Search for hidden heavy elements in ancient materials by electron beam-induced bremsstrahlung spectroscopy

Maxence Binot, Louis Bodart, Oscar Boquillon, Alexandre Bourdon, Lucas Breyne, Lalie Delecourt,
Thomas Delfosse, Gaspard Dereux, Mathys Desmettre, Valentin Dupriez, Tristan Honvault,
Pauline Huchin, Louis Janin, Arthur Jehoulet, Cyprien Kerampran, Arthus Labey,
Philippine Lambrechts, Jules Lebeurre, Amicie Lefebvre, Maelys Lefranc, Matthieu Vanbelle

Lycée de la Croix Blanche – Bondues, FRANCE

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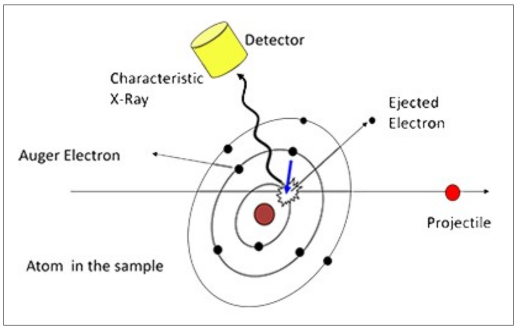
I - Introduction

Certain ancient artifacts, artworks, or valuable objects may still conceal information, not on their surface, but within their internal structure. Our team, BREM (Bremsstrahlung Research of Elementary Mysteries), aims to design a high-energy particle beam experiment capable of detecting heavy elements, such as gold or tungsten, embedded inside ancient objects. Crucially, the method must allow detection at trace levels and operate in a fully non-destructive manner.

Currently, several non-invasive techniques used in museums and archaeometric institutes — such as PIXE (Particle Induced X-ray Emission) [1] or RBS (Rutherford Backscattering Spectrometry) [2] — provide precise elemental analysis. However, these methods are limited to analyzing surface layers, typically probing only the first few tens of microns of material.

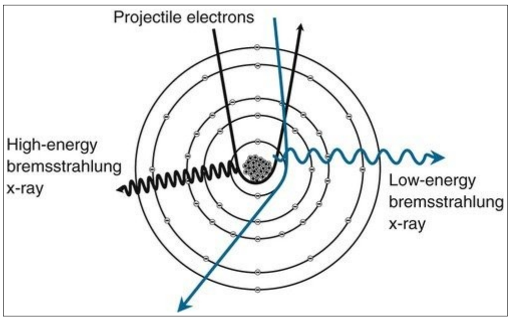


Operating principle of the PIXE analysis method.
https://www.cmam.uam.es/facilities/iba-techniques/pixe/

Our project aims to push beyond this limitation : could we imagine a method capable of penetrating matter to reveal hidden inclusions, like ancient gilding or concealed metal structures, without damaging the object under study? This is the challenge we seek to take on by coming to the LHC or DESY laboratory.

II - Experiment proposal

To investigate the presence of heavy atoms within objects, we will rely on bremsstrahlung radiation, an electromagnetic phenomenon that dominates when high-energy beams interact with matter. Bremsstrahlung corresponds to the emission of photons (typically in the X-ray or gamma-ray range) produced when a charged particle, such as an electron, is decelerated or deflected by the electric field of an atomic nucleus.



Bremsstrahlung radiation
https://physicsopenlab.org/2017/08/02/bremsstrahlung-radiation/

1) Theoretical description of Bremsstrahlung radiation

Although the full theoretical calculations are beyond our academic knowledge, we can nonetheless make use of the formulas derived from these theories to gain insight into the phenomenon.

Within the framework of classical electrodynamics, the power radiated by an accelerated charge q is given by the Larmor formula [3] :

$$P = \frac{q^2 a^2}{6\pi \varepsilon_0 c^3}$$

where P is the radiated power, q is the particle's charge, a its acceleration, c the speed of light in vacuum, and ε_0 the vacuum permittivity.

