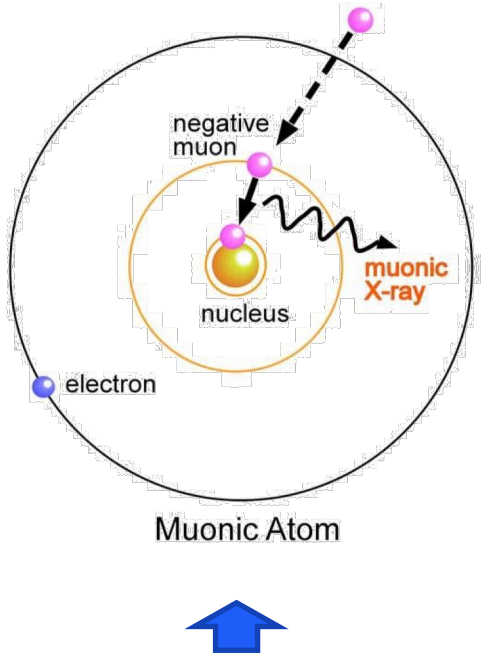
-/+

μ

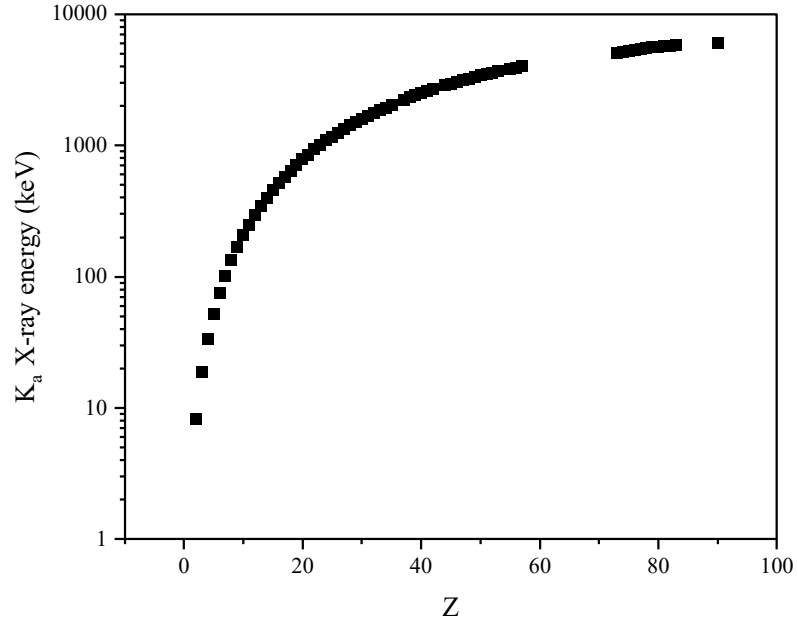
105.7 MeV/c^2

2.2μs

When a **Negative** muon interacts with matter, a "**Muonic atom**" is formed.



As the muon travel towards the nucleus, **high energy <u>muonic X-rays</u>** are emitted.



The radiation is **characteristic of the emitting atom** and can be used for material characterization (***0.01 – 6 MeV range) [1].***

Muonic atom X-ray Emission spectroscopy (μ-XES) is based on the collection and the analysis of this radiation

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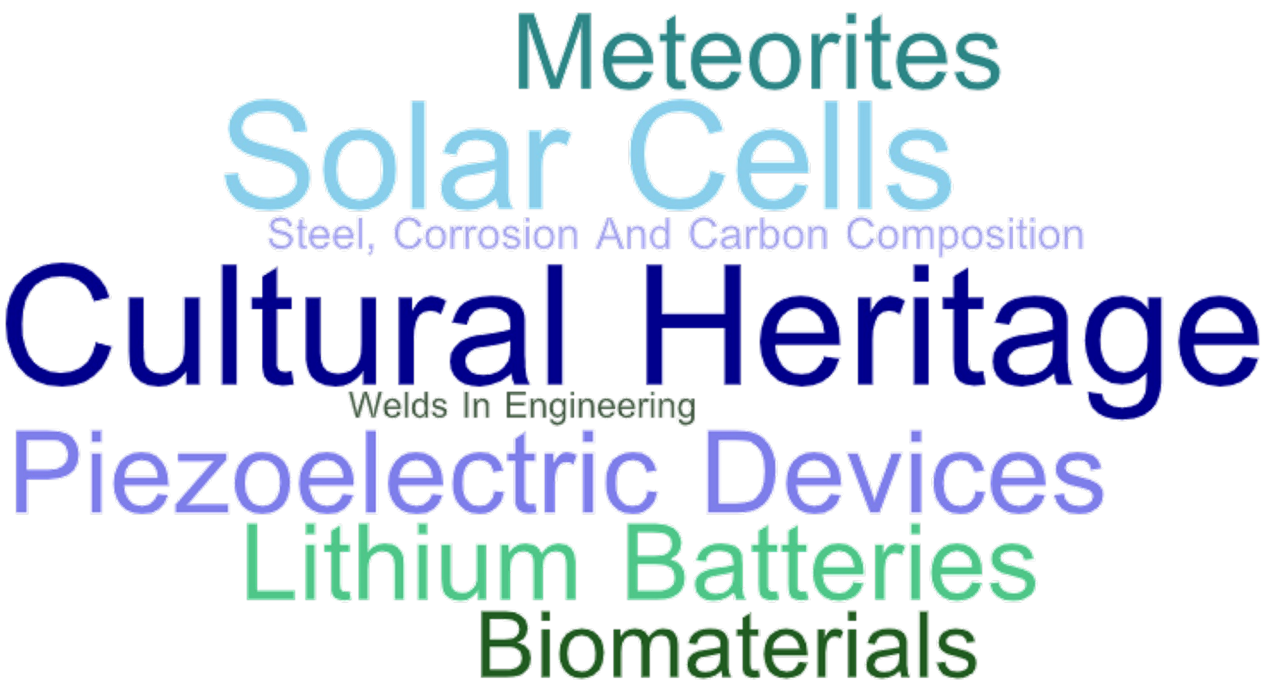
[1] Engfer R., Atomic data and nuclear tables,14, 509-597 (1974)

