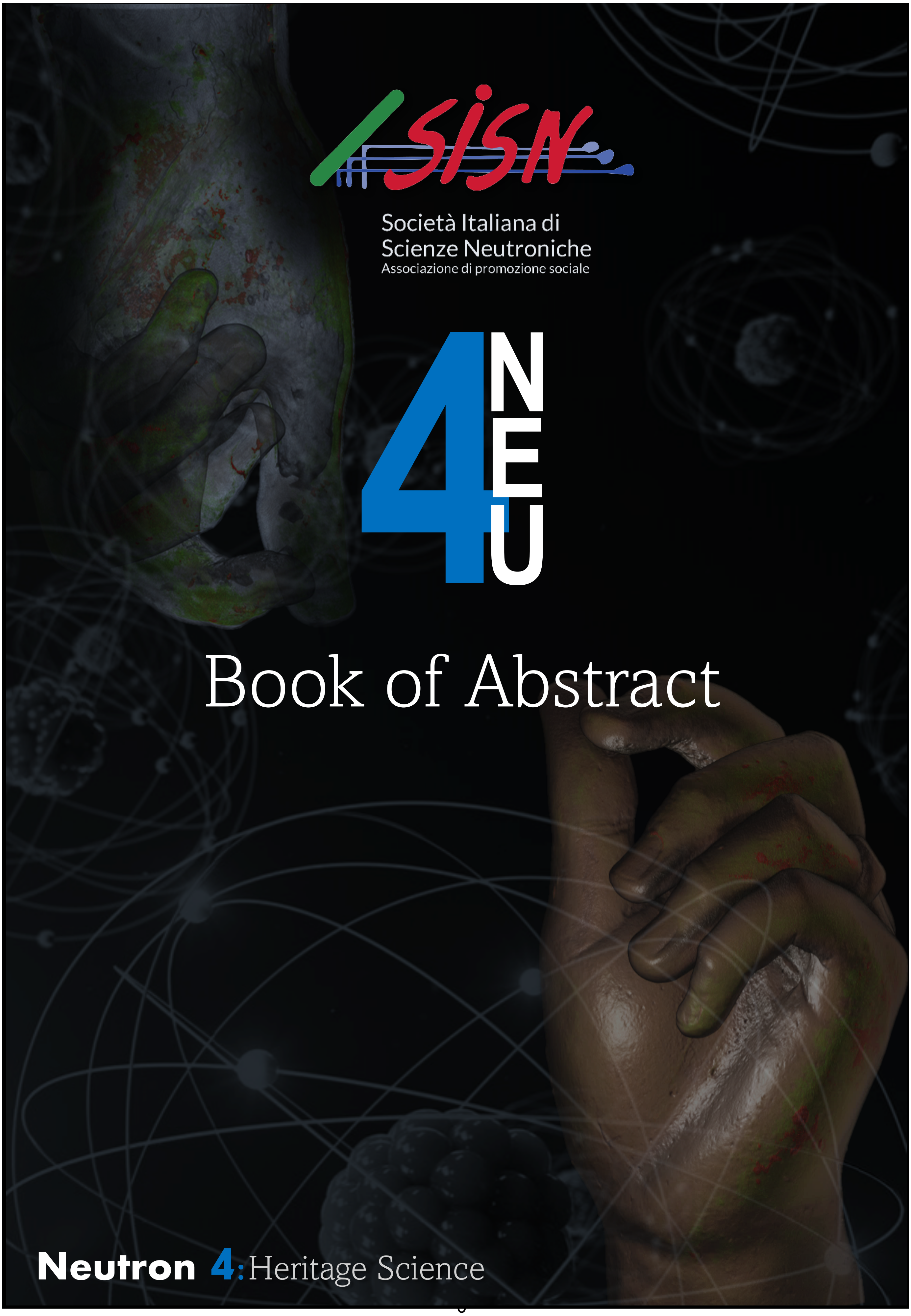
SISN
Società Italiana di
Scienze Neutroniche
Associazione di promozione sociale
4NEU
Book of Abstract
Neutron 4: Heritage Science

Preliminary program

Sala Olimpica, Teatro Vittoria
Piazza Guglielmo Marconi 35
Bosco Chiesanuova (Verona, Italy)

Tuesday, 9th September 2025

18:00 - 19:30 *Welcome & registration*

20.00 *Dinner*
Hotel Frizzolan,
Piazza Borgo 5, Bosco Chiesanuova.

Neutrons4: the crash course

Wednesday, 10th September 2025

9:00 - 10:00 **N. Kardjilov**, General introduction on neutrons & comparison with other probes.
10:00 - 10:30 *Coffee break*
10:30 - 12:00 **B. Schillinger**, Imaging: introduction & case studies.

12:00 - 14:00 *Lunch*
Hotel Frizzolan,
Piazza Borgo 5, Bosco Chiesanuova.

14:00 - 15:30 **F. Grazzi**, Neutron diffraction: introduction & case studies.
15:30 - 16:30 **A. Scherillo**, Elemental analysis with neutrons

16:30 - 17:00 *Coffee break*
Frac Caffè Bistrot,
Piazza Borgo 9, Bosco Chiesanuova.

17:00 - 18:00 **F. Cantini**, Experiments with neutrons: from the proposal to the publication

20:00 *Dinner*
Hotel Frizzolan,
Piazza Borgo 5, Bosco Chiesanuova.

Neutrons4: the conference

Thursday, 11th September 2025

9:00 - 9:50 *Keynote lecture*
Gilberto Artioli, Neutrons for cultural heritage: State-of -the-art and perspectives
9:50 - 10:10 **Y. Kiyanagi,** Japanese Sword Study by Using Neutron Imaging and Muon Lifetime Measurement.
10:10 - 10:30 **F. Grazzi**, Non-invasive analysis of Japanese swords through Neutron methods Lessons learnt after 18 years of research.

10:30 - 11:00 *Coffee break*
Frac Caffè Bistrot,
Piazza Borgo 9, Bosco Chiesanuova.

11:00 - 11:20 **A. Williams**, Complementary methods of analysis for Indian swords? Neutron diffraction and metallography.
11:20 - 11:40 **O. Cocen**, Multimodal Characterization Approach for Studying Corrosion of Archaeological Iron Artifacts.
11:40 - 12:00 **G.A. Green**, Muonic X-ray Emission Spectroscopy (μXES) for Sub-surface, Non-destructive Analysis of Ancient Gold.
12:00 - 12:20 **A. Scherillo**, Neutron techniques for Cultural heritage at ISIS: New developments and some successful stories.

12:40 - 14:30 *Lunch*
Hotel Frizzolan,
Piazza Borgo 5, Bosco Chiesanuova.

14:30 - 14:50 **M.P.M. Marques**, Probing the Effect of Fire on Egyptian Mummies by Neutron Spectroscopy and Neutron Activation Analysis.
14:50 - 15:10 **A. Venturi**, Characterisation of water-induced damage in painting varnishes using neutron scattering techniques and optical coherence tomography.
15:10 - 15:30 **C. Mondelli**, Neutrons for conservation of stone materials and organic based artefacts in cultural heritage. The project nanoHERCULES.
15:30 – 15:50 **N. Kardjilov**, Neutron imaging in cultural heritage preservation.

15:50 - 17:30 *Poster session*

20:00 *Social dinner*
Ristorante "Il Caminetto",
Località Malga San Giorgio, Bosco Chiesanuova.