In our case, the acceleration a of an electron subject to the Coulomb attraction of a nucleus with charge Ze at a distance r, is given by :

$$a = \frac{Z e^2}{4\pi \varepsilon_0 m_e r^2}$$

By inserting this expression into the Larmor formula, we obtain an estimate of the power radiated by an electron under Coulomb acceleration :

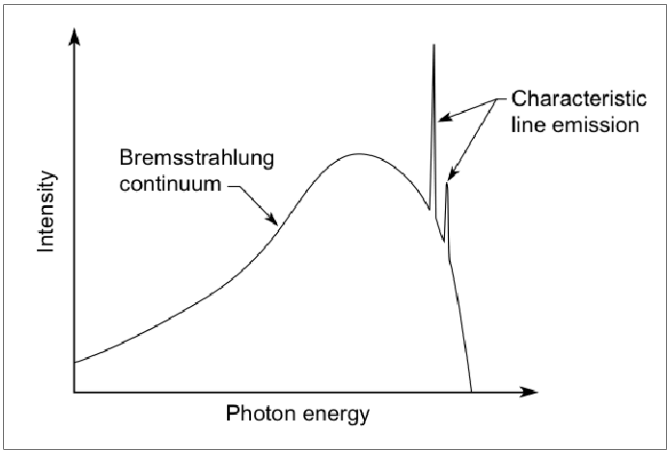
$$P = \frac{Z^2 e^6}{96\pi^3 \varepsilon_0^3 m_e^2 c^3 r^4}$$

In the relativistic framework, the radiated power is given by the relativistic Larmor formula :

$$P = \frac{q^2 \gamma^6}{6\pi \varepsilon_0 c}\left(\vec{a}^2 - (\vec{\beta} \wedge \vec{a})^2\right)$$

This expression shows that the radiated power increases significantly with the Lorentz factor γ, which becomes very large at velocities approaching the speed of light. A quadratic dependence on acceleration also appears, which implies, indirectly, a dependence on the square of Z, the atomic number of the target nucleus.

More advanced theories also make it possible to predict continuous spectrum of the bremsstrahlung radiation.



Bremsstrahlung spectrum

Bremsstrahlung radiation is exploited, for example, in radiotherapy to generate X-rays or in astrophysics to analyze nebulae.

Since both the radiated power and the bremsstrahlung spectrum depend on Z, could we, through spectral analysis, identify the presence of heavy atoms in an irradiated material ? Is it possible to estimate their concentration within the material ? And to what depth within the object can such an analysis be performed ?

2) Experimental setup

Before we can analyze real works of art, we must establish a reference framework by generating characteristic spectra using targets of well-known composition. This is the objective of our experiment. It will allow us to determine whether the study of such objects is feasible and to calibrate the method accordingly.

The study of bremsstrahlung radiation is typically conducted using electrons, as they interact strongly with matter during traversal. The higher the energy, the more the dominant bremsstrahlung emission extends into the high-energy photon ranges, and, more importantly, the more penetrating the beam becomes. We therefore plan to use an **electron beam of a few GeV energy**.

Our target must simulate a “typical” object. It is therefore appropriate to choose a base material with a low atomic number : **solid carbon (graphite)**. We also want to be able to vary the target thickness and easily incorporate different quantities of heavy metals. For this reason, we plan to construct our targets using **graphite plates** combined with **thin metal foils** or ultra-thin **gold leaf**.

