

NUCLEAR PHYSICS METHODS IN CULTURAL HERITAGE RESEARCH — ACCELERATORS FOR ART*

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A review will be given on the use of nuclear physics techniques in non-destructive investigations on our cultural heritage objects. It focuses on making use of the production and detection of X-rays as a tool for micro analysis. At ‘small accelerators’, a versatile approach to determine elemental compositions as major constituents or as trace elements is the proton induced X-ray emission (PIXE), especially when combined with Rutherford backscattering spectroscopy (RBS), a powerful technique for near-surface investigations with micrometer resolution, and nowadays, with the use of improved detection sensitivities, set up for elemental mapping of large areas in a reasonable time for data taking. Such ‘small accelerator’ installations are well complemented by larger facilities, synchrotron radiation sources as well as medium energy ion accelerators for high energy PIXE. When high energy protons are used as inducing particles — with energies between about 20 and 100 MeV — elements deeply buried under several hundreds of micrometer of corrosion layers, can easily be identified, too. These techniques are complemented by X-ray fluorescence, which have recently been developed into a 3-dimensional micro analytical technique with a resolution of around 30 micrometers by employing multi capillary X-ray guiding lenses. The state-of-the-art methodology will be illustrated on examples from painted glass windows and luster ceramics closely related to basic research on nanometer sized metallic inclusions in glasses for plasmonics in photonics. Finally, an outlook will be given for a new generation under way of almost mono-energetic high-energy and high-intensity X-ray sources being developed as ‘table-top’ instrumentation with MeV-electron LINACS rather than GeV-electron synchrotrons.

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1. Introduction

There is an increasing effort for interdisciplinary research on our cultural heritage, for its preservation and conservation as well as its understanding in terms of authenticity, provenance, historical, geographical, and social background, but also understanding the techniques developed for the production of these objects. Natural science, in general, provides the tools for such studies, with special effort for the development of *non-destructive* or minimal invasive techniques. A tremendous progress has been achieved in developing extremely sensitive laser techniques, not only in the optical region but in infrared, in terahertz and other frequency ranges as well. In nuclear physics, techniques have been developed over years, especially in combination with accelerators, which can be very useful in micro-analytics and in high-quality imaging to ‘look behind’, ‘look inside’ or ‘look underneath the surface’ of valuable objects non-destructively which means without mechanical or chemical treatment of the objects.

An indisputable proof is rarely obtained applying just one single technique or investigation. A complete understanding and solution of the problems associated with an artefact, an archaeological finding, a cultural heritage object, can only be obtained by collecting as much information as possible and, therefore, applying as many techniques as are reasonably available. And similarly essential, only a close exchange, or better, an interdisciplinary cooperation can yield substantial answers and solutions in the investigations performed. In this context, one of the simplest question centers around the problem of *elemental composition*, either as part of the major components, or as traces within the objects. The next step would be to determine the *chemical form* in which the elements are found. Here, sometimes one single element may already be sufficient as a representative for a certain compound like a fingerprint, and a complete list of all the elements forming the compound is not needed. The next step could be the question of spatial or areal distribution of the elements or the chemical compounds, whether they are found only at or near the surface, or at random or in inclusions within the bulk.

Closely related to nuclear physics techniques, X-rays are in the focus for determining elemental compositions. From ‘Moseley’s law’ [1], the energy of the so-called characteristic X-rays directly yields the element number Z . To induce the emission of such X-rays, the object under investigation has to be irradiated either by X-rays (or synchrotron radiation), then the characteristic X-rays are emitted as fluorescence radiation resulting from the photo effect (XRF), or by charged particles, typically protons, then the X-rays are emitted as follow-up of the kicking-out of electrons, the technique being

called particle (or in the case of protons, proton) induced X-ray emission (PIXE)¹.

The dream of an archaeologist or a museum's director, of course, is the portable instrument with which all questions arising with the object could be answered. The cooperation between natural science and 'cultural science' in general has considerably improved over the last decade. As a result, progress in experiments on large scale facilities like neutron sources, synchrotrons, ion beam facilities has led to developments and improvements of small laboratory size systems and portable setups letting the more difficult experiments to such facilities for very special objects and questions. Thereby, the risks coming along with transportation and handling are reduced. This development illustrates the need to perform studies on cultural heritage objects on large scale facilities and the benefits obtained for both communities, improvements on the experimental setups (higher detection sensitivity, reduced exposure to radiation, installations for proper environment for the objects with respect to humidity, temperature, *etc.*) at the facility and 'outsourcing' for field studies. The objective of this review is to illustrate the recent progress along these lines.

2. Elemental analysis

As outlined in the introduction, the element number Z is unambiguously determined by measuring the X-ray energy of the emitted characteristic X-rays. However, in practice, this is only possible for elements heavier than Na due to electron emission as an alternative process (Auger-process) following the excitation. The so-called fluorescence yield (number of emitted photons per total number of ionizations) increases with Z , X-ray emission becomes dominant beyond iron. In addition, information from deep inside a sample is hampered by absorption of the emitted X-rays, low energy X-rays can only be detected when emitted from elements near the surface.

