

Luiten and company reduced the electrons' temperature from 300 K to 10 K. The concomitant narrowing in the width of the diffraction peaks behaved just as they expected.

To resolve molecular structures, the transverse coherence length of diffracting electrons must be larger than a material's lattice constant. For the diffraction pattern in figure 2b, imaged with 10-K electrons focused to a 100- μm spot size, the researchers estimated the coherence length at no smaller than 15 nm. Reassuringly, that's high enough for complex macromolecular diffraction, a common goal among many groups.

Toward single-shot imaging

Ultrafast electron beams from hot photocathodes may also possess that large a coherence length. But it comes at the cost of electric current. The most coherent beams come from a point source. But in so confined a space, researchers must turn off the interactions among electrons by photoemitting them one at a time. Accordingly, they resort to a stroboscopic mode that builds up patterns from millions of shots.⁵

That mode isn't problematic for processes that are, like phase transitions, reversible and robust through repeated experiments. Capturing irreversible chemical processes, on the other hand, requires packing all those electrons into a single shot. Free-electron lasers are bright enough—nine orders of magnitude brighter than the best synchrotron light sources—to pull that off with x rays. Ultracold electron sources, however, have not yet solved the flux problem. Each ionizing laser pulse in the Eindhoven experiment generates a bunch containing a few hundred electrons. At roughly 40 μm in diameter, the relatively extended size of the laser spot on the atomic cloud is large enough to avoid a “Coulomb explosion” that otherwise would blow apart electrons emitted from a more tightly confined space.

A year before Luiten originally proposed ultracold electron beams, he argued that an electron bunch whose charge density is somehow uniformly distributed in a three-