1. PhD project overview – Why μ-XES?

- **Multi-elemental technique**: sensitive to all elements (including light ones);
- Implantation depth controllable: both **superficial** and **bulk** analysis;
- **Non-destructive;**
- **No residual activity** left in the sample;
- No-significant self absorption.

Elemental analysis and depth profile characterization studies



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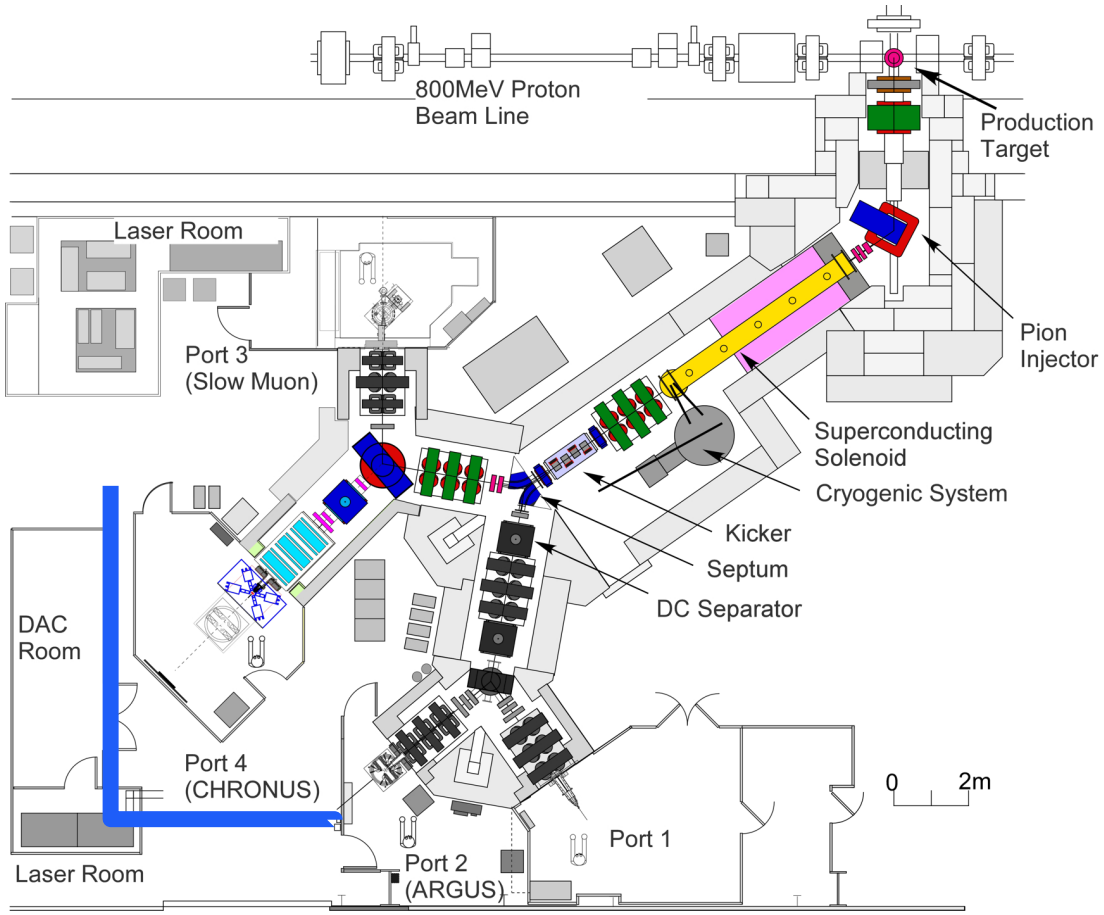
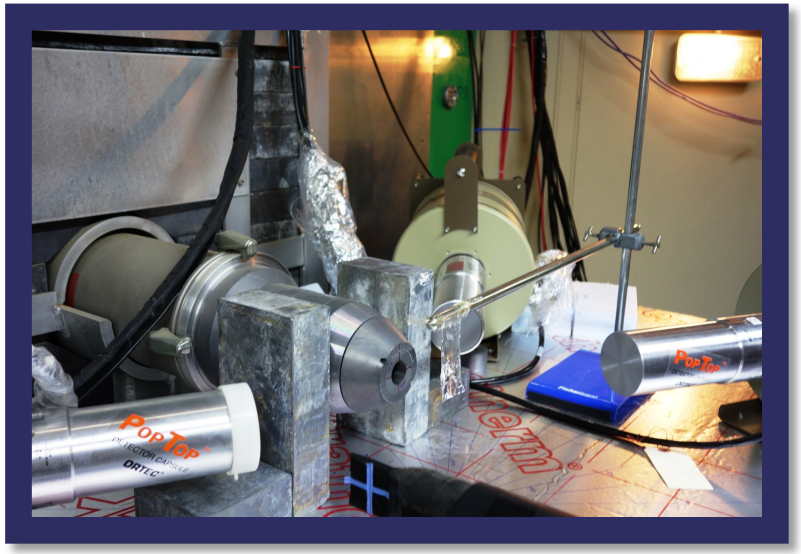
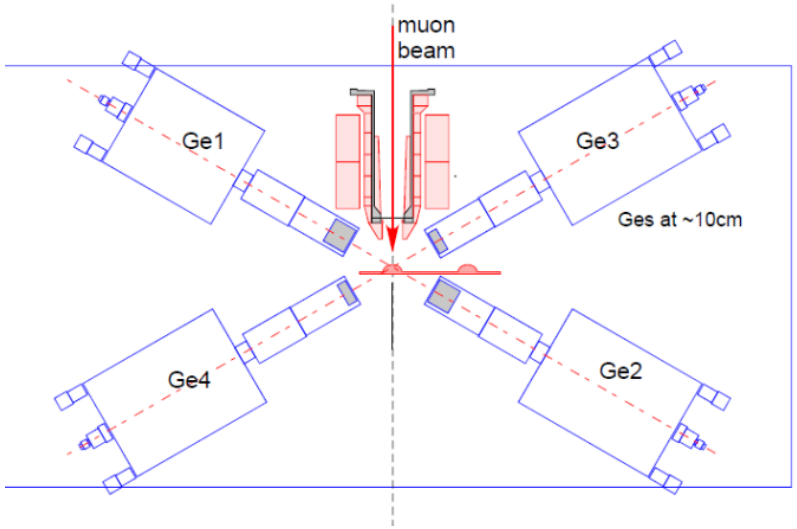
1. PhD project overview – The instrument