The X-ray fluorescence detection is typically understood as the follow-up of the atomic excitation by X-rays (photo effect). For two major reasons the excitation by charged particles, protons or heavier ions, may be a favorable complementary technique: in the case of protons (PIXE), the difficulty due to the fluorescence yield detecting elements lighter than Na and the absorption of low-energy X-rays can be compensated by simultaneous nuclear excitation resulting in energetic γ -ray emission, so-called proton (particle)-induced gamma emission PIGE; additionally, high-energy PIXE can excite X-ray emission deeper within the material than X-rays so that absorption is

¹ The use of electrons is also possible, as often done in electron microscopes as an additional feature for energy dispersive X-ray spectroscopy EDX, but electrons typically need vacuum conditions for the samples.

significant only for the outgoing fluorescence radiation. Furthermore, PIXE can be simultaneously complemented with RBS which provides an improved depth resolution near the surface (see the review [2]).

There are various levels of problems connected to the necessity of elemental analysis which leads to major questions to be answered before setting up a roadmap how to proceed, such as:

- Can one expect a homogeneous distribution of the elements in the sample?
- Can one identify trace elements?
- What are the main components?
- Are there elements which could be used as signature for the chemical compound?

For inhomogeneous samples, the procedure depends on spatial/areal distribution on the surface or in the bulk.

2.1. Trace elements reveal context and background

Precious gemstones or minerals, in general, contain trace elements which are typical for their geological origin. Thus identifying these trace elements may tell us the provenance of the material. Depending on the location where the object with such gems or minerals were found we might learn about

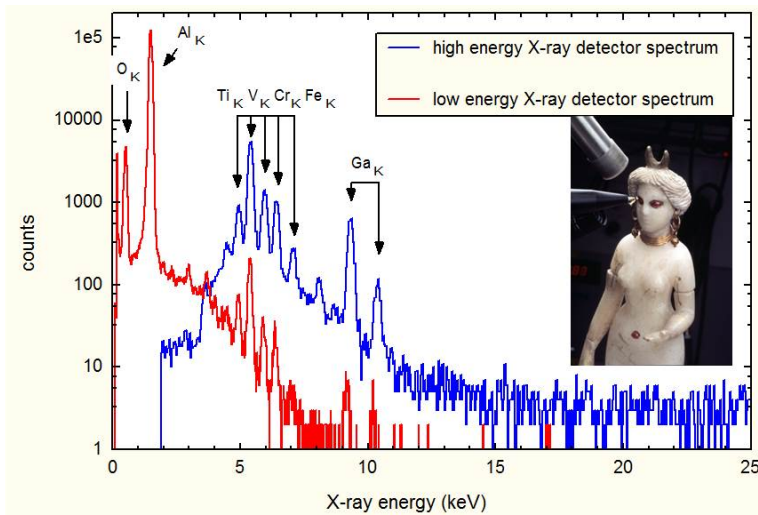


Fig. 1. X-ray spectrum detected in two Si(Li) detectors in the PIXE analysis with 3-MeV protons hitting the alabaster statuette positioned close to the beam exit foil. The air in the beam and X-ray paths is replaced by flushing helium gas. Insert: Standing nude statuette of a goddess, Louvre AO 20127 (courtesy of T. Calligaro, C2RMF).

cultural links, trade routes and relationships. The investigation of inlays in an alabaster statuette at the Centre de Recherche et de Restauration des Musées de France (C2RMF) some years ago can be considered as a textbook example. Calligaro and co-workers [3] showed by PIXE analysis at the AGLAE accelerator (Accélérateur de Grand Louvre pour Analyse Elementaire) at the C2RMF that the red inlays for the eyes and the navel in an alabaster statuette made by Parthians are rubies and not red glass (Al_2O_3 with Cr yielding the red color, and other traces), originating from the region Sri Lanka or Myanmar as derived from a careful analysis of a number of impurities (see Fig. 1). The analysis which is based on the similarity in the content of trace elements for a large body of rubies is also in accordance with a Sanskrit text in which the extraction of rubies from deposits in India and Sri Lanka was mentioned.

Other objects for which trace elements may be successfully used for obtaining information on provenance are obsidian, jade, and with special care noble metals like gold. Especially in the case of metals, special care has to be given to possible metallurgical treatment, alloying and mixing with material from different sources.

2.2. Elemental mapping for revealing hidden paintings

Since the discovery by W.C. Röntgen, X-rays are widely used for revealing hidden objects without disassembling, *i.e.* non-destructively, simply by monitoring the transmitted X-rays ('radiography'). In the case of paintings, the standard radiography often turned out to be too insensitive for a clear representation of what is underneath the surface. In recent years, however, 'looking behind the surface' has been improved considerably beyond the standard radiography. Taking advantage of a special feature of the materials used as pigments in paintings, some of the major pigments can be unambiguously identified simply by one element which is then used as a signature for this particular compound. One well-known example is cobalt, in connection with color better known as cobalt blue.