Friday, 12th September 2025

9:00 - 9:50 *Keynote lecture*
Monica Galeotti, Neutrons and bronze heritage: a happy marriage? Pros and cons of neutron analysis from a stakeholder's perspective
9:50 - 10:10 **F. Salvemini**, Neutron study of Roman medical utensils from the RD Milns Antiquities Museum - University of Queensland.
10:10 - 10:30 **F. Cantini**, White beam and monochromatic neutron imaging for the reconstruction of the casting process of ancient bronzes: an overview of results and interpretation.

10:30 - 11:00 *Coffee break*
Frac Caffè Bistrot,
Piazza Borgo 9, Bosco Chiesanuova.

11:00 - 11:20 **M. Wu**, The progress of CARR neutron imaging and its applications in culture heritage.

11:20 - 11:40 **M. Marabotto**, Calibration of Bragg Edge Neutron Transmission analysis for the characterisation of archaeological bronzes.

11:40 - 12:00 **X. Zhao**, Advances in Muon-Induced X-ray Emission (MIXE) with the GIANT Instrument at PSI: Applications in Archaeology, Cultural Heritage, and Energy Materials.

12:00 - 12:45 *Round table*
Neutron beamtime, projects and opportunities

12:45 - 13:00 *Conclusions*

13:00 - 14:00 *Light lunch*
Sala Olimpica, Teatro Vittoria,
Piazza Guglielmo Marconi 35, Bosco Chiesanuova.

Oral Presentations

Thursday, 11th September 2025

Thursday, 11th September 2025 9.00

Keynote lecture

Neutrons for cultural heritage: State-of -the-art and perspectives

Gilberto Artioli*
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Neutrons offer a number of well-known advantages in the investigation of materials. Of importance for cultural heritage (CH) and natural heritage (NH) studies is the extreme penetration allowing for non-invasive characterization. While in the past neutron activation analysis and autoradiography [1] were the major techniques employed in the field, nowadays neutron investigations of archaeological objects and art works encompass imaging, chemical analysis, and crystallographic analysis, including phase identification, texture analysis, and structural/microstructural analysis [2]. In principle, such information may be obtained simultaneously in a single combined experiment, thus minimizing neutron exposure and the risks and the costs related to the handling of unique objects/specimens (Fig. 1). Muon investigations are also rapidly expanding the area of non-invasive chemical characterization and depth profiling [3].

A brief history of the applications of neutron sources to cultural heritage investigation will be presented, with a discussion of present trends and possible future developments based on technical advances [4]. The planned improvements on both neutron sources and detectors technically should foster applications in the CH area, though serious infrastructures are needed to link heritage users to dedicated facilities.

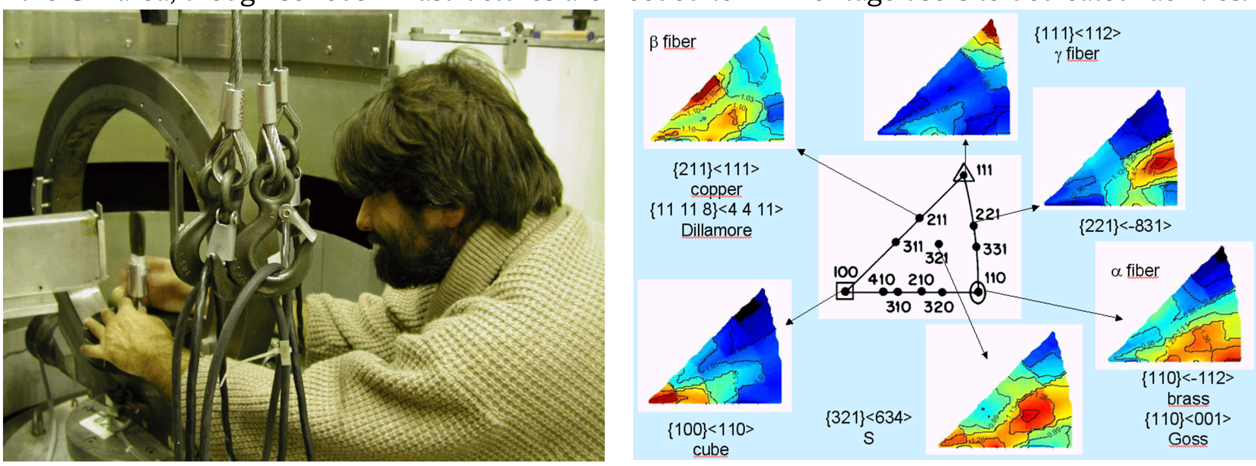

Fig. 1. Crystallographic texture analysis of the Iceman copper axe by neutron diffraction [5]

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Japanese Sword Study by Using Neutron Imaging and Muon Lifetime Measurement

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Japanese swords are known for beautiful iron artifacts and sophisticated fabrication techniques. The Japanese swords produced before about A.D. 1600 are called as Koto (old swords) and making process of the Koto have not been fully well known. Steel characteristics of each sword is useful to know feature of the sword and will give information to consider making process. We have studied 13 Japanese swords, 2 spears and 1 naginata. In these studies, we mainly used neutron imaging (Bragg edge transmission and CT) to investigate the crystallographic information and internal structure, and muon life time measurement to obtain carbon content. The Bragg edge transmission method can provide large area crystallographic information, such as crystallite size, texture, strain and martensite[1]. The data can indicate continuous change of such information, which is useful since Japanese swords are inhomogeneous. The negative muon life time measurement uses large life time difference in iron (206 ns) and carbon (2026 ns). Therefore, we can distinguish these two decays to obtain each content[2].

We performed experiments at Material Life Science experimental Facility (MLF) in J-PARC in Japan. Neutron experiments were performed on RADEN[3]. As an example of the results obtained by the Bragg edge transmission, Fig. 1 shows the results of a sword, Nirimitsu made in 15th century[4]. The sword blade length is about 46 cm. The crystallite size is larger in back side than edge side (see Fig. 1 (a)). This suggests there are two kinds of steels with different crystallite sizes, which may imply different carbon contents. The preferred orientation is very strong at back side (see Fig. 1 (b)), which may be due to forging and/or heat treatment. CT results around a tip area indicated a layered structure. Based on the results of the crystallite size and the CT, it was guessed the sword had a layered structure composed of two different carbon content steels. To confirm this, we performed the negative muon life time measurements at D1 muon beam line at MLF[5]. We measured two positions of the sword around the center of a length direction. One was around edge and the other around shinogi at a distance about 7 mm from the back side. The carbon content at the edge area was 0.41% and that at the shinogi area 0.18% at a depth of about 0.75 mm from the surface. 0.18% corresponds to content of core steel and 0.41% to surface steel of the layered structure sword. This indicated the core steel appeared at surface around the shinogi and the surface steel exists around edge. Therefore, the sword was made by forge welding of two steels with different carbon contents. We found different crystallite size distributions. Uniform distributions of small crystallite size and patterns different from Norimitsu. Such information will be helpful for considering the structure of each sword. In the presentation we will introduce various crystallographic information obtained for the swords.