The RIKEN-RAL Facility @ ISIS [2]



Current instrument set-up



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[2] Matsuzaki, T., Ishida, K., Nagamine, K., Watanabe, I., Eaton, G. H., & Williams, W. G. (2001). The RIKEN-RAL pulsed Muon Facility. In Nuclear Instruments and Methods in Physics Research A (Vol. 465).

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1. PhD project overview – Main goals

Given the novelty of the technique, **limitations**, such as **long measurement time**, **poor solid angle**, difficult interpretation of data, represent an important issue.

The project aims to develop the existing limitations and improve the technique.

It is divided into two main themes: **software** and **hardware** depevelopment.

In both cases, the work is based on the use Monte Carlo Simulations softwares.

@Bicocca we use a «ARBY» a GEANT4 application with a user friendly interface.

2. Current work: Software development

The GEANT4-ARBY simulation software is not yet implemented and validated for our purpose.

From simulations, indeed, inconstencies in x-ray generations, especially for high energy transition were observed.

The GEANT4 class (G4EmCaptureCascade Class) seems to be mostly implemented for low energies transitions and low Z atoms.

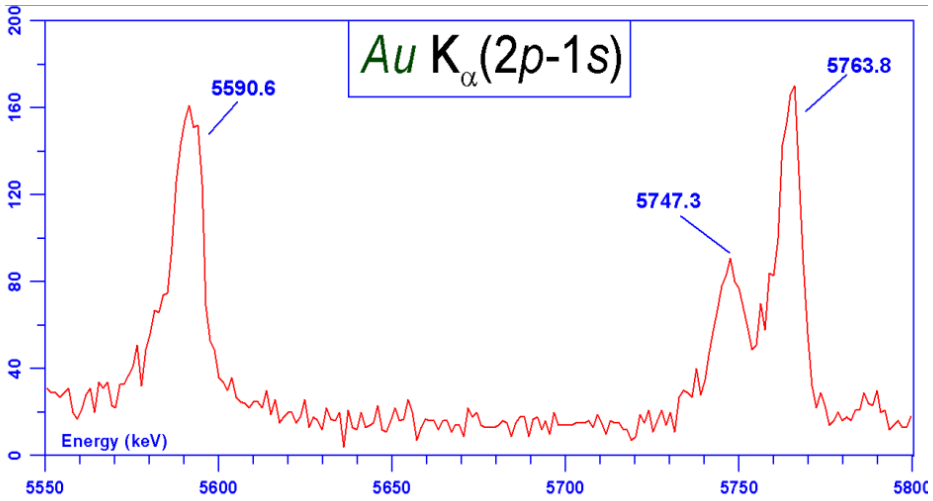
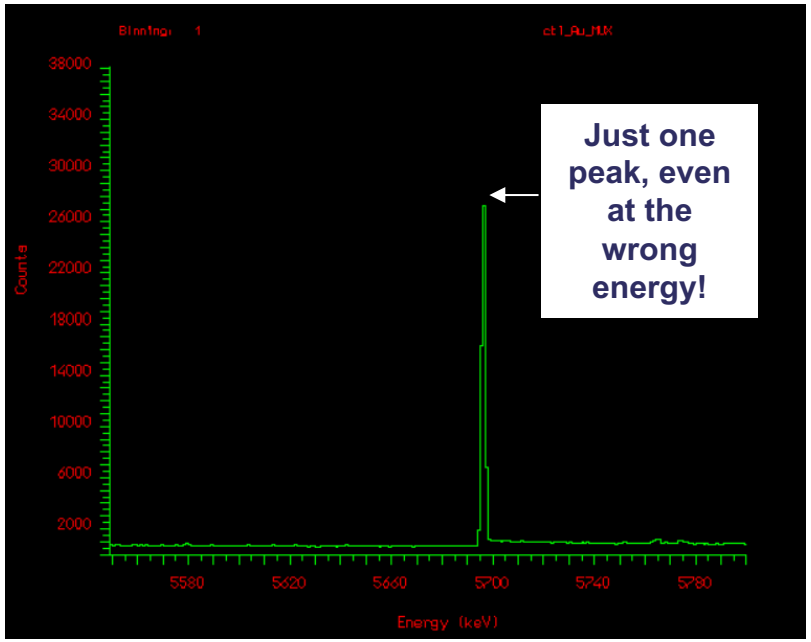


Image taken and adapted from: http://muxrays.jinr.ru/

Measured data

Simulated data



Possible solution: by using MUDIRAC, a software that computes all the transition energies, **creation of a database** that can be implemented in GEANT4 (still an on-going discussion) [3].

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[3] Sturniolo, S., et al., Mudirac: A Dirac equation solver for elemental analysis with muonic X-rays. X-Ray Spectrometry, 1–17, (2020)

