ACTA IMEKO
ISSN: 2221-870X
June 2024, Volume 13, Number 2, 1 - 5

Archaeometry at synchrotrons: how to get the most out of ancient materials

Ilaria Carlomagno[1], Gangadhar Das[1], Giuliana Aquilanti[1]

[1] *Elettra-Sincrotrone Trieste, SS 14 km 163.5, 34149, Trieste, Italy*

ABSTRACT
X-rays techniques are widely utilised in the field of archaeometry because of the numerous advantages they present. Using X-rays, structural and chemical details of specimens can be assessed while preserving artefacts integrity, with the additional benefit of requiring little or no sample preparation procedures. Synchrotron sources produce high-intensity, highly collimated beams whose energy can be easily tuned over broad ranges going from the infrared (IR) to the X-rays. Their peculiarities include unbeatable spatial resolution, enhanced elemental selectivity, and extraordinary chemical sensitivity. In recent years, synchrotron beams have achieved a significant evolution thanks to several factors, such as advancements in source and optics design, acquisition of higher-level technical and scientific expertise, etc. This has ignited an increasing interest in synchrotron-based techniques which are expanding more and more, approaching always new frontiers. This work presents the main characteristics of synchrotrons and aims to help the unfamiliar readers in the non-trivial choice between laboratory and synchrotron sources for their scientific investigations.

Section: RESEARCH PAPER

Keywords: Synchrotron radiation; X-ray techniques; archaeometry; cultural heritage

Citation: I. Carlomagno, G. Das, G. Aquilanti, Archaeometry at synchrotrons: how to get the most out of ancient materials, Acta IMEKO, vol. 13 (2024) no. 2, pp. 1-5. DOI: 10.21014/actaimeko.v13i2.1843

Section Editor: Fabio Leccese, Università Degli Studi Roma Tre, Rome, Italy

Received March 20, 2024; **In final form** June 7, 2024; **Published** June 2024

Corresponding author: Ilaria Carlomagno, e-mail: ilaria.carlomagno@elettra.eu

1. INTRODUCTION

In the broad field of archaeometry, a wide variety of complementary investigation techniques find their application to the study of ancient materials. Among the main requirements, the preservation of the specimen integrity plays a paramount role in the archaeological, biological, physical and chemical analysis.

Obtaining a detailed description of the samples without any damage can be done using advanced analytical techniques [1], [2]. Among other probes, X-rays have shown a huge potential: given their (i) intrinsically high penetration-depth, (ii) exceptional chemical sensitivity, (iii) elemental selectivity, and (iv) wavelength range ideally suited to probe interatomic distances in solids, x-ray beams proved to be an optimal choice both for structural and chemical investigations of ancient findings [3], [4].

X-ray beams are routinely produced and exploited in laboratories all over the world. However, in the last four decades, the spread of synchrotrons has revolutionised the world of X-ray sources, offering the above-mentioned peculiar characteristics for new, better science. These advanced light sources are ideally suited to investigate the structural and chemical nature of materials, however, to access such facilities, researchers need to follow selection procedures which are quite different from the ordinary laboratories. Although the field of archaeometry is not new to the use of synchrotron radiation [5], the latter could be expanded and further explored to address many scientific questions still left unanswered in the archaeometry community. In this work, the fundamental role played by synchrotron-based techniques in assessing the finest details of our past will be presented and discussed. In particular, in the next section, we will present and discuss the core characteristics offered by synchrotron sources. To help the unfamiliar readers, many examples will be made using laboratory sources as a term of comparison. Throughout the text, we will highlight the major advantages offered by these sources and we will explain what are the main reasons to justify and support a request for access to synchrotron beamlines.

2. CHARACTERISTICS OF SYNCHROTRON SOURCES

In archaeometry, the scientific analysis of any ancient material is carried out to obtain details on manufacturing processes, materials provenance, dating, tracing etc. This is commonly achieved through the analysis of a sample's compositional