The recent demonstration on a painting by van Gogh performed at a large scale facility, the synchrotron laboratory HASYLAB at DESY, has initiated the development of mobile systems now commercially available which makes such studies possible for museums without the risks and costs of transportation. In the experiment at the synchrotron, Dik *et al.* [4] could clearly show the portrait of a woman underneath the painting 'Patch of grass' by elemental mapping, the portrait in the typical style of quite a few portraits by van Gogh (see Fig. 2). Already the mapping of Sb using the *K* X-rays of Sb excited by the monochromatic synchrotron radiation with sub-mm resolution clearly showed the portrait, an even better representation was obtained when Hg data from the *L* X-lines were included.

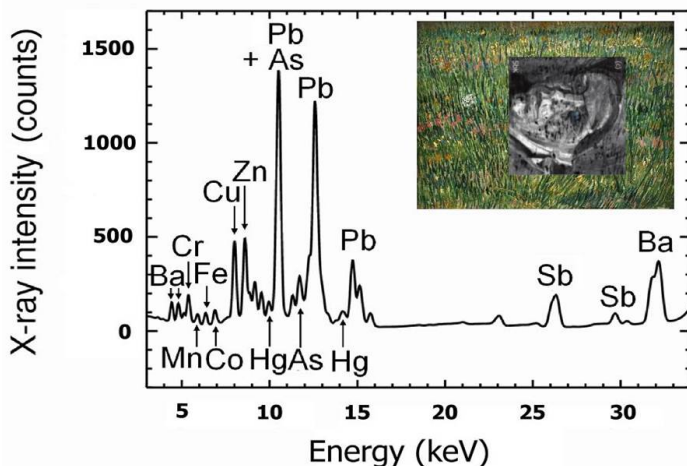


Fig. 2. XRF using monochromatic synchrotron radiation for the detection of medium to high Z elements on the painting ‘Patch of grass’ by van Gogh. The X-ray spectrum reveals the occurrence of antimony (Sb). Already by mapping the Sb K -lines the hidden painting underneath the present version is revealed much clearer than in earlier radiography (for details, see Ref. [4], we thank the authors for allowing the use of their data for this review).

In another recent collaboration between scientists and art historians, a painting for which the assignment to van Gogh was in doubt (‘Flower still life’) showed underneath a wrestling scene with two ringers, made ‘visible’ by scanning Zn. Van Gogh himself explicitly described the preparation of such a painting in his drawing class at the Antwerp Academy in a letter to his brother, as is well known among art historians. After summing up all the evidence (including *e.g.* additional information on the pigments used), the painting is now safely attributed to van Gogh and on display in the Kröller-Müller-Museum Otterlo [5].

While both examples discussed were studied at the synchrotron source at the HASYLAB, a mobile system has recently been developed [6] based on an earlier realization for applications on art and archaeological objects [7]. It is designed especially for multi-elemental mapping based on the major improvements in experimental setups for users at synchrotrons with respect to intense and well-focused X-ray beams employing polycapillary X-ray optics with sub-mm resolution [8] and the fast and effective detection of X-rays based on either PIN diodes or silicon drift detectors.

2.3. Materials composition

Among our cultural heritage, whether in archaeology or in museum's science in general, glass and ceramics play a major role. Both types of objects have in common that the raw and base materials are metallic oxides and the final objects often are very beautiful and colorful pieces, like sculptures made out of glass or stained glass windows, ceramics with metallic like shiny surfaces, luster ceramics, but also objects for daily use. In both categories of cultural heritage objects, highly sophisticated processes, such as melting and firing, are involved which are also strongly influenced by impurities and additives and depend on the technological knowledge achieved within the community. The recipes of workshops manufacturing such objects were often unique like a signature or trademark. The final result nowadays, if analyzed carefully, may reveal details about the process, the technological steps or simply the routes of trading.

In the case of ceramics, there are often many sherds or fragments of broken pieces available, both of the main body as well as of surface parts. Therefore, the methods yielding the most accurate results may be chosen, independently whether it is non-destructive or needs material which is lost afterwards, *e.g.* by powdering for chemical micro-analysis, fluorescence analysis, neutron activation or similar techniques.

In the case of glasses, as part of public space like church windows, a complete analysis is needed to come up with a proper procedure for restoration and preservation. Many admired stained glass windows survived several centuries from their creation by the artists in medieval times, but were heavily damaged during the last hundred fifty years due to industrial pollution.

In principle, XRF is a method very much suited to non-destructively determine the composition of ceramics and glasses. However, both types of objects, ceramics as well as glasses, can be quite inhomogeneous with respect to depth. And for decorated ceramics and stained glass, of course, a lateral resolution is definitely needed in the μm regime, sometimes even less. With these requirements PIXE with well-focused external ion beams may be an appropriate complementary method. On accelerator systems like AGLAE, fully dedicated to analytical work on cultural heritage objects with typical ion beams like protons and alpha particles between 1 and 4 MeV, the PIXE analysis is additionally and simultaneously complemented with PIGE for low- Z elements like Na or even lower- Z elements and with Rutherford backscattering spectroscopy RBS, simultaneously, too, so that the near-surface region can be analyzed for their composition with sub- μm depth resolution (for details about the system AGLAE, see [9]).