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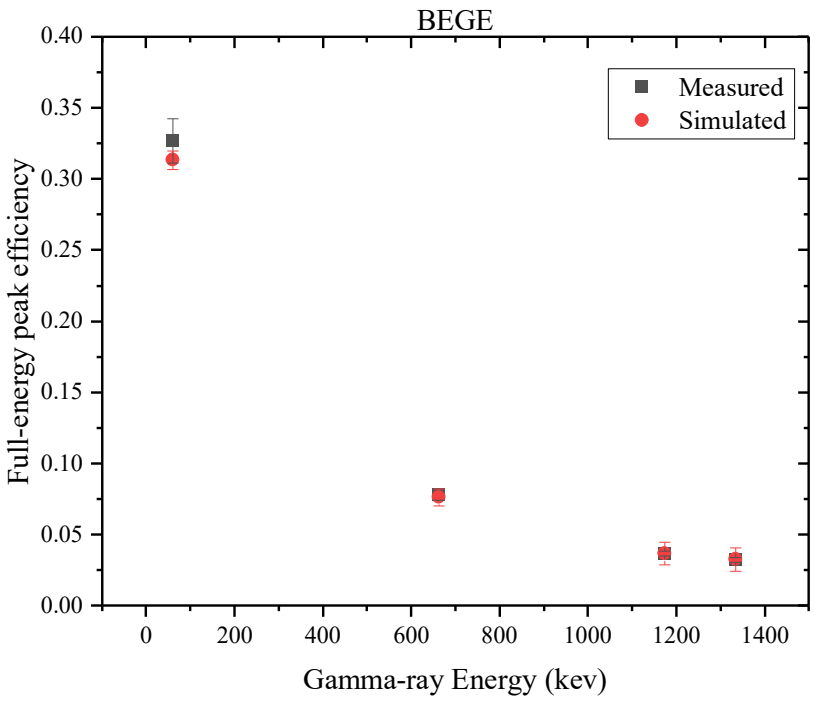
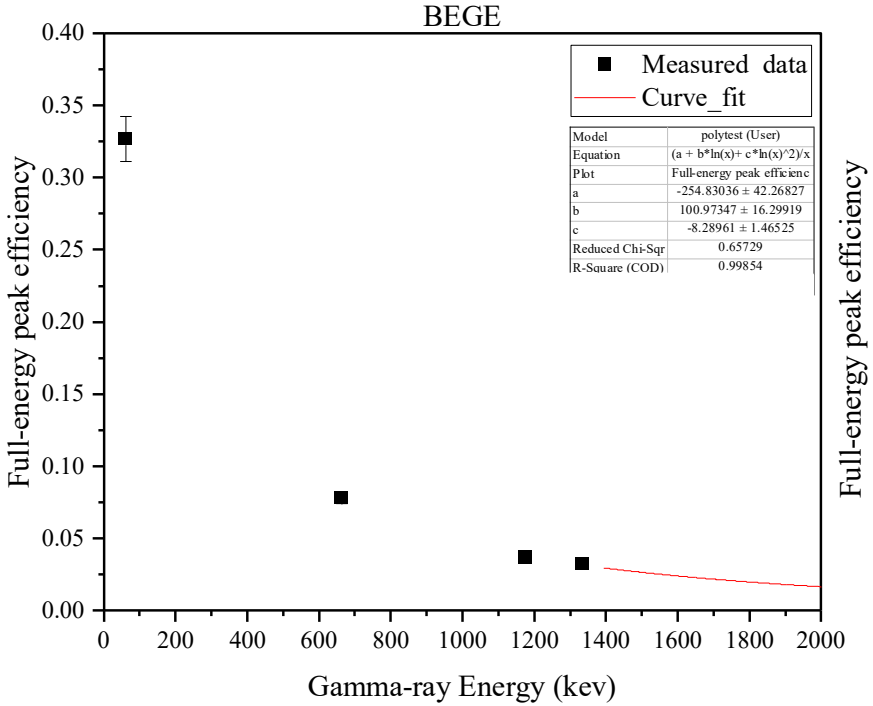
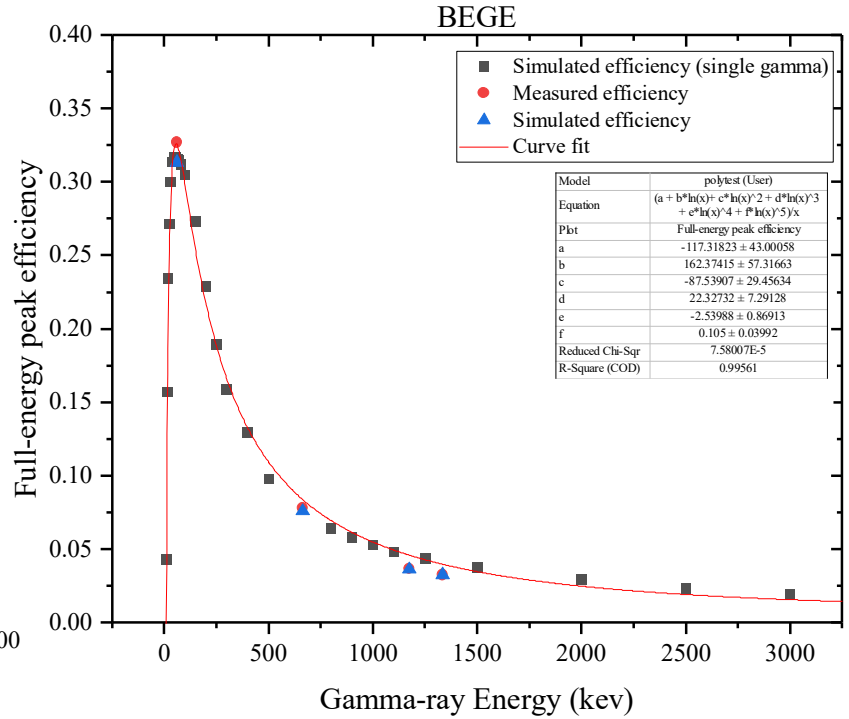
2. Current work: Software validation







With GEANT4/ARBY it is possible to **simulate the calibration procedure** of a HPGe detector and then determine the efficiency curve at a given distance (here, the source is placed close to the detector) [4].

To validate the model, the resutls from MC simulation were compared to with experimental measurements, and a good agreement was reached.

A validated software can speed up the measurements, since by doing simulations, one can **avoid to make calibration measurements for each change in the detectors positioning,** as it usually happens at RIKEN.

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[4] Alnour I. A., New approach for calibration the efficiency of HpGe detectors, AIP conference proceedings,1584, 38 (2014)