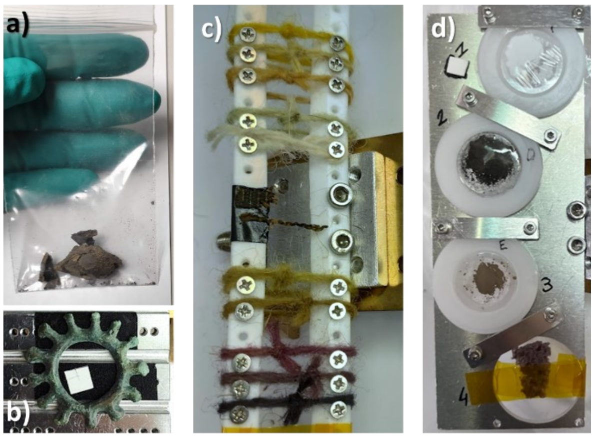

Figure 1. A set of samples of different nature: a black-painted eye, fallen from an Egyptian wooden statue (a), bronze artefact (b), wool strings fermented and/or dyed with different dyes (c), powder samples (d).

and/or structural profiles, which serve as proxies to navigate the historical background and retrieve information related to technological advancements, craftsmanship, trade networks, and cultural practices.

In this context, synchrotron techniques are well suited to characterise a wide variety of samples including (but not limited to), those reported in Figure 1. The typical samples can range from a wooden fragment (a) to single wool knots coming from ancient carpets (b) similar to the materials studied in [5], to bronze artefacts (c), to powder samples (d). The only limitations are presented by the experimental set ups.

As far as the incoming radiation is concerned, synchrotron sources produce photon beams having wavelengths from the IR to the hard X-rays, with a high degree of collimation and intensity, and, in some cases, coherence. Due to the nature of the interaction between light (at those wavelengths) and matter, most of the investigation techniques are non-destructive. Indeed, just as laboratory IR and X-ray sources, at synchrotrons it is possible to probe the chemical and structural details of materials while preserving the integrity of the specimen [6]. However, the other intrinsic characteristics of synchrotron sources that have just been mentioned offer numerous advantages being hardly if not impossibly attainable by laboratory sources.

2.1. Photon flux

Probably, the most famous peculiarity of synchrotron beams is represented by the high photon flux which is several orders of magnitude larger than the typical laboratory sources. The first direct benefit of this lies in the shorter measuring times needed to obtain good statistics. This benefit applies to any technique (scattering or absorption based). The shorter measuring times alone, however, are not sufficient to grant the request for beamtime. If the only advantage is time-saving, then the outstanding advantages of a large-scale facilities are most likely underexploited, making the request for beamtime rather unjustified.

In the case of scattering based techniques, a higher flux translates directly into the possibility of assessing structures having a low degree of periodicity (e.g. thin films of few atomic monolayers) or, simply, low amounts of analytes (e.g. nanoparticles or nanoclusters).

On the other hand, in the case of absorption-based techniques, the high photon flux is beneficial to achieve minimal detection limits of trace elements down to the ppb (an example is reported below).

2.2. Energy tunability

In absorption-based techniques, the possibility of finely tuning the incident photon energy plays a paramount role. X-ray absorption strongly depends on the photon energy in terms of probability of interaction and, accordingly, of the magnitude of the signal observed [7].

In this context, X-Ray Fluorescence (XRF) represents a clear example. XRF is a technique based on the photoelectric effect: it provides an elemental profile of the sample's content by measuring the fluorescence emitted by the sample. XRF spectra collected in laboratories or even with portable devices are routinely used to evaluate the chemical content of a sample but the possibility to tune the incident photon energy has a great effect on the outcomes of the measurement. In particular, one can enhance (or suppress) the fluorescence emission of a given element, which is extremely useful whenever two or more peaks are overlapping or weak.

In Figure 2 we present two XRF spectra collected at the XRF beamline of Elettra [8] on the same sample and under the same experimental conditions. The sample is an ancient gold coin dating back to the V century DC. The spectra were collected using a monochromatic SR-beam at two different energies: 10 (black line) and 11.6 keV (red line). The two energies were selected using a Si(111) monochromator and they were purposefully chosen to be below and above the Pt L_3 absorption edge (11.564 keV) so that the higher energy would maximise the signal from this trace element. Indeed, Figure 2 shows how the two spectra overlap in the low-energy part of the spectrum, while major differences can be observed in the energy region related to Pt (around 9.5 keV). In this area, the red spectrum presents a peak which is absent in the black spectrum due to the exciting energy being below the Pt L_3 absorption edge. The comparison of these two spectra yields two practical benefits: in the case of the 10 keV, Cu and Zn peaks are clearly visible, and they stand out from the background; in the case of the 11.6 keV, the peak (and hence the presence) of Pt leaves no doubt.