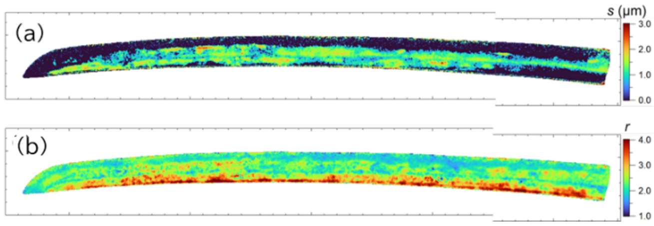

Fig. 2 *Mapping of crystallite size (a) and degree of preferred orientation (b) (from*

References

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Non-invasive analysis of Japanese swords through Neutron methods Lessons learnt after 18 years of research

Francesco Grazzi[1,2*]
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[2]*Istituto Nazionale di Fisica Nucleare (INFN), Sesto Fiorentino, IT*
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The metallurgy of historic combat weapons (swords, in particular) is one of the most significant topics in archaeometallurgy because these objects have been manufactured for thousands of years using the highest quality materials and the most advanced (if intuitive) technologies of the time [1]. Historical Japanese steel swords represent one of the most interesting topics in the field of metallurgy. Their forging techniques were almost unique, combining the use of different carbon steel specifically selected for different parts of the composite blades. Since ancient times Japanese Swords have been famous among all others throughout the world as the most effective in terms of hardness, resilience and, last but not least, aesthetics and cultural significance [2-3]. Every single type of steel was strongly pre-treated in order to redistribute their slag inclusions and to homogenize their compositions. Carefully selected high and low carbon *tamahagane* steels from the *Tatara* furnace [3] were forge-welded, cut, folded and forge-welded again to form a new sheet. After repeating these steps several times, the sheet was then shaped and used to form specific parts of the blade such as edge, sides, core and back according to its carbon content and the number of folding. As a final treatment, after the forging, the blade was covered with a layer of clay, with a different thickness depending on the area (thin on the edge, thick on most of the other parts). The blade, now differentially thermally insulated, was then heated up to a specific temperature and quenched in water so that the desired part of the steel was uniquely transformed into martensite, a much harder material, particularly on the cutting edge and adjacent areas. The back of the blade could be described as air-cooled steel.

This method of production fully developed in Japan through the centuries, most likely dating back to the 10th Century C.E., or even earlier [3]. Since the very beginning, several sword-making dynasties were established as well as traditional forging procedures related to specific periods and places. The set of forging and thermal treatments all leave an imprint within the metal which can be read through analytical techniques able to provide morphological, compositional and microstructural features. Neutron imaging and neutron diffraction-based methods offer the best example of techniques able to non-invasively characterize such features. This presentation offers an overview of 18 years of research in this field.

References

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Thursday, 11th September 2025 11.00

Complementary methods of analysis for Indian swords: neutron diffraction and metallography

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Traditional methods of analysis such as metallography can supply a great deal of information about historical artefacts, such as armour and swords.

However, it is microinvasive and is therefore less suited to the most important historical artefacts.

So, neutron techniques have become the preferred method for museums. One particularly interesting group of objects is the so-called “Damascus swords” that is swords made in India, Persia and Central Asia from hypereutectoid steels, which may display a surface pattern (said to resemble “watered silk”) formed by the anisotropic distribution of cementite.

Neutron diffraction on a number of such swords from the Wallace Collection (London) the Princely Arsenal of Hyderabad, and other collections has enabled the carbon content of these blades to be measured at several points, and their anisotropy to determined. This latter property can vary for reasons which are not yet fully understood.

However, metallography on blades can determine the morphology of the cementite (which in turn depends upon its thermomechanical history) and an explanation may then be formulated for its anisotropy. So, information about workshop practices may be derived from combining both methods of analysis.

Multimodal Characterization Approach for Studying Corrosion of Archaeological Iron Artifacts

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Anders Kaestner[2], Jean-Marie Drezet[3], Laura Brambilla[1]

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The corrosion study of metals buried in an opaque, porous medium, such as soil, involves diverse challenges, including (1) no visual and physical access to the corroding materials when they are in the original burial environment; (2) corrosion layers formed during burial may transform when exposed to a new environment post-excavation. Therefore, conventional analyses and characterization performed after removing artifacts from the ground may no longer accurately represent the as-buried conditions. Those issues raise a long-standing question: is the state-of-the-art analytical method on buried objects producing relevant information about corrosion processes occurring during burial? In the field of archaeological heritage conservation and restoration, an analytical method is necessary to capture the corrosion condition during burial, enabling an accurate assessment of an artifact's condition and informed planning of handling and treatment.

Neutrons and X-rays interact differently with matter as they have different attenuation coefficients to elements. By combining the complementary detection capabilities of neutrons and X-rays, artifacts' physical information, i.e., the spatial distribution of remaining metal parts, corrosion layers, and cracks, can be gathered non-destructively and with minimal sample disturbance from the excavation site. Additionally, the chemical information of the artifacts is supplemented through tomographies of calibration pellets made from ferrous corrosion compounds, either commercially available or synthesized, such as hematite, magnetite, and polymorphs of iron-oxyhydroxide: goethite, akaganeite, and lepidocrocite. Hence, changes that occurred in the artifacts due to storage and conservation treatments can be described visually [1,2] and chemically, thanks to further information obtained from microscopy and spectroscopy results of the artifacts' cross-sections [3]. Various dechlorination and corrosion inhibition treatments on archaeological nails will be evaluated using muon-induced X-ray spectroscopy, adding a new level of information to the bimodal tomography experiment results.

Results that will be presented in the oral presentation are case studies on archaeological nails excavated from Bois de Châtel, a forest archaeological site of the Aventicum Roman Museum (Site et Musée Romains Avenches – SMRA), Switzerland. Both bimodal computed tomography using neutrons and X-rays and muon spectroscopy are performed at Paul Scherrer Institute's ICON and MIXE beamlines, respectively, in the scope of the Swiss National Science Foundation Sinergia CORINT project.

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Muonic X-ray Emission Spectroscopy (μXES) for Sub-surface, Non-destructive Analysis of Ancient Gold

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Muonic X-ray emission spectroscopy (μXES) is a powerful tool for generating important archaeological conclusions from high-value cultural heritage objects that simply cannot be destructively analysed, but need to have their interior compositions sampled. By controlling the momentum of the muons, they can be implanted into an object at a specific depth. Here they are captured by atoms and the energy of the resulting muonic X-rays from the capture indicates the element from which it came. This enables us to determine sub-surface elemental composition in discrete 'slices' non-destructively.

Ancient gold coins present a particularly compelling use case for μXES. They are rare, valuable and arguably objets d'art in their own right, meaning destructive sectioning is almost impossible to sanction. However, they are fundamentally artefacts of monetary economies, meaning understanding their true composition can give us important insights into ancient state finances and supply chains, technological choices, and the economic consequences of political and historical events. To articulate this, we present a case study from the Roman Empire's 'Year of the Four Emperors'.

During the AD 68/9 Civil Wars, Galba, Otho, Vitellius and then Vespasian fought for — and gained — control of the Roman Empire. Our textual sources suggest that this was a period of serious and sustained disruption. However, existing analyses of gold coinages produced in AD 68/9 show only a minor reduction in the purity of the gold coinage. Using X-ray fluorescence, we identify a number of heavily debased gold coins issued during the AD 68/9 Civil Wars, and many slightly debased coins issued in their immediate aftermath. We then confirm the interior composition of these coins totally non-destructively using muonic X-ray emission spectroscopy, thus eliminating hypothetical problems of 'surface enrichment' or compositional differences between 'surface' and 'core'. We will show that heavily debased Civil War gold coinages were indeed produced; that copper was used to debase Roman gold coins during this time, c. 185 years earlier than first shown; and that slightly debased gold coins were regularly issued in the years immediately after the Civil Wars. The metallurgical evidence from the gold coinage now allows us to show that the AD 68/9 Civil Wars caused significant and sustained disruption to the Roman economic system.