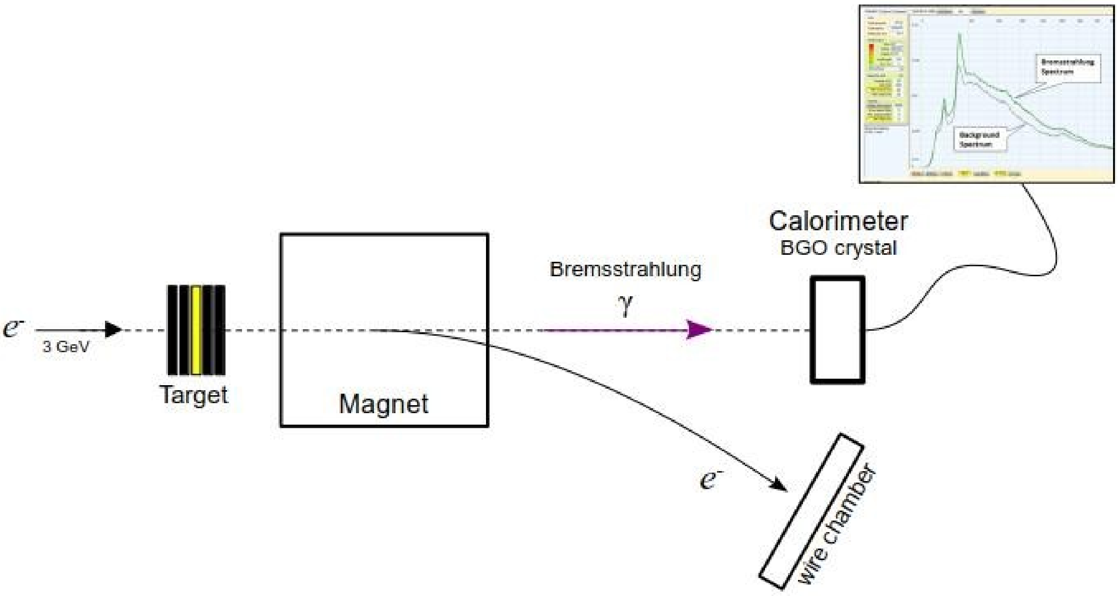
Graphite plates

Gold leafs

Tungsten foils

Our setup is straightforward : the electron beam strikes the target. At high energy, bremsstrahlung radiation is predominantly emitted in the forward direction. To isolate the photon signal, we place a magnet immediately downstream of the target to deflect electrons that pass through. A wire chamber is used to detect these deflected electrons.

The bremsstrahlung spectrum is measured using a calorimeter (a scintillator coupled to a photomultiplier). The BGO crystal (bismuth germanate) is a scintillator well-suited for the high energies involved in our experiment. It enables the acquisition of the full bremsstrahlung spectrum. It also opens the possibility of using a hybrid approach : leveraging bremsstrahlung to detect heavy elements, and secondary X-ray fluorescence for precise identification.



Experimental setup diagram

3) Experimental protocol

- The first measurement consists of recording the bremsstrahlung spectrum without any target, in order to obtain the initial beam spectrum (i.e., its interaction with air).

- Next, we need to establish the spectra of targets composed solely of graphite, with varying thicknesses (from 1 cm to 20 cm). This will provide us with the characteristic bremsstrahlung spectrum of our base material.

- **Study of the influence of heavy metal content :** we will measure the spectrum for different targets of identical thickness, but composed of various metals in varying amounts and positioned at different depths. All measurements will be performed under identical beam conditions (same energy, same intensity, etc.). Data analysis will allow us to understand how the spectra evolve as a function of these parameters.

- **Study of thickness influence :** for a given fraction of heavy metal, we will vary the total thickness of the target. As before, analyzing how the spectrum evolves will allow us to identify the influence of thickness.

- **Data analysis and interpretation :** To accurately analyze the spectra, background noise correction will be required. Quantities such as the area under the spectrum and the mean energy of the detected photons may provide valuable information. Finally, a comparison between the experimental results and a Monte Carlo simulation [4] (e.g., using Geant4) will help consolidate and validate our findings.

III - What we hope to take away

This project allowed us to explore a lesser-known aspect of physics, rarely covered in standard school curricula. We also developed our scientific approach by formulating hypotheses, designing the experiment, and drafting a detailed protocol. Group cohesion was another key takeaway from this experience, as we shared ideas and perspectives, ultimately bringing out the best in each member of the BREM team.

We therefore hope to carry out our experiment in one of the laboratories in order to test the bremsstrahlung effect on real-world objects. If, through this experiment, we succeed in detecting heavy metals, we could assist museums and help uncover hidden wonders invisible to the naked eye.

IV - Outreach proposal

Thank you for reading our proposal. Through this project, we learned a lot about particle physics and how accelerators work, as well as the various non-destructive analysis methods used to study the composition of artworks.

Building on this experience, we hope to present to a non-scientific audience not only our project, but also to the scientific methods that serve art and art history. This will be an opportunity for us to share our passion for science that led us to start and enjoy this project together.

First, before the end of the year, we will organize presentations in nearby middle schools, in partnership with art teachers. We would then like to host a lecture at the Louvre-Lens museum, located 50 km from our high school, to explain simply and in a fun way how particle physics can contribute to discoveries in art and art history.

For example, the C2RMF at the Louvre museum uses PIXE to determine the chemical composition of ancient pottery. This reveals the origin of the clay and helps trace trade or cultural influences.

We believe that raising public awareness of the real-world applications of science can spark greater interest in discoveries in physics. This will also demonstrate how seemingly complex theories can be applied to real life — in this case, art — and influence the way we live and solve problems.

V - Acknowledgments

First of all, we would like to thank CERN, and in particular the BL4S project team, for giving us the opportunity to prepare this experimental proposal.

We would also like to thank Mr. Arnaud Gniady, our dedicated mathematics teacher. He encouraged us to take part in the competition, created the team, answered our questions, led the project, and devoted a great deal of time to helping us develop the ideas of the BREM team.

VI - Références

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