Similar results cannot be achieved with laboratory or portable sources as the X-ray emission of such sources is not monochromatic and cannot be tuned at wish. Synchrotron beamlines, on the other hand, thanks to their high energy-resolution and energy tunability, can detect the presence of elements even at very low concentrations even in the case of extremely high dilutions (ppb) [9]. Although other techniques (such as inductively coupled plasma-based techniques) are in fact capable of reaching similar detection limits, synchrotron-based XRF combines the results of a fine quantitative analysis together with the surface distribution of the detected elements and possesses the added benefit of requiring no sample preparation [10].

For the sake of clarity, we can consider some direct applications of XRF to the field of archaeometry, where the technique can be used, for example, to reconstruct lost images, as reported in this example of ancient daguerreotypes [11]. A similar approach was applied with spectacular results to the analysis of the Dead Sea Scrolls. In this case, XRF was employed not only to reveal the chemical composition of the ink, yielding insights into the ink recipe and origin, but also to unveil the hidden text and layers of parchment, providing essential information to decipher the damaged or overwritten text [12], [13].

The energy tunability alone is so critical that it lies at the heart of X-ray Absorption Spectroscopy (XAS). XAS measures the variation of the absorption coefficient as a function of the incident energy. The energy range for XAS is chosen across the absorption edge of the element of interest. From the evolution of the absorption coefficient over this range, one can obtain information on the different chemical species of the target element present in the sample and evaluate their relative abundance. Such information can be used, for instance, to estimate the geographical location of some soil (see the case of Fe K-edge XANES analysis in [14]) or to prevent degradation [15].

The combination of the high photon flux with the energy tunability is already a tremendous advantage for the study of trace elements. A further advantage can be obtained using vacuum chambers, to enhance even more the signal-to-noise ratio of the fluorescence emission from light elements. Vacuum chambers, such as the one in Figure 3 minimise the fluorescence signal degradation in the path between the sample and the detector [16].

2.3. Beam divergence and polarization

Synchrotron light has an intrinsically low divergence and high degree of linear polarization. These strongly affect the geometry of Compton and elastically scattered X-ray photons, which are the major contributors to the spectral background in fluorescence-based techniques such as XRF and XAS. By measuring the emitted fluorescence photons in the horizontal plane (i.e. in the plane of the synchrotron storage ring) and perpendicular to the primary beam, better signal to noise ratios can be achieved, thus leading to improved detection sensitivity typically in the range of parts per billion (ppb) levels (see, for example [8]).

2.4. Complementary information: multi-scale and multi-techniques approaches

High-intensity beams carry an indirect potentiality: they can be reshaped using not only focusing optics, but also slits or pinholes to tune their horizontal and vertical dimension (of course, the use of slits and pinholes comes at the price of photon intensity: for this reason, such strategy can only be applied when the starting intensity is high enough). In other words, the spatial resolution of the analysis can be pushed easily to the micro and nano scales, investigating heterogeneities over different scales of ancient materials and assessing information about local composition, structure, and/or degradation patterns.

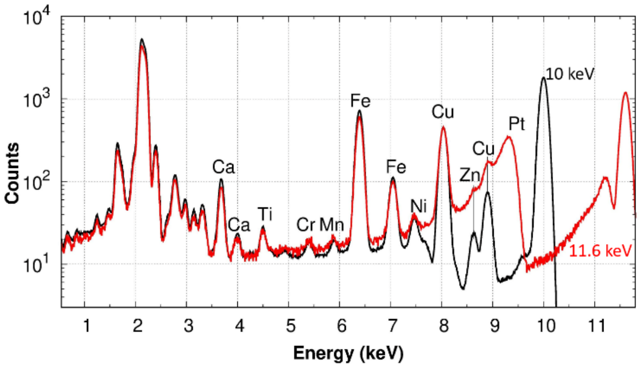

Figure 2. XRF spectra collected on an ancient gold coin, under the same experimental conditions (beam size, beam position on the sample, sample-detector distance and geometry, dwell time) using two monochromatic beams of different energies: 10 keV (black line) and 11.6 keV (red line). The higher energy spectrum is showing a peak around 9.5 keV related to the Pt L emission which is absent in the lower energy spectrum. The sample, a high-purity gold coin, contains Pt as a trace element contaminant. The comparison of the two spectra demonstrates how the energy tunability is crucial to highlight the presence of certain elements even when their concentration is very low.