One example is shown in Fig. 3 where the analysis of two glass pieces is illustrated, one from the cathedral in Evreux, the other from the church St. Ouen in Rouen. From the PIXE analysis it appears that the glass piece from

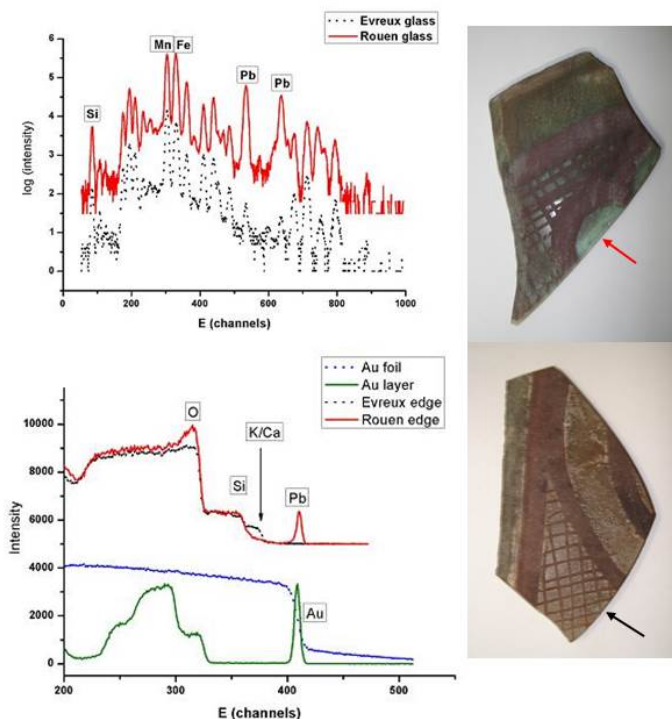


Fig. 3. PIXE (top) and RBS (bottom) analysis with 3-MeV protons on glass pieces from Evreux (bottom) and Rouen (top). The spectra were taken on glass edges as indicated by the arrows. The Evreux glass was analyzed on a freshly broken edge (dashed line in black, lower curve), the Rouen glass was analyzed with an edge originally in contact with the Pb came metal (solid line in red, upper curve). The RBS spectra in the lower part are compared with spectra for a thin Au layer ($46 \mu\text{g}/\text{cm}^2$ corresponding to 23 nm) and a thick Au foil to illustrate the near surface occurrence of Pb on the glass piece. We thank C. Loisel from the Laboratoire de Recherche des Monuments Historiques LRMH, Champs-sur-Marne for supplying the glass pieces.

Rouen contains a small amount of Pb like a lead glass, which is not observed for the piece from Evreux. However, the RBS, taken simultaneously, clearly shows that the Pb does not originate from the bulk, but it is rather a surface contaminant, paralleled by a reduction of K/Ca at the surface, which may be taken as an indicator for a chemical surface reaction. The spot analyzed at the piece from Evreux is actually on a ‘freshly’ broken edge (after it was taken from the window) with no sign of chemical attack, so that it may be taken as representative for the bulk. Pb is known not to diffuse into standard glass,

but under the unfavorable weathering conditions with condensing water, non-neutral pH-value, and the vicinity of Pb in the grisaille (glass paint), frames, and comes, a surface reaction is a plausible explanation for what we found in the case of the Rouen glass piece [2, 10]. This example illustrates the advantage when two analyzing methods can be applied — in this case simultaneously PIXE and RBS — on the same spot excluding a possible misinterpretation.

Like the preparation of the main body, the coloring of glasses and ceramics was and is still done with quite similar ingredients. The standard procedure is to add certain colored oxides as pigments to the glass melt or the top clay layer. But in contrast to paintings, where pigments are used for coloring ('pigmentary' colors) some colors like red and yellow, can be obtained by light scattering on nanometer sized objects ('structural' colors) rather than absorption and/or reemission at ions or atoms in pigments. These objects are metallic nanoparticles and the physical process is surface plasmon excitation leading to broad absorption bands and finally resulting in special colors like the ruby red (gold particles) or silver yellow (from silver particles), and sometimes copper as well in glass. In the case of ceramics, such particles arranged near the surface and in much higher density (as compared to the highly dispersed clusters in glass) lead to the so-called luster ceramics due to additional structural effects, giving the reddish-yellow color a metallic glance.