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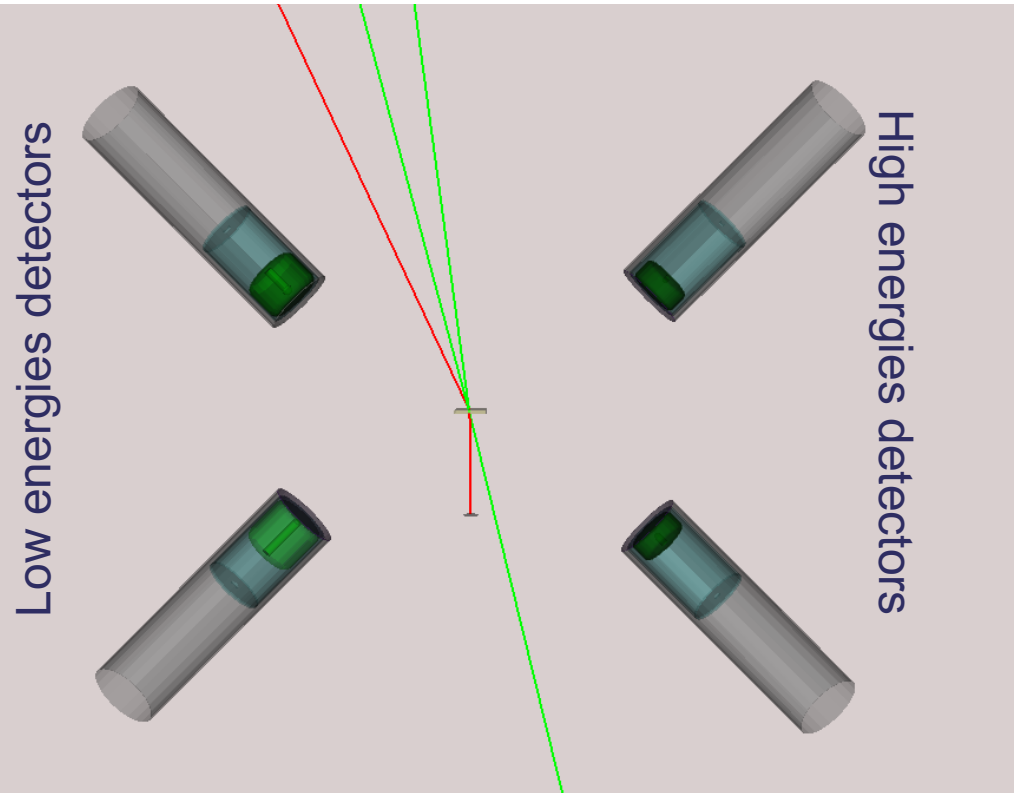
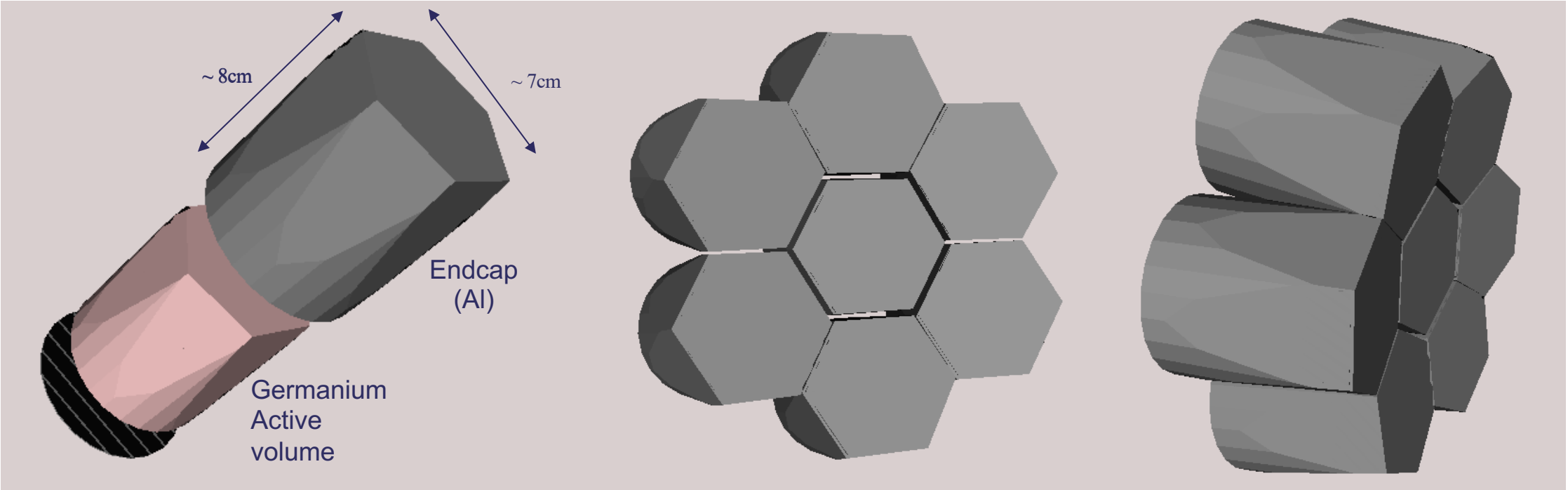
2. Current work: Hardware development



Port4 detectors array: ISIS is looking forward to implement the detector arrays.
So, simulation will be used as a tool for selecting the most suitable geometry;

2. Current work: Hardware development



Development of a set up that can **increase the overall efficiency** of the system, **increase the solid angle coverage** and **reduce counting time**.