Fig. 1 *Two* aurei *of the Emperor Galba produced during the AD 68/69 Civil Wars. Despite the colour of the metal being very similar between these two coins, the coin on the left contains 99% gold and 1% silver, where the coin on the right contains 89% gold, 5% silver and 6% copper: demonstrating the importance of scientific analyses for understanding these objects. The Romans deliberately enriched their silver coins, meaning there is always the lingering hypothetical of whether they may choose to do this to the gold in times of crisis. Muons allow us to analyse deep beneath the surface and confirm the true purity of these objects non-destructively.*

Thursday, 11th September 2025 12.00

Title: Neutron techniques for Cultural heritage at ISIS: new developments and some successful stories

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Scientific investigations and archaeometric studies have played a major role in the field of archaeology, especially with regard to materials that have been transformed through human activity, like metals. Neutron techniques can be used to shed light on the inner structure of artefact, their microstructure, but also can be used for elemental investigations.
Scientific investigations have played a major role in the field of Heritage Science, especially with regard to materials that have been transformed through human activity like metals, ceramics etc…. Thanks to the high penetration power of thermal and epithermal neutrons, measurements performed through neutron methods allow for quantitative determination of bulk properties of the sample in a non-destructive way. This opens up the possibility of investigating objects otherwise unsuitable, due to their cultural and/or historical importance.
At the ISIS neutron and muon source, investigations in the field of Heritage Science are now routinely performed, taking advantage of the available portfolio of instruments and techniques. These includes more conventional methods like neutron diffraction and neutron imaging, and more innovative ones like elemental imaging and analysis with isotopic sensitivity, based on neutron resonance absorption spectroscopy and negative muons, also available at the ISIS facility.
In this talk, I will give some examples of how neutron methods at the ISIS neutron and muon source, in conjunction with other techniques, can be pivotal to improve our knowledge of ancient manufacturing processes of metals in particular, their technological evolution over the centuries, and how they degrade over time, as illustrated by the work done in the last years on Nuragic bronzes from Sardinia, roman and Italian renaissance bronze statues, bimetallic swords from China etc...
I will also present novel advances in the implementation of Neutron Resonance Transmission Imaging (NRTI), a non-destructive novel quantitative chemical imaging technique, performed at the INES beamline operating at the ISIS neutron and muon source. obtain 2D radiographies of the sample. The main difference with standard neutron radiography, is that through NRTI it is possible to obtain the distribution of elements and isotopes within a sample, enhancing the contrast between elements with similar neutron attenuation coefficients. This striking features of NRTI make it suitable for the characterization of inhomogeneous samples, in particular but not limited to Cultural Heritage studies.

Probing the Effect of Fire on Egyptian Mummies by Neutron Spectroscopy and Neutron Activation Analysis

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In September 2018 a fire at the Brazilian National Museum (Rio de Janeiro) severely damaged several mummies from the Egyptian Collection. The present study applied the complementary vibrational spectroscopic techniques inelastic neutron scattering (INS), Fourier transform infrared (FTIR) and Raman to probe the structural and chemical changes prompted by the fire in skeletal remains from four different mummies. In addition, neutron resonance capture analysis (NRCA) and neutron activation analysis (NAA) were used for a better identification of contaminants, both from the mummification process and from the construction materials that may have been intermingled with the bone fragments during the fire and subsequent building collapse. This is a pioneering project – the first application of neutron scattering techniques to the analysis of skeletal remains from mummified corpses. The data thus obtained, interpreted in the light of previous studies by the authors on modern and archaeological bones [1-3], delivered the burning conditions to which the mummies were subjected (*e.g.* temperature, oxygen availability) and provided clues on the extent of heat-induced effects and the way they were impacted by the mummification process. INS spectroscopy allowed the detection of all the modes associated with bone´s hydroxyl groups (translational, librational and stretching), not all of which are accessed by optical vibrational spectroscopy, as well as the low frequency vibrations characteristic of the bone lattice. Interestingly, for some of the mummies different heating temperatures were identified within the same skeleton (Fig. 1). Contaminants were also detected, such as natron ($Na_2CO_3.10H_2O/NaHCO_3$), pigments, cyanamide and gypsum ($CaSO_4.2H_2O$). These results provided reliable data for a precise characterisation of the burning and environmental conditions during the fire at the Museum and should help to establish suitable preservation methods for these unique ancient remains.

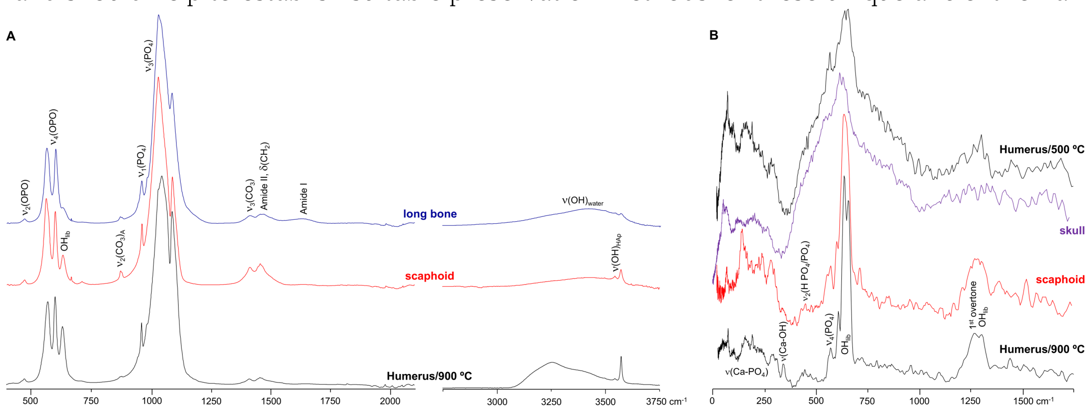

Fig. 1 – Spectra of burned skeletal samples from the Sha-Amun-em-su mummy: (A) FTIR-ATR for long bone and scaphoid; (B) INS (measured in TOSCA, https://www.isis.stfc.ac.uk/Pages/tosca.aspx) for skull and scaphoid. (The spectra of modern human humerus burned aerobically at controlled temperatures are also shown for comparison [2]).

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Thursday, 11th September 2025 14.50

Characterisation of water-induced damage in painting varnishes using neutron scattering techniques and optical coherence tomography

Alessia Venturi[1,2*], Lucas Goehring[1], Najet Mahmoudi[2], Haida Liang[1], Antonella Scherillo[2]
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[2]Science and Technology Facility Council, ISIS Neutron and Muon Source, Didcot, OX11 0QX, UK
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Varnishes are transparent finishing layers applied to paintings to enhance their optical properties. However, when stored in high humidity or directly exposed to water, these polymeric coatings turn opaque, altering the painting's appearance. During this whitening process, known as blanching, moisture penetrates and expands the varnish's pre-existing nanoscopic pores. As a result, the final pore size scatters visible light, causing a white haze. This study aims to correlate alterations in the polymer structure with the resulting optical changes by combining elastic neutron scattering techniques and optical coherence tomography (OCT).
We prepared samples of mastic varnish, commonly used in paintings, by spin coating the solution onto inert substrates. Once dried, films of realistic thicknesses (ranging from 20 to 80 μm) were produced and immersed in deuterated water to simulate blanching. Whitening was monitored over time using simultaneous measurements of small-angle neutron scattering (SANS) and optical coherence tomography (OCT). This integrated approach provides information at different scales: OCT probes the expansion of the varnish layer at the microscale, and SANS resolves pore growth at the nanoscale. Results show that water infiltrates the varnish surface, causing pore growth before visible swelling. In later degradation stages, the varnish layer expands. This behaviour observed in samples of different thicknesses suggested that water interaction is confined to the upper few microns of the varnish. Therefore, we used neutron reflectometry (NR) and grazing incidence small-angle neutron scattering (GISANS) to probe the in-plane and out-of-plane structural changes in films between 150 and 400 nm. The outer layer becomes water-rich, and the monitoring of the alteration confirms that the degradation is initiated at the surface, and it proceeds until 20 hours in the thin layers.
This study provides detailed insight into the varnish blanching mechanism: the nanoscale pore growth induced by water penetration precedes, leading to micrometric swelling and opacity. However, early-stage whitening may still be reversible if water is removed within three days. Understanding these distinct timescales highlights the importance of humidity control to prevent irreversible damage in varnished paintings. Moreover, the demonstrated combination of SANS and OCT shows how structural and optical changes in cultural heritage materials can be monitored in parallel at different scales. Lastly, these outcomes inform conservation strategies supporting the preservation of painted artworks.