For synchrotron beamlines the possibility to adjust the beam size (through optics and/or slits and pinholes) is ordinary practice. Thus, the possibility of probing samples at different scales is rather frequent and a wide range of accessible spatial resolutions (from mm to the nm [17]) is therefore available. The possibility of inspecting heterogeneities at different scales is an asset in any field where samples nature may vary significantly, including archaeometry [18].

Accessing different scales can be achieved in a more complex way leading to more intriguing results and insights. This way is represented by multi-technique approaches. Most beamlines offer a set of techniques which provide, if used synergistically, complementary details on the same sample, yielding an all-round picture of a given system. The complementarity can be expressed in terms of different kind of information: for instance, one could complement the elemental distribution, obtained with XRF, with the chemical speciation of some of the elements, assessed by XAS. This can be the first step to retrieve information about the provenance of archaeological materials or on trade networks of artefacts [19], [20]. Another example, a bit more audacious, could be the combination of the results of X-ray Photoemission Spectroscopy (XPS) with those of X-ray Absorption Near Edge Structure (XANES). These two techniques are both based on the X-ray absorption process, but they focus on the detection of photoelectrons (XPS) and photons (XANES). Due to the different penetration depth of photons and electrons in matter, the two techniques can assess the chemical state of a sample within some nm (XPS) or some µm (XANES) from the surface. A striking example where the two techniques were applied obtaining results that were apparently in contrast can be found here [21].

Complementarity can also be found in the combination of radically different types of information, such as the chemical nature probed by absorption-based techniques and the structural features assessed by X-ray diffraction (XRD). XRD can provide the structural parameters of crystalline materials, identifying and quantifying different crystalline phases, yielding fine details on the average crystalline structure probed by the incoming X-ray beam. A great example of combining different techniques to obtain complementary information on a sample is reported in [22], where the authors employed several techniques to analyse a sample of ancient ink. Other examples showing the combination of different techniques assessing the elemental sensitivity, chemical speciation, and structural details at different length scales are reported in [23].

2.5. The IR case

Although most beamlines are dedicated to soft or hard X-rays, those exploiting IR radiation are definitely worthy of mention, as IR photons represent a complementary probe to X-rays. IR spectroscopy can be employed to analyse organic residues on ancient materials. In particular, from the absorption bands in the IR spectrum, one can retrieve the molecular composition of oils, resins, and adhesives, or identify organic materials on surfaces that may be challenging with conventional IR spectroscopy.

Synchrotron radiation Fourier-Transform IR (FTIR) microscopy was successfully employed in the study of the materials and methods related to the production of ancient musical instruments [24] and to inks, pigments, and dyes used in ancient artworks and manuscripts [22]. Another example of FTIR analysis on pigments is the case of the Roman wall paintings, where the authors could assess details of ancient coloration techniques [25].

2.6. Radiation damage

Although X-ray techniques are all widely known as non-destructive, high intensity and high brilliance sources might induce a wide variety of modifications in some materials. Such modifications can take the form of visual alterations (e.g. colour change) or mechanical deformations (e.g. cracks) or, sometimes, they could occur at the micro and nano scale, thus being invisible to common inspections used by curators. Some alterations are reversible, while others might be permanent, possibly including the destruction of a specimen by thermal stress. All these effects, known as radiation damage, primarily depend on the X-ray dose delivered to the samples. Therefore, brilliant X-ray beams such as those produced by synchrotrons might result into a high probability of radiation damage, thus calling for analysis of possible roots of alterations. This analysis should be carried out even before the experiment starts to provide a reliable term of comparison for post-experiment analysis [26].

On the other hand, the spread of fourth generation synchrotrons has contributed to raise awareness on the topic, fostering the development of strategies to minimise the risk and the gravity of radiation damage. For instance, synchrotrons high intensity can be used with measuring times being short compared to laboratory sources: this keeps the dose to low levels ensuring the sample safety. An example at hand is the case of pigments irradiated with an 18-keV monochromatic X-ray beam of ~ 10^{10} photons/s for a series of 100 intervals of 10 s [27]. Alternative measures with similar results could be, for instance, the use of a chopper placed in the beam path, or the choice of X-ray energies far away from the X-ray absorption edge of the major elements in the sample matrix or even the sample cooling to reduce the thermal stress [28].

When dealing with synchrotron sources, radiation damage can occur, but it does not necessarily represent a limit. Rather, it is a condition that should be carefully considered and, if needed, promptly addressed.