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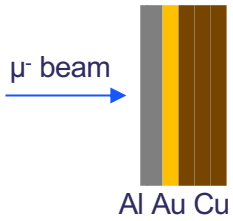
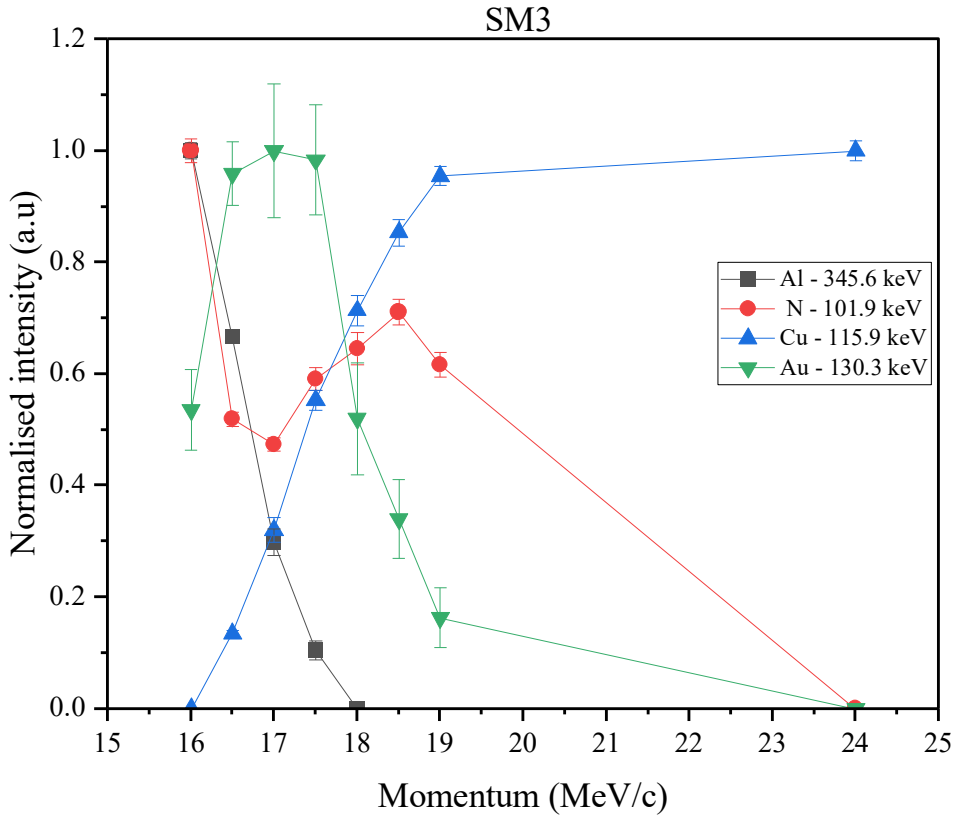
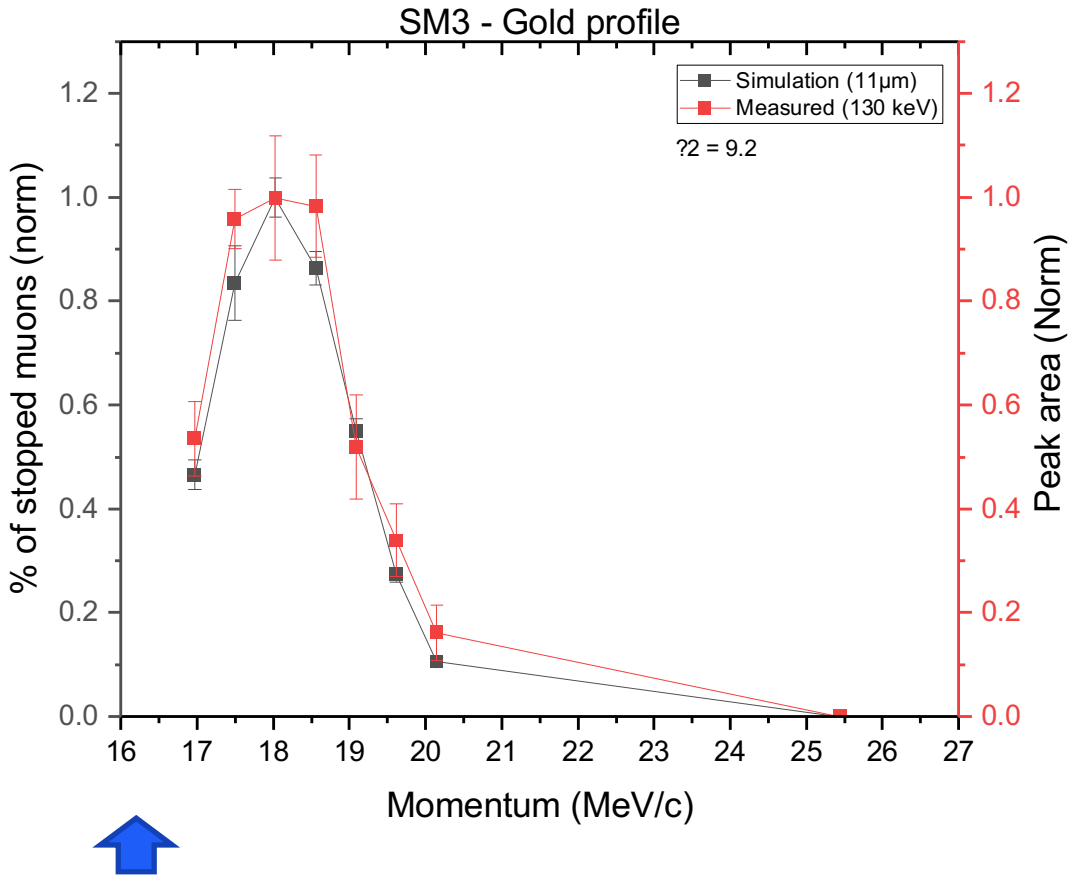
3. Applications in Cultural heritage science – Thin layers characterization