A famous and rather early example for colored glass is the Lycurgus cup, assigned to the late Roman period (4th century AD), showing the strong red/green coloring effect in different illumination geometries (see Fig. 4). A detailed description is given in [11]. From the present understanding of how to prepare such colored glasses, the final product was presumably



Fig. 4. The Lycurgus cup in reflected light (left) and transmitted light (right). © British Museum AN36154.

the result of ‘try and error’ and the recipes used in the glass workshops were a well-kept secret. It depends on the kind of compound mixed into the oxides before preparing the melt, the ingredients and the firing procedure which help to reduce the metal ions to metal and its growth to the proper nanometer size. Therefore, the information about elemental composition may then not be enough, the information about the chemical form, *e.g.* compound or metal, is needed. That information can be obtained from X-ray absorption techniques such as extended X-ray absorption fine structure EXAFS, as available at synchrotron radiation facilities such as *e.g.* the HASYLAB at DESY. Since the amplitude of the photoelectron wave following the absorption results from the superposition of scattered waves coming from neighboring scattering centers around the central absorbing atom, the energy dependence of the absorption coefficient near the absorption edge shows modulations which are signatures for the atomic arrangements thereby reflecting the chemical compound as defined by coordination and local binding length. In Fig. 5, the Fourier transform of such EXAFS absorption spectra is shown for two glass pieces cut out of a glass bowl [12] containing copper, the piece for the lower spectrum was additionally heat treated. The marked positions of the major components in the Fourier transformed

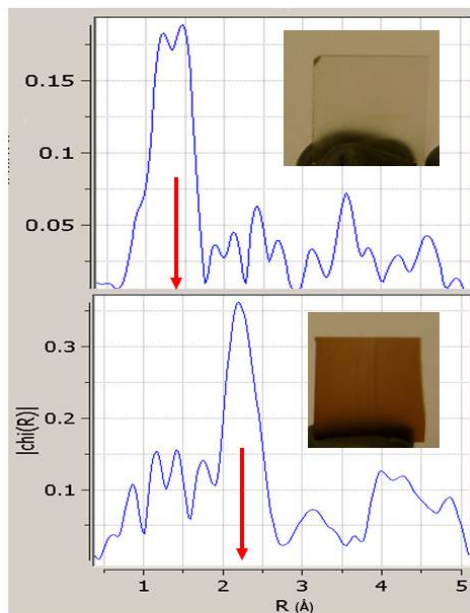


Fig. 5. Fourier transform of the EXAFS spectrum of Cu in glass pieces cut out of a glass bowl (courtesy of F.X. Nachtmann [12]), no extra treatment (top), after heat treatment (bottom).

R space are typical for Cu-oxide (upper curve) and copper metal (lower curve) thus demonstrating the color change from transparent to opaque (here into brownish-yellow) as due to the change in oxidation state, the transformation into metallic objects.

In principal, the same transformation is achieved in the preparation of luster ceramics. The metallic nature of the Cu, Ag, and Au or mixtures and alloys thereof is well established by EXAFS (*e.g.* [13]). The main difference between the color due to nanoparticles in glass and in ceramics is the density and distribution as indicated in Fig. 6. To obtain information about the depth distribution of these clusters in the case of luster ceramics, RBS combined with PIXE are very useful to get at least an elemental depth profile combined with the lateral extensions, complementing information obtained in synchrotron and laser experiments. In Fig. 7, an example for such an analysis is given, illustrating the different composition in Cu and Ag for the different colors red and brown on the ceramic (a more complete presentation was given at the 20th International Conference on Ion Beam Analysis IBA 2011 [15]).

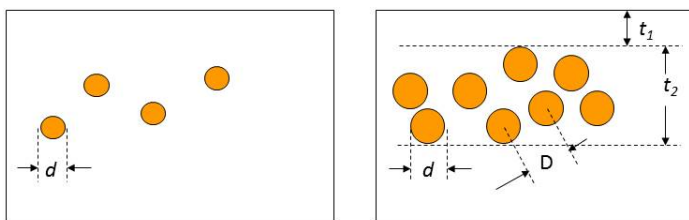


Fig. 6. Schematic principle of metallic nanoparticle arrangement in glass (left) and luster ceramics (right) for ‘structural’ colors. While in glass often a random distribution with low density is found, in ceramics the structure is more strictly defined with t_1 , the distance from the surface of the order of several tens nm, t_2 , the thickness of the luster layer of the order of μm , d the diameter of the clusters between 5 and 50 nm, and the ratio of mean distance, D , over size D/d between 1.14 and 1.7 leading to the metal like shine (the values are taken from [14]).

As one may realize in the case of ceramics, the color is not so precisely defined as in the case of glass. It certainly has to do with compositional details, sizes and density. Therefore, more refined analytical approaches are needed for studying production techniques, production workshop and sources, revealing connections *etc.* For such investigations an upgrading program for AGLAE to NewAGLAE has been started to simplify large area elemental mapping due to improved sensitivity, detection efficiency, and beam stability for routine automation [16], a photo is presented in Fig. 8 and a first example for elemental mapping applied to a piece of Islamic ceramics in Fig. 9 [17].