2.7. Access procedures

The appealing opportunities offered by synchrotrons can be exploited by academic researchers provided that an experimental proposal has been positively evaluated by an independent review panel (see, for example [29]). Experimental proposals explain the details of a given scientific study, from the available literature, to the particular case study, to the intended measurement strategy. For academic research, proposals are ranked on the basis of the scientific merit. A fundamental point of the experimental proposal is to justify the need for the synchrotron facility. This is done by highlighting how the experiment would exploit the main features of the synchrotron source (e.g. intensity, energy tunability, spatial resolution, coherence, divergence, etc.). Of course, this procedure makes the access to synchrotrons not straightforward and requires some careful planning way ahead of the experiment. After a positive evaluation of the proposal, each experiment is assigned a limited time (usually few days, with the beam available 24h non-stop) and measurements should be carried out within the allocated time slot. It goes without saying that researchers are expected to follow closely the data collection and be ready to correct possible deviations from the expected direction. This demanding working modality does not allow for improvisation and requires extensive knowledge of the topic, deep expertise in the technique and instrumentation to be used.

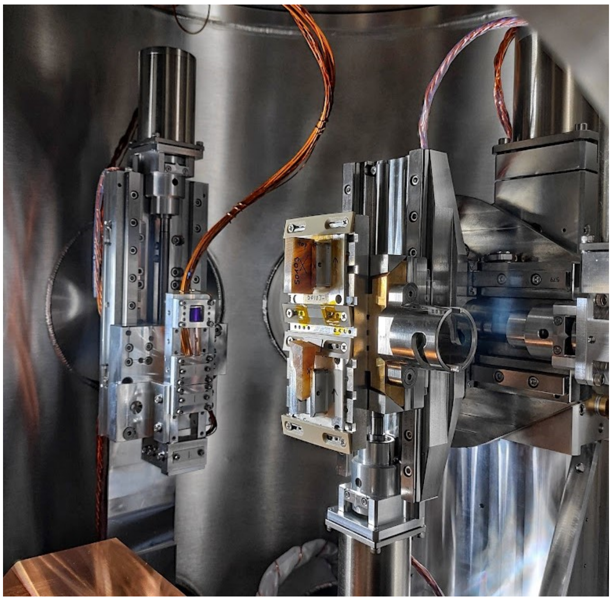

Figure 3. Samples in the IAEAXspe end station at the XRF beamline, at Elettra [8]. The vacuum environment enhances the sensitivity to light elements as the path between sample and detector is (almost) free from scattering particles that can be found in air at ambient pressure.

3. CONCLUSIONS

In the last four decades, synchrotron light sources have spread and become a widely used tool for the structural and chemical characterization of materials. Thanks to the unique properties of their light beams, the finest details of materials can be assessed with unprecedented detail.

In the archaeometry community, many works have proven the potentialities of synchrotron radiation which are based on the high-intensity photon beams, energy tunability from the IR to the hard X-rays, extremely high spatial resolution (down to the nm range), multi-technique characterization.

In this work, we have presented and discussed the main advantages brought by the above-mentioned characteristics. Also, we have warned the reader of the present limitations that have to be accounted for when planning an experiment at a large-scale facility: mainly the beam damage and the access procedures.

The ongoing technical upgrades involving synchrotron sources and end stations will soon result into a new better science. However, to fully exploit the new opportunities, the complexity of synchrotron instrumentation should be dealt with. The best results involve multidisciplinary teams, where the competences of scientists and archaeologists are shared in fruitful collaborations. Indeed, any advancements would be vain without a synergistic effort involving both the disciplines. As discussed elsewhere, science and history are two different worlds which can be hard to blend, and without a genuine dialogue bridging the gap between good science and meaningful historical questions, “little of value can be achieved” [30]. Therefore, a successful collaboration will empower both worlds, bringing new challenges to the scientific analysis and new insights to the historical interpretation of the data, pushing the boundaries of both communities.