Thursday, 11th September 2025 15.10

Neutrons for conservation of stone materials and organic based artefacts in cultural heritage. The project nanoHERCULES

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The conservation of our cultural heritage (CH) is of utmost and ever increasing importance. Considerable effort has been devoted to better understand the degradation processes and to find new techniques for conservation and restoration tailored to materials relevant to CH applications. The variety of materials in use as well their intrinsic complexity (composite nature, multifunctionality…) poses a challenge to scientists and conservators working in this area. Often validation of materials and formulations is limited to laboratory tests; the development of technologies for large-scale applications may highlight new problems, particularly when seeking long-term solutions.
In the last years, nanoparticles (NPs) of earth-alkaline metal hydroxides were proposed for conservation of stones materials and for wood de-acidification, but their use presented a lot of limitation due to the synthesis method: they generally require organic compounds (no health compatible), and multi-step, time and energy-consuming procedures, with low specific yields of production and high costs, limiting them to niche uses or on very small areas. Prof. G. Taglieri patented [1] a new one-step process of synthesis of NPs overcoming many of the problems associated with previous procedures. The new protocols combine synthesis of highly dispersed NPs (few tens of nano-meters), in water, with higher reactivity, stability and deeper penetration into damaged materials, produced on large scale and feasibility to modify and optimise functionality. The innovative NPs are tailored to enhance compatibility, sustainability and long-term preservation, restoration and consolidation, on a large scale, of decorative architectural surfaces (stones, mortars, stuccos, mural painting and frescos), and of organic materials, such as ancient paper and wooden artefacts (shipwrecks, statues, ancient tools and utensils). We used neutron tecniques, as small angle neutron scattering, to study the NPs directly in suspension (in terms of shape, size, size distribution and solvent interaction and aggregation state), to drive their production on large scale, for curative and preventive eco-friendly treatments for waterlogged wood and stones materials. Furthermore, we used neutron diffraction and neutron tomography to investigate the substrates and the changes after NPs treatment. We investigated mortars and stones from the new excavation of Colosseum and from the Greek theatre of Agrigento and ancient wood from shipwreaks of Gallo-Roman period. See Fig. 1.
I will present the main results of our study together with the perspectives of using neutrons in our project, recentely funded: nano-HERCULES nano-particles for HERitage and CULture in Environmental Sustainability).

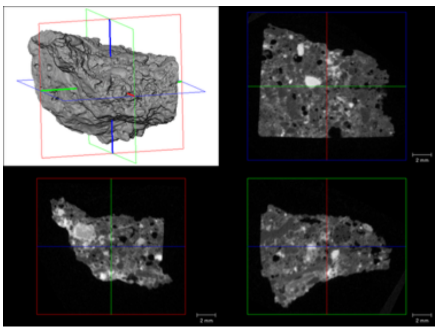

Fig. 1*Tomography of a mortar from the floor of Colosseum*

References

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Neutron imaging in cultural heritage preservation

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A wide range of chemical, physical, and microstructural techniques are employed by museums and art experts to characterize objects of cultural significance. Most of these methods are invasive, with probes like X-rays and charged particles having limited penetration power. Neutrons, however, can penetrate thick layers without substantial attenuation, making them ideal for studying and visualizing the interior (bulk) properties of materials in a completely non-destructive and non-invasive way. The high sensitivity to specific light elements (e.g., hydrogen) is an additional special property of the neutron probe. Neutron techniques are increasingly used for the quantitative, non-invasive analysis of various aspects of cultural heritage preservation, including museum collections, artifacts, sculptures, metallic armours and weapons, pottery, and archaeological findings.
Examples of investigations into cultural heritage artifacts using neutron imaging techniques will be presented and discussed.

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Poster Session

Thursday, 11th September 2025

15.50 -17.30

Neutron-based characterization of corrosion phenomena in ancient iron artefacts from the Nissia shipwreck

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The Nissia shipwreck (18th century), submerged at 27 m depth in Famagusta Bay (Cyprus), offers a unique opportunity to investigate long-term corrosion processes affecting iron-based artefacts in marine environments. Among the structural remains, several iron nails were selected for advanced characterization using neutron scattering techniques, in order to investigate their compositional, structural, and microstructural features. Preliminary analyses by SEM-EDS and μ-Raman spectroscopy revealed complex corrosion layers rich in iron oxides and oxyhydroxides, alongside traces of alloying and environmental elements (e.g., Ti, Si, S) (*Fig. 1*) [1].
Neutron diffraction (ND) on D20 will allow the identification of crystalline phases and alloy structures, while SANS measurements (D16, D11) will provide unprecedented insights into corrosion-induced porosity [2]. The combined use of these instruments enables the investigation of open vs. closed porosity distributions across corrosion layers and their relation to environmental exposure.
This approach provides a high-resolution multiscale understanding of corrosion patterns within the Nissia nails and contributes to broader efforts aimed at decoding underwater metal corrosion. The results will inform both the conservation of submerged artefacts and predictive models assessing the vulnerability of maritime heritage under changing environmental conditions [3].
This research has been allocated neutron beamtime at the Institut Laue-Langevin (ILL) for autumn 2025. In future proposal, the same nails are also suitable to be studied through neutron tomography to complete the multiscale analysis of corrosion morphology and structural preservation.

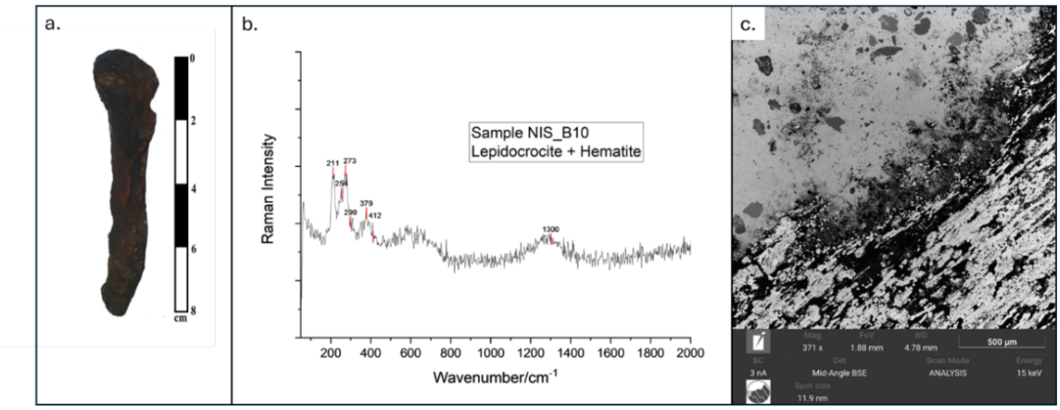

Fig. 1 *(a) Photograph of a Nissia nail, (b) its corresponding micro-Raman spectrum from the surface, and (c) a mid-angle BSE SEM microphotograph highlighting microstructural features.*

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Acknowledgements

This research has been funded by European Union's Horizon Europe research and innovation programme under the THETIDA project (Grant Agreement No. 101095253) (Technologies and methods for improved resilience and sustainable preservation of underwater and coastal cultural heritage to cope with climate change, natural hazards, and environmental pollution).