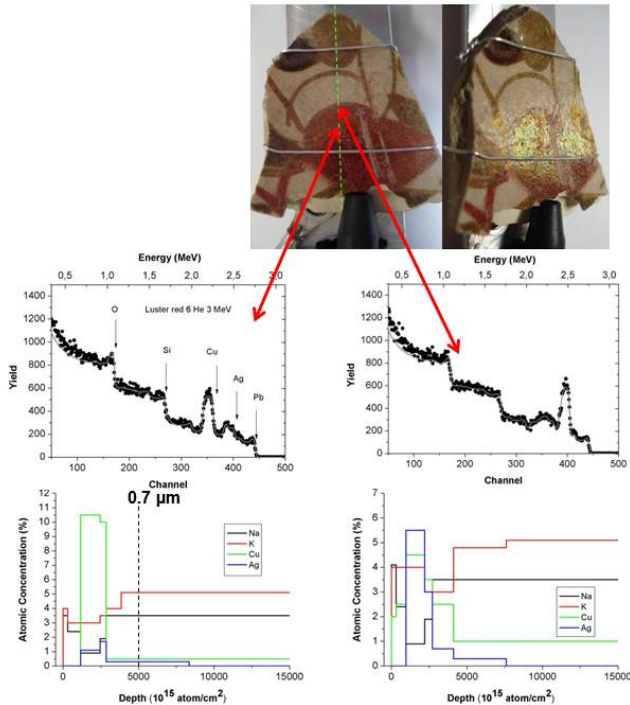


Fig. 7. RBS with 3-MeV He-4 ions and depth distribution of the essential elements Na and K of the basic ceramic material and Cu and Ag of the clusters on the red and brown color of the luster ceramics as indicated by the arrows on the piece (ceramic piece Louvre MAOS 657).

The physics behind the structural color with the nanometer sized metallic clusters has been realized and explained by surface plasmon excitation which has led to the modern topic of plasmonics applied in photonics. On the road to tailoring metallic nanoclusters for optical transport, it has been realized that materials modification by fast heavy ions, a special topic at heavy ion accelerators (see the proceedings of the latest conference on Swift Heavy Ions in Matter SHIM 2012 [18]), may be a possible approach due to the highly concentrated transferred energy (so-called electronic energy loss) within a nanometer wide and micrometer long region ('ion tracks'). By irradiation of soda lime glass with 600-MeV Au ions, Ag nanoclusters have been found to be produced in chains parallel to the direction of the ion beam [19]. The Ag was incorporated prior to the irradiation by chemical ion exchange, *i.e.* replacing Na by Ag ions diffused into the oxide network of glass, a process similarly to the production of silver yellow in stained glass windows and other art work in glass.

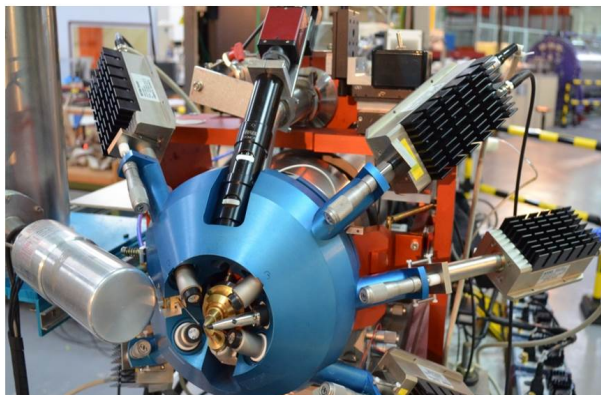


Fig. 8. Photograph of the NewAGLAE accelerator system at the C2RMF (Palais du Louvre) with a close-up of the exit for the beam and the improved detection system (© NewAGLAE, UPMC-LAMS).

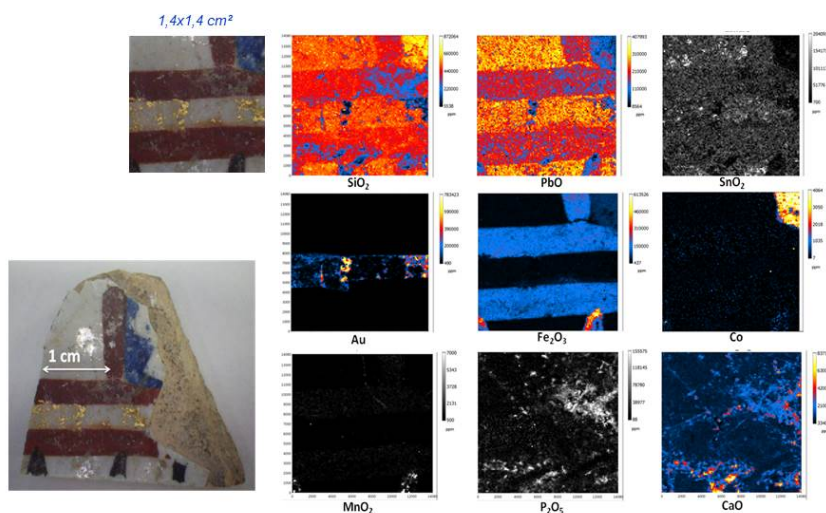


Fig. 9. Elemental mapping of a ceramic piece (Islamic, 14th–15th century) (see [17]).