REFERENCES

[1] I. Liritzis, N. Laskaris, A. Vafiadou, I. Karapanagiotis, P. Volonakis, C. Papageorgopoulou, M. Bratitsi, Archaeometry: an overview, Scientific Culture 6 (2020), pp. 49-98.
DOI: 10.5281/zenodo.3625220

[2] M**.** Pantos, Synchrotron radiation in archaeometry, Synchrotron Radiation News 13 (2000), pp. 6-10.
DOI: 10.1080/08940880008261073

[3] M. Milazzo, Radiation applications in art and archaeometry: X-ray fluorescence applications to archaeometry. Possibility of obtaining non-destructive quantitative analyses, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 213 (2004), pp. 683-692.
DOI: 10.1016/S0168-583X(03)01686-0

[4] M. C. Corbeil, Applications of X-ray diffraction in conservation science and Archaeometry, Adv. in X-ray Analysis 47 (2004), pp. 18-29.

[5] G. Harbottle, B. M. Gordon, K. W. Jones, Use of synchrotron radiation in archaeometry, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 14 (1986), pp. 116-122.
DOI: 10.1016/0168-583X(86)90431-3

[6] A. Späth, M. Meyer, T. Huthwelker, C. N. Borca, K. Messlinger, M. Bieber, L. L. Barkova, R. H. Fink, X-ray microscopy reveals the outstanding craftsmanship of Siberian Iron Age textile dyers, Scientific Reports 11 (2021), p.5141.
DOI: 10.1038/s41598-021-84747-z

[7] S. Mobilio, F. Boscherini, C. Meneghini (editors), Synchrotron Radiation, Springer, Berlin, 2016, ISBN: 978-3-642-55314-1. DOI: 10.1007/978-3-642-55315-8

[8] W. Jark, D. Eichert, L. Lühl, A. Gambitta, Optimisation of a compact optical system for the beam transport at the x-ray fluorescence beamline at Elettra for experiments with small spots, Adv. in X-Ray/EUV optics and components IX 9207 (2014) pp. 100-111.
DOI: 10.1117/12.2063009

[9] K. Janssens, K. Proost, G. Falkenberg, Confocal microscopic X-ray fluorescence at the HASYLAB microfocus beamline: characteristics and possibilities, Spectrochimica Acta Part B: Atomic Spectroscopy 59 (2004), pp. 1637-1645.
DOI: 10.1016/j.sab.2004.07.025

[10] S. Majumdar, J. R. Peralta-Videa, H. Castillo-Michel, J. Hong, C. M. Rico, J. L. Gardea-Torresdey, Applications of synchrotron μ-XRF to study the distribution of biologically important elements in different environmental matrices: A review, Analytica Chimica Acta 755 (2012), pp. 1-16.
DOI: 10.1016/j.aca.2012.09.050.

[11] M. S. Kozachuk, T. K. Sham, R. R. Martin, A.J. Nelson, I. Coulthard, J. P. McElhone, Recovery of degraded-beyond-recognition 19th century daguerreotypes with rapid high dynamic range elemental X-ray fluorescence imaging of mercury L emission, Scientific reports, 8 (2018), pp.1-10.
DOI: 10.1038/s41598-018-27714-5

[12] I. Mantouvalou, T. Wolff, O. Hahn, I. Rabin, L. Lühl, M. Pagels, W. Malzer, B. Kanngiesser, 3D micro-XRF for cultural heritage objects: new analysis strategies for the investigation of the Dead Sea Scrolls, Analytical chemistry 83 (2011), pp.6308-6315. DOI: 10.1021/ac2011262

[13] Y. Nir-El, M. Broshi, The red ink of the Dead Sea Scrolls, Archaeometry 38 (1996), pp.97-102.
DOI: 10.1111/j.1475-4754.1996.tb00763.x

[14] I. Carlomagno, P. Zeller, M. Amati, G. Aquilanti, E. Prenesti, E., G. Marussi, M. Crosera, G. Adami, Combining synchrotron radiation techniques for the analysis of gold coins from the Roman Empire, Scientific Reports 12 (2022), p.15919.
DOI: 10.1038/s41598-022-19682-8

[15] E. J. Schofield, Illuminating the past: X-ray analysis of our cultural heritage Nature Reviews Materials 3 2018 pp. 285-287.
DOI: 10.1038/s41578-018-0037-4

[16] A. G. Karydas, M. Czyzycki, J. J. Leani, A. Migliori, J. Osan, (+ 6 more authors), An IAEA multi-technique X-ray spectrometry endstation at Elettra Sincrotrone Trieste: benchmarking results and interdisciplinary applications, Journal of Synchrotron Radiation 25 (2018), pp.189-203.
DOI: 10.1107/S1600577517016332