Gilded bronze







With simulations, it is possible to evaluate the thickness of a specific layer of the investigated sample [5].

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[5] Ziegler, J.F. et al. SRIM—The stopping and range of ions in matter. Nucl. Instrum. Methods B 2010, 268, 1818–1823.

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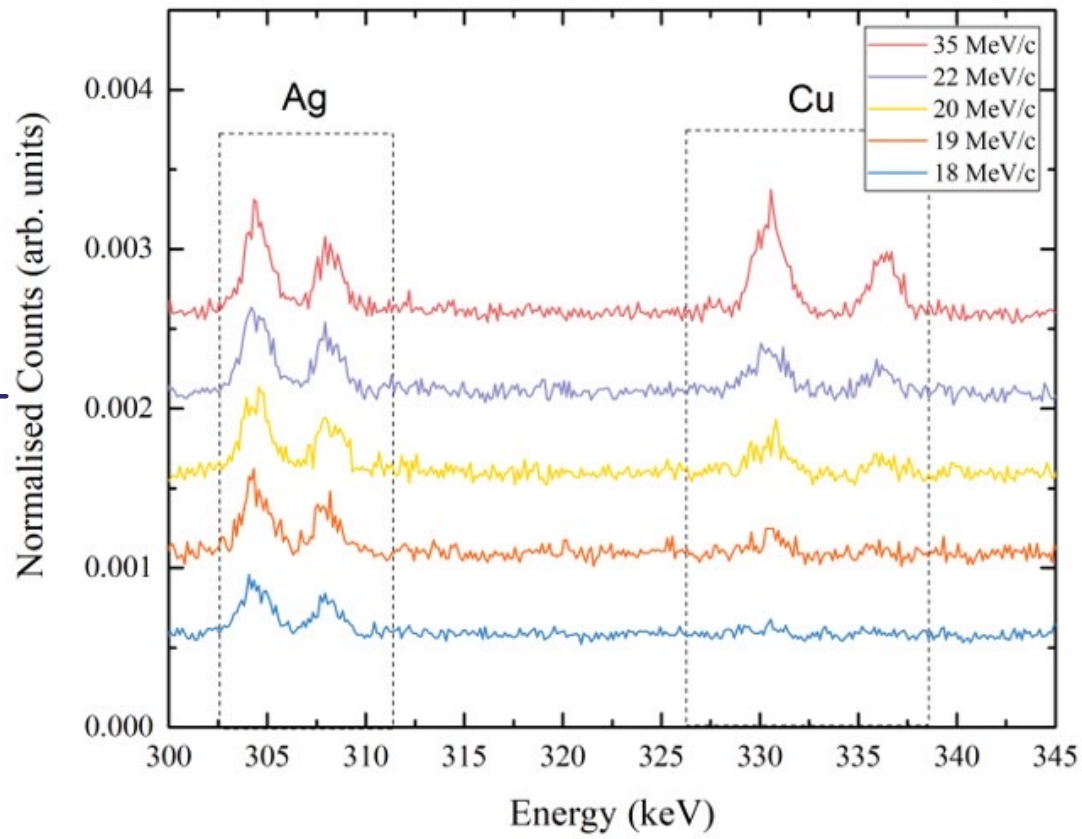
3. Applications in Cultural heritage science – Roman coins

Julia Domna – 3rd Century (AD 211-217) [6]

The **fineness** and **quality of a coinage** is often taken by historians to be a comment on the fiscal health of the issuing state.

The study of these material is of relevance, especially for rare coins.

Samples for analysis are commonly taken from the surfaces, or from just beneath the surfaces, of silver coins, and these are not representative of the original alloys used, **leading to erroneous estimates of overall composition** (especially with enriched surfaces)



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[6] Data from: B. Hampshire et al., Using Negative Muons as a Probe for Depth Profiling Silver Roman Coinage. Heritage 2, (2019), 400–407

4. Final remarks

To sum up, **μXES** is:

- Non destructive
- Depth controllable
- Sensitive to almost all elements

And **μXES** can have:

- Wide range of applications
- Elemental (and isotope) analysis

Yet, some more efforts are required to improve the technique.
The reliability of the software represent quite an issue and its development will be of foremost importance, as well as the implementation of the detector array.

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