3. Non-destructive analysis — radiation damage

When an object of cultural value needs an investigation, it should be done non-destructively. This is possible only in carefully designed highly sophisticated quantum mechanical experiments in the purest possible meaning. Here, the word ‘non-destructively’ applies to any mechanical or wet chemical treatment. Any exposure to radiation results in interactions with the components of the object, otherwise we could not get any information. It

follows that any influence should be minimal, *i.e.* practically no permanent damage, or an almost full recovery within a reasonable time.

Naturally, the standards change with increasing understanding of the ongoing processes. But it may also happen that the measures to protect the objects may be too strict because of incomplete knowledge of the phenomena and the substances in question. As a typical example, the ban of flashlights in museums may be too rigid since the effect of intense light depends on the wavelength.

In the context of the discussion on elemental analysis above, one has to be concerned about radiation damage due to X-rays at the energies used, and on the damage caused by the ions used for PIXE and RBS and similar techniques. While on the one hand negative side effects when applying X-rays are well known today, on the other hand, the application of X-raying for investigating cultural heritage objects have become more or less accepted by curators under the condition of minimizing the dose. Radiation effects (damage) can be almost totally neglected for metallic or inorganic materials, but they may become severe when organic materials are studied, *e.g.* as binders in paintings or fibers in manuscripts. Then the methods have to be optimized in all possible respect (minimize intensities and densities of irradiation, optimize efficiency of detection *etc.*).

While such problems are widely known, accepted, and taken care of in the case of X-rays, such problems are not well understood or not well enough known and acknowledged in the case of ion beam analysis like in PIXE, PIGE and RBS. Accelerator facilities for analysis in cultural heritage are mainly low energy machines, *i.e.* around a few MeV, at which the radiation damage effects of organic materials are the highest. For this reason paintings are rarely investigated by PIXE using facilities like AGLAE, and if at all, then with extreme caution and very low dose.

At much higher energies, however, a well-known characteristic of the ion-solid interaction favors the use of particles like protons, as illustrated in Fig. 10, where the energy loss of protons in copper is given as an example. It may easily be checked that *e.g.* within a layer of 50 μm , a typical layer in a multilayer painting, a proton beam of 70 MeV transfers an amount of energy to the material lower by 2 to 3 orders of magnitude than at around 1 MeV (equivalent to the range in such a layer), where the energy loss is at its maximum. Thus such energy transfer becomes almost comparable to the energy release by X-raying. Additionally, the cross section for X-ray production increases considerably with proton energy (for higher Z elements) because of a better match of the velocity of the kicked-out electron and the exciting proton ('Bohr criterion'). A comparison of the X-ray absorption (for fluorescence) and the X-ray production by PIXE at high (68 MeV) and low (3 MeV) energy is presented in Fig. 11. Furthermore,

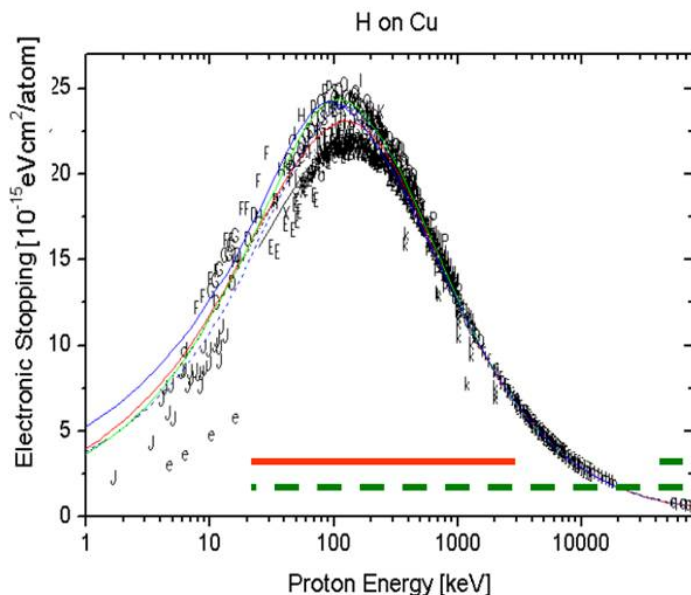


Fig. 10. Energy transfer (‘stopping power’), dE/dx , for protons in copper. The graph contains a large collection of experimental data (for details, see [2]). The solid bar (in red) indicates the relevant region of the energy deposition for 3-MeV protons in conventional low-energy PIXE, while the dotted line (in green at the bottom) indicates the total region for 68-MeV protons, the energy when entering the object is at the right end of the respective lines (conversion: 10×10^{-15} eV cm^2/atom equals $84.6 \text{ keV}/\mu\text{m}$ for Cu).

due to the larger range at higher energy, information may be obtained from greater depth of the object, provided the X-rays are not absorbed. If absorption becomes the limiting factor, then alternatively for some favorable elements (isotopes), γ rays from PIGE can be used for the analysis instead. The study of the composition of the bronze of the statue ‘Boy of Xanten’ by Denker *et al.* may serve as an example [20]. Two additional aspects should be mentioned which are highly advantageous when using high energy: (i) the precise position of the objects to be analyzed is totally non-critical, the energy loss during travel in open air is negligible at high energy, (ii) corrosion layers do not disturb the analysis in greater depth. In summary, high-energy proton beam analysis (*e.g.* PIXE, PIGE) complements elemental analysis using high-energy X-rays, either from laboratory or transportable sources or from synchrotrons.