[17] M. Cotte, A. Genty-Vincent, K. Janssens, J. Susini, Applications of synchrotron X-ray nano-probes in the field of cultural heritage, Comptes Rendus Physique, 19 (2018), pp.575-588.
DOI: 10.1016/j.crhy.2018.07.002

[18] G. Artioli, I. Angelini, Mineralogy and archaeometry: fatal attraction, Europ. Journal of Mineralogy 23 (2011), pp. 849–855.
DOI: 10.1127/0935-1221/2011/0023-2119

[19] I. Reiche, E. Chalmin, Synchrotron radiation and cultural heritage: combined XANES/XRF study at Mn K-edge of blue, grey or black coloured palaeontological and archaeological bone material, Journal of Analytical Atomic Spectrometry 23 (2008), pp. 799-806.
DOI: 10.1039/B717442J

[20] K. Janssens, M. Cotte, The use of XAS and related methods in cultural heritage investigations, International Tables for Crystallography (2023). Vol. I.
https://doi.org/10.1107/S1574870720004802

[21] I. Carlomagno, J. Drnec, A. M. Scaparro, S. Cicia, S. Vlaic, R. Felici, C. Meneghini, Co-Ir interface alloying induced by thermal annealing, Journal of Applied Physics 120 (2016), p. 195302
DOI: 10.1063/1.4967845

[22] M. Sibilia, C. Stani, L. Gigli, S. Pollastri, A. Migliori, (+ 11 more authors), A multidisciplinary study unveils the nature of a Roman ink of the I century AD, Scientific Reports 11 (2021), pp. 7231
DOI: 10.1038/s41598-021-86288-x

[23] L. Bertrand, L. Robinet, M. Thoury, K. Janssens, S. X. Cohen, S. Schöder, Cultural heritage and archaeology materials studied by synchrotron spectroscopy and imaging, Applied Physics A 106 (2012), pp. 377-396.
DOI: 10.1007/s00339-011-6686-4

[24] S. Grassi, G. Fiocco, C. Invernizzi, T. Rovetta, M. Albano, (+ 6 more authors), Managing complex Synchrotron radiation FTIR micro-spectra from historic bowed musical instruments by chemometrics, IMEKO TC4 Int. Conf. on Metrology for Archaeology and Cultural Heritage (MetroArchaeo 2019), Florence, Italy, 4-6 December 2019, pp. 114 – 119. Online [Accessed 21 June 2024]
https://www.imeko.org/publications/tc4-Archaeo-2019/IMEKO-TC4-METROARCHAEO-2019-22.pdf

[25] L. Pronti, M. Romani, G. Viviani, C. Stani, P. Gioia, M. Cestelli-Guidi, Advanced methods for the analysis of Roman wall paintings: Elemental and molecular detection by means of synchrotron FT-IR and SEM micro-imaging spectroscopy, Rendiconti Lincei. Scienze Fisiche e Naturali 31 (2020), pp.485-493.
DOI: 10.1007/s12210-020-00888-9

[26] L. Bertrand, S. Schöder, I. Joosten, S. M. Webb, M. Thoury, T. Calligaro, E. Anheim, A. Simon, Practical advances towards safer analysis of heritage samples and objects, TrAC Trends in Analytical Chemistry 164 (2023), pp. 117078.
DOI: 10.1016/j.trac.2023.117078

[27] L. Bertrand, S. Schöeder, D. Anglos, M. B. H. Breese, K. Janssens, M. Moini, A. Simon, Mitigation strategies for radiation damage in the analysis of ancient materials, Trends in Analytical Chemistry 66 (2015), pp. 128-145.
DOI: 10.1016/j.trac.2014.10.005

[28] Z. Zhang, Z Liu, Y. Jiang, H. Zhu, T. Ji, (+ 5 more authors), In situ investigation of synchrotron radiation damage effect of ancient paintings by time-resolved ED-XAS and IR combined techniques, X-Ray Spectrometry 51 (2022), pp. 394–402. DOI: 10.1002/xrs.3289

[29] Elettra-Sincrotrone Trieste. Online [Accessed 21 June 2024] https://www.elettra.eu/userarea/apbt.html

[30] A. M. Pollard, P. Bray, A bicycle made for two? The integration of scientific techniques into archaeological interpretation, Annual Review of Anthropology 36 (2007), pp. 245-259.
DOI: 10.1146/annurev.anthro.36.081406.094354