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Probing Beneath the Surface without a Scratch: Using Muonic X-ray for Depth Sensitive Elemental Analysis on Roman Coinage

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Non-destructive compositional analyses are extremely important in many cultural heritage fields. The use of negative muons (an electron analogue) has seen a resurgence in recent times, with developments occurring at several muon sources. After implanting negative muons into a sample muonic x-rays and gammas are released –these can then be detected to determine the composition of the sample. While similar in principle to X-ray fluorescence, the negative muon technique can analyse deep beneath the surface of the sample. By controlling the muons'momentum (or energy) the implantation depth of the muons can be controlled, ranging from 10s of μm to 10s of mm. This means the composition at different depths within the sample can be determined non-destructively. Here we review the technique and its recent applications to cultural heritage, and present case studies on Roman gold and silver coinage: the former showing no evidence of surface enrichment, the latter unambiguous evidence of it, as well as the discovery of fake coins and corroded materials.
Part of the 'Rome and the Coinages of the Mediterranean'(RACOM) project (funded by the European Research Council under the Horizon 2020 programme, grant agreement 835180) is to use muonic X-rays to determine the core composition of silver coins of Mediterranean states from c. 150 BCE to the mid-first century CE. The quality of ancient silver coinage is often seen as a comment on the fiscal health of the issuing states. Two processes are detectable: a reduction in the fineness of the alloys; and a reduction in weight standards. However, the hypothesis here is that the two processes are interlinked and that the second is largely an illusion caused by the first. These Roman silver coins were, often, produced from an alloy of copper and silver. This enabled mints to disguise debasements from the general public by exploiting the dissimilarity between the electrode potentials of the two metals. The blanks for the coins were cast and, after solidifying, they were probably kept at red heat, or reheated to red heat, for a period of time, to oxidise the copper at the surfaces of the blanks. Once oxidised, the copper oxide could then be stripped out of the alloy by soaking in an organic acid or other solution. This left a honeycomb structure of nearly pure material at the surface of the blanks, which would then be consolidated as a rich layer when the blanks were struck between two dies to make the coins. The technique could even be made to work on alloys that contained more than 80% copper, with the result that coins left the mint looking as if they were pure.
However, Roman gold coins were thought to be pure –except for brief periods of crisis when they were debased. Due to the high art market value of the coins, aggressively destructive techniques are simply not viable. Negative muons, then, give us a unique opportunity to determine whether the surface composition of Roman gold is actually representative of the bulk composition.

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