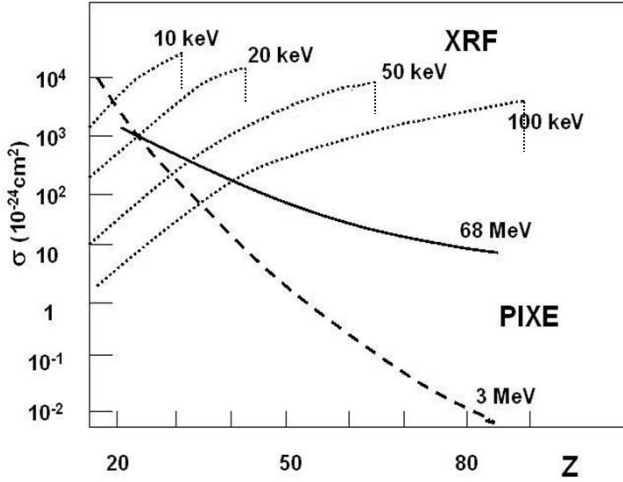


Fig. 11. Comparison of the cross section for photo absorption just above the K -edge and for the K -shell ionization by protons at 3 and 68 MeV as a function of Z . The photo absorption curves end when the energy is not sufficient to ionize the K -shell of the respective Z element (for details, see [2]).

4. Outlook

In principal, synchrotrons and high energy ion beam facilities provide the analytical tools needed in cultural heritage research. But they are not part of a museum's laboratory and they are not necessarily optimized to the needs. An accelerator development promising for various applications, from accelerator physics projects such as linear electron colliders to medical applications in hospitals, and also of interest for analytical purposes and imaging of museum's objects, is presently yielding first results, the actual realization of an inverse Compton source. The basic idea is to bring two well-defined, well-focused beams, an electron and a photon beam to a collision. Then under 180 degree, the highest possible photon energy is obtained, monochromatic with a resolution determined by the quality of the two beams and the definition of the scattering angle, with energy control (in principle) and with a high degree of coherence. The process is sketched in Fig. 12. By describing the process as an elastic collision, the resulting photon energy is given by

$$E_{X\text{-ray}} \approx 2\gamma^2 E_{\text{photon}}(1 - \cos(\delta_{\text{photon}})) / (1 + \gamma^2 \Theta_x^2) ,$$

where γ is the ratio of the total energy and the rest mass energy of the electron. As an example: the collision of a 50-MeV electron beam with 1-eV photons results in 40-keV X-rays emitted in the direction of the incoming electron beam.

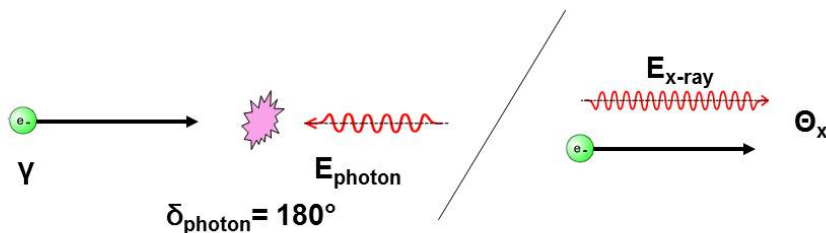


Fig. 12. Principle of the inverse Compton effect in a colliding beam geometry.

Since the process is simply an elastic electron–photon collision, it is called ‘Inverse Compton Source’, where the name ‘inverse’ indicates the upgrade in photon energy. The perspectives for such a source are that it may become the next generation X-ray source comparable in photon intensity to present-day synchrotron beam lines, but with the advantage of a normal laboratory size due to the much lower electron energy needed. One commercially available system is presently being installed at the TU München (excellence cluster ‘Munich Advanced Photonics’ (MAP) and the ‘Centre for Advanced Laser Applications’ (CALA) [21]). A recently published result on the prototype system at Lyncean Technologies, the commercial partner from Palo Alto, CA, USA, demonstrates the new possibilities [22]. Another inverse Compton system, named ThomX, is in the construction phase as a prototype at Orsay in close cooperation between UPMC-LAMS and LAL and additional partners [23]. This system, intended as a totally dedicated system for X-ray research either in a hospital or in a museum, illustrates the synergy possible from the developments in nuclear physics to totally different fields.

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