Characterization of Cultural Heritage materials using a laboratory-based phase contrast X-ray imaging system, within the PITCH project

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X-ray imaging is a standard tool for the investigation of the internal structure of materials. Thanks to its high-resolution and non-invasive inspection, this technique has been used in recent decades in various fields, from material science to cultural heritage and medical applications.
In order to characterize medium-density samples or to distinguish materials with different attenuation powers the conventional absorption contrast method is particularly suitable. On the other hand, materials composed of light elements exhibit poor contrast under X-ray irradiation. In weakly absorbing samples, Phase-Contrast (PC) X-ray imaging is an effective technique for the investigation of low contrast details [1]. This method is based on the observation of the interference pattern between diffracted and non-diffracted waves, caused by spatial variations in the real component of the refractive index introduced by a sample placed in the wave path. PC imaging is able to provide high quality information on the microstructure of the sample. Among the PC methodologies, X-ray Grating Interferometry (GI) is very powerful because it enables the realization of systems that can be implemented in a laboratory setting. This technique provides differential phase and scattering (dark-field) images in addition to the standard absorption-based image, opening interesting opportunities in the cultural heritage field, such as conservation, archaeology, archaeometry, anthropology, paleopathology.
This work illustrates the application of GI-PC imaging as a characterization tool in the field of cultural heritage, within the PITCH project (funded in the framework of PRIN2022). This project aims at designing, developing and characterizing a laboratory GI-PC imaging setup based on a liquid-anode X-ray source, as well as at investigating and developing different data acquisition methods and algorithms for signal extraction and tomographic reconstruction. A selection of relevant materials, original fragments and possible mock-ups to use for preliminary tests has been made: pigment layers, metallic yarns, textile material, leather, gilding on paper, parchment, cartonnage, Barniz de Pasto, wood artifacts, shells and eggs from archaeological findings, pearls, mummified remains, animals preserved in formalin. Different samples' geometries will be tested as well. The preliminary characterization of mock-ups will lead to the study of real artifacts coming from museums and other cultural institutions.

References

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The Issue of Identifying the Stratification of Polychromies on Ancient and Post-Antique Sculptures

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In the last few years, the Istituto Centrale per il Restauro (ICR) carried out some conservation interventions on polychrome and gilded stone and stucco sculptures and architectural decorations belonging to different Museum Collections, artistic contexts and historical periods [1 - 6]. During the study and the restoration work about these artworks we had to solve some issues, primarily with regard to the identification of the pigments used and their possible stratification, the composition of any ground layers for colour finishings applied on the stone or stucco surface of the sculptures [Fig.1, A; B], the binders used and the manner in which the gildings were made and applied. In some cases, over time sculptures have been decorated with new polychrome finishings that covered the older coloured layers, either to restore decorations that are no more well preserved or to change the vision of the artworks according to different and new aesthetic styles.
We have carried out multispectral diagnostic analyses (digital video microscope, Infrared Reflectography, Infrared False Colour Photography, UV-induced visible fluorescence imaging), that showed the presence of restorations and different ground layers, as well as traces of colours and gildings, which are, in some cases, totally invisible to the naked eye. Furthermore, we have carried out SEM-EDS analysis, XRF analysis, micro-Raman and Gas-Chromatography Mass Spectrometry (GC-MS) carried out to identify pigments and binders used on polychrome sculptures. Often, polychromies and gildings were only preserved in small traces, and it was not always possible to take micro-samples that could be investigated in stratigraphic section under an optical microscope and SEM-EDS to verify the overlapping layers present. Therefore, it will be very important for our research to be able to use other diagnostic methods to verify the existence and composition of the various layering of pigments and gildings on the sculptures under study. We hope that investigations with neutrons could perhaps be among these.

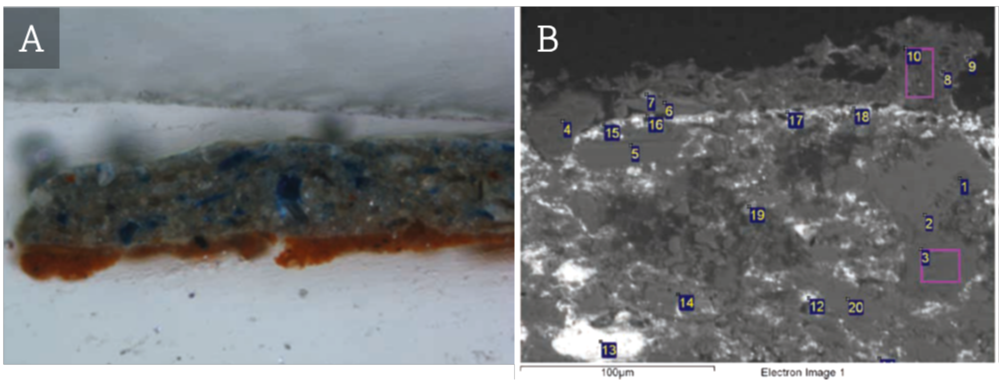

Fig.1 *Statue of Bodhisattva from Museum Guimet (Paris):* A) *Microphotography of cross section of sample of blue pigment (100x) [1].* B) *SEM-EDS image of cross section of sample of blue pigment [1].*

References
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Conserving Wooden Artefacts from Shipwrecks: A Nanoparticle-Based Approach Supported by Neutron Diffraction

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The preservation of wooden artefacts poses a significant challenge in cultural heritage conservation. Among these, shipwrecks are particularly rare and valuable, acting as time capsules that provide critical historical insights from archaeological, anthropological, and historical perspectives.

Waterlogged archaeological wood is often severely degraded and highly fragile due to cellulose breakdown caused by bacteria, algae, and fungi. Additionally, iron residues from nails and decorative elements can react with sulfur introduced by anaerobic bacterial metabolism, leading to the formation of iron sulfides such as pyrite. When the artefacts are landed, under oxygen exposure or specific temperature and humidity conditions, these compounds oxidize into sulfuric acid, causing irreversible structural and visual degradation. Our research focuses on mitigating this deterioration using Calcium Hydroxide Nanoparticles (CH-NPs), synthesized at a large scale through an innovative, safe, sustainable, and cost-effective water-based process. CH-NPs possess alkaline properties that counteract acidification. Initial studies on small shipwreck wood samples demonstrated their ability to neutralize acidity in a single step while forming a nanoparticle reservoir that prevents further degradation [1 and ref inside-2].

The primary aim of this study is to assess the effectiveness and penetration depth of CH-NPs in waterlogged wood samples provided by ARC-Nucleart. The samples underwent artificial aging to induce acidification before being treated with nanoparticles for a controlled period to restore a neutral pH. Post-treatment, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) was used to map nanoparticles distribution at varying depths, see Fig. 1.

Additionally, neutron diffraction, a highly sensitive and non-destructive technique, was employed to conduct a comprehensive qualitative and quantitative analysis of the presence of iron and sulfur. This allowed for the identification and quantification of both the elemental forms and their specific crystalline compounds within the sample, see Fig. 2. Preliminary results from this investigation, along with a detailed data analysis, will be presented.

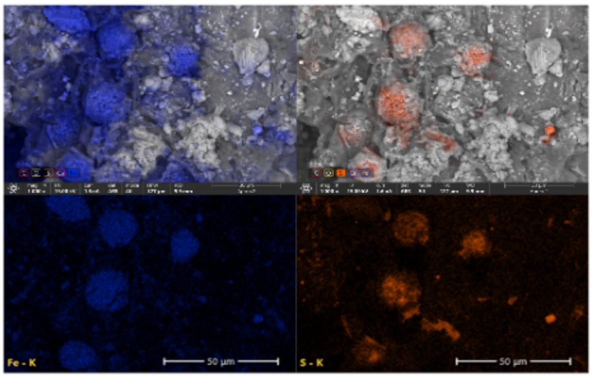

Fig. 3 SEM-EDX micro-analysis.

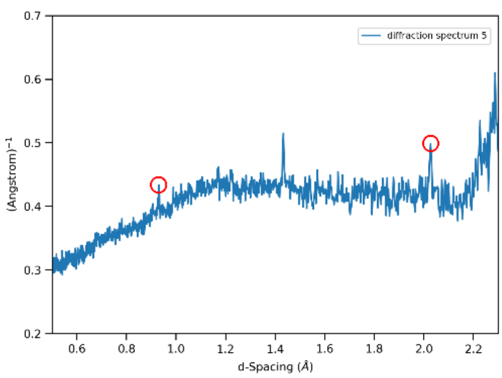

Fig. 2 Representative diffracion spectrum.

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X-ray Computed Tomography and 3D Analysis for the Characterization of a Wichí Pipe from the Argentinean Gran Chaco

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Non-destructive techniques, including imaging methods, are essential tools for the study and preservation of cultural heritage [1]. This work presents the X-ray computed tomography (CT) analysis of a wooden pipe crafted by the Wichí people from the semi-arid Gran Chaco region of Argentina [2 - 3], currently held in the collection of the Juan A. Domínguez Museum of Pharmacobotany, Faculty of Pharmacy and Biochemistry, University of Buenos Aires, Argentina.

The objective was to characterize the internal morphology and determine relevant physical and structural parameters, such as the total volume and the density of the object.

The scan was carried out at the Centro Atómico Constituyentes using a Nikon XT H 225 ST 2X system, which allows for a resolution of up to 3 μm depending on sample size. For this acquisition, the scan parameters were: 110 kV voltage, a 2.5 mm aluminum filter, 1200 projections, and a spatial resolution of 80 μm. The pipe was scanned in its entirety, and tomographic reconstruction was performed from the acquired images. A 3D segmentation process was subsequently applied to isolate the geometry of the pipe from the background and unrelated structures, enabling the generation of a precise volumetric model.

The segmented model was used to calculate the pipe's volume. With this data, and the externally measured mass, the wood's density was determined. This value was used as a reference to estimate the density of other wood samples scanned under the same acquisition parameters. By correlating the grayscale levels in the CT images with the known density of the Wichí pipe, it was possible to infer the density of other objects that exceed the maximum sample size for this microCT system. These inferred values offer useful insights for comparative characterization of wooden heritage artifacts.

Tomographic reconstruction also revealed manufacturing features, such as internal cavities created by combustion, consistent with traditional fabrication techniques [3], as well as the overall good preservation state of the piece, with no visible signs of biological or mechanical damage. This work highlights the potential of microCT imaging for the analysis of wooden heritage objects [1]—a material often difficult to characterize—thus promoting their study, conservation, and appreciation without compromising their physical integrity.

References

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Oral Presentations

Friday, 12th September 2025

Friday, 12th September 2025 9.00

Keynote lecture

Neutrons and bronze heritage: a happy marriage? Pros and cons of neutron analysis from a stakeholder's perspective

Monica Galeotti[1],
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In my talk I will present the interdisciplinary work carried out at the Opificio delle Pietre Dure for the conservation of historical and ancient bronzes, which includes the application of neutron techniques to investigate the composition of the metal, the casting and working technology, and the presence of defects, cracks, hollow sites and pins not visible with the naked eye. Case studies showing achievements along with practical issues will be presented, and pros and cons of the neutron probes for bronzes will be discussed from the point of view of an informed user.

Friday, 12th September 2025 9.50

Neutron study of Roman medical utensils from the RD Milns Antiquities Museum - University of Queensland

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This paper presents a non-invasive investigation of a set of Roman bronze medical instruments, dated between the 1st and 4th centuries AD and currently housed in the RD Milns Antiquities Museum at the University of Queensland (Australia).
The legacy of Roman medicine has significantly influenced modern medical knowledge and practice. While early Roman approaches were rooted in herbal remedies and superstition, contact with Greek medical traditions in the 1st century BCE introduced more systematic, science-based methods. These practices were further refined through cultural exchanges with colonized territories and rapidly disseminated throughout the Empire, often via military campaigns.
The medical tools that have survived to the present day offer valuable insights into ancient medical practices. Scientific analysis of these instruments can illuminate both technological and societal aspects of Roman life. Despite their potential, most studies have focused primarily on typological classification. Only a few investigations have examined the material composition and manufacturing techniques of these artefacts and those have generally relied on surface-level or invasive analytical methods.
By contrast, neutron-based techniques offer a powerful, non-destructive alternative within the field of heritage science. Thanks to their neutral charge, deep penetration capability, and interaction with atomic nuclei rather than electron clouds, neutrons are especially well-suited for probing the internal structure of dense materials such as metals.
In this study, we present the results of a neutron-based analytical campaign aimed at uncovering the manufacturing techniques used in the production of Roman medical tools.

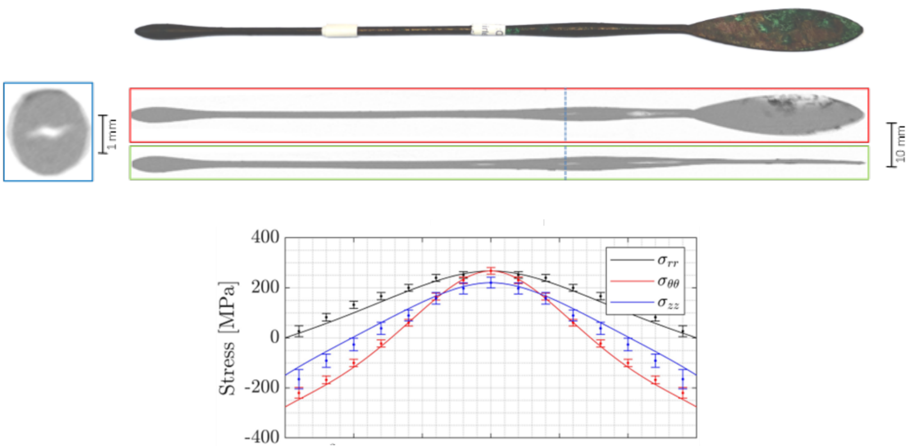

Fig. 4 *From top to bottom: Photographic image of one artefact; orthogonal cross-section through the neutron tomography reconstruction of the sample, with the dotted red line indicating the location of the xy section along the blade; profiles of the axial, radial, and hoop stress components of the sample. The stresses were measured with an accuracy <15 MPa [1].*

References

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White beam and monochromatic neutron imaging for the reconstruction of the casting process of ancient bronzes: an overview of results and interpretation

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The history of technology of ancient civilizations is mainly the history of their metallurgical capabilities. In fact, metal tools, weapons and art objects were produced using the most advanced knowledge developed by the different civilization, since metalworking requires a wide amount of technical skill and empirical knowledge of complex thermal and mechanical phenomena. Ancient metal artefacts are often studied by extracting sections and applying analytical methods developed within contemporary industrial metallurgy. Several of these methods are destructive or based on basic assumptions on sample composition and thermo-mechanical history that are not available for historical artefacts. What is necessary is, actually, a sort of reverse engineering to derive manufacturing procedures. The most effective and, in practice, the only methods able to provide such analysis in a non-invasive way are those based on neutron methods as White Beam Neutron Tomography (WB-NT), Time of Flight Neutron Diffraction (ToF-ND) and Bragg Edge Neutron Transmission (BENT) analysis.We present here an overview of the results of the analysis performed on historical bronze artefacts belonging to different civilizations and time periods obtained through WB-NT and BENT, showing how it is possible to map the main compositional, morphological and microstructural characteristics of different technological procedures. From the position of the casting moulds (Fig. 1), reconstructed through the distribution of porosity or the presence of single crystal spots, to the identification and reconstruction of welding, repair and cast-on interventions. It will be highlighted how these two imaging techniques can precisely characterize the artefacts, not only from a morphological but also a microstructural point of view [1; 2]. Thanks to the collaboration with prestigious Italian and international museum and conservation institutes, which have made it possible to study bronze masterpieces from the Bronze age to the Renaissance, the versatility and utmost importance of WB-NT and BENT will be highlighted in deepening the diagnostic study of these artefacts, allowing a cognitive advancement not only of the materials, but also of their manufacturing history.

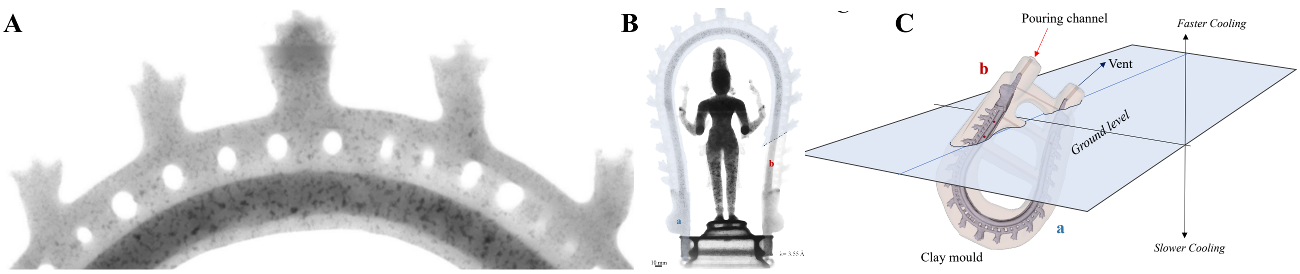

Fig. 2. *An example of how it is possible to exploit the distribution of oligocrystals, revealed by BENT (**A** - **B**), to propose a hypothesis on the position of the mould during casting(**C**).*

References

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Friday, 12th September 2025 11.00

The progress of CARR neutron imaging and its applications in culture heritage

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Based on the 60MW China Advanced Research Reactor, two neutron imaging instruments have been built at China Institute of Atomic Energy (CIAE). The thermal neutron imaging is located at the H8 horizontal channel of the reactor, and the cold neutron imaging is positioned at the terminal of the CNGC neutron guide. The measured neutron flux at the sample position can reach 6.4×10^{8} n / cm^{-2}・s (L/D=180) and 2×10^{7} n / cm^{2} ・ s (L/D=160) for thermal neutron imaging and cold neutron imaging, respectively.

In recent years, several advanced imaging methods have been successfully developed at CIAE. Thermal neutron imaging provides real-time neutron imaging, multi energy spectrum neutron imaging (including thermal, fast, and epithermal neutron imaging modes), and neutron irradiation of electronic components. Cold neutron imaging enables energy selective imaging, high resolution imaging, polarized neutron imaging, combined neutron and X-ray tomography and indirect neutron computed tomography. These techniques have been utilized in the research of cultural heritages like Xi Zhen and arrowheads relics from the Han Dynasty, offering important information for the study of the manufacturing techniques and conservation conditions.

A B

*Fig1 Photographs of the (***A***) thermal and (***B***) cold neutron imaging instrument*

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Calibration of Bragg Edge Neutron Transmission analysis for the characterisation of archaeological bronzes

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The study of ancient metallurgy, particularly the analysis of bronze and copper alloys, plays a crucial role in understanding the technological and artistic advancements of past civilisations. Neutron-based methods offer a highly promising solution for the non-invasive characterisation of the elemental, isotopic, and phase composition of the objects under study [1][2][3].

The work presented here is part of the INFN CHNet_BRONZE project, which aims to develop and quantitatively calibrate techniques that exploit neutron probes for the analysis of Cu-based archaeological artefacts. The project assesses three bulk analysis methods: Time-of-Flight Neutron Diffraction (ToF-ND), Neutron Resonance Transmission Imaging (NRTI) and Bragg-Edge Neutron Transmission analysis (BENT).

This work will focus on the measurements carried out with the BENT technique, that can reveal elemental and phase composition, microstructure, texture and other properties of crystalline solids non-invasively [4]. It is based on the coherent elastic interaction between an incident neutron beam and the crystalline structure of the sample. Exploiting a 2D imaging detector, position-dependent Bragg-edge transmission spectra are acquired, enabling reconstruction of phase spatial distribution. A set of purposely prepared copper-based reference samples, in powder and cast form with known composition and structure, are used to define experimental and analytical methodologies and later aid in the interpretation of data obtained from historical bronze artefacts. In particular, the analysis of the BENT spectra with the specific purpose of extracting elemental composition information will be presented, including the derivation of calibration curves that correlate spectral features with Cu, Sn and Pb content in the material. The results can help to answer questions of historical and cultural interest on archaeological bronzes, allowing to extract compositional information from the bulk of the objects non-invasively.

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Advances in Muon-Induced X-ray Emission (MIXE) with the GIANT Instrument at PSI: Applications in Archaeology, Cultural Heritage, and Energy Materials

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Muon-Induced X-ray Emission (MIXE) is a fully non-destructive analytical technique that combines the unique properties of negative muons with the high energy resolution of high-purity Germanium detectors (HPGe) to perform depth-resolved elemental analysis. At the Swiss Muon Source (SμS) of the Paul Scherrer Institute (PSI), the Germanium Array for Non-destructive Testing (GIANT) instrument leverages a high-intensity continuous muon beam (15–60 MeV/c) to implant muons at tunable depths (μm to cm scale) in materials. The subsequent emission of muonic X-rays during atomic de-excitation provides element-specific (and often isotope-specific) fingerprints, while gamma rays from nuclear capture deliver complementary isotopic information. GIANT enables rapid data acquisition (typically <1 hour per spectrum) with exceptional sensitivity at the permille level for nearly all elements in the periodic table [1,2].

Recent applications highlight MIXE's versatility. In archaeology, the technique facilitated the confirmation of the meteoritic origin of a Late Bronze Age iron arrowhead (900–800 BCE) from Mörigen, Switzerland. The precise measurement of the high Ni (7.1–8.3 wt%) content of the bulk material further allowed to exclude the suspected local meteoritic source [3]. The analysis of a Late Antique knob bow fibula (4th–5th century CE) revealed dual bronze alloys: high-Pb cast components (12–13 wt%) and low-Pb forged parts (3.2 wt%), indicating advanced metallurgical tailoring [4]. In energy materials, MIXE paves the way for operando analyses of batteries, such as studying transition-metal plating on electrodes, which is a critical factor for improving the longevity and performance of advanced cells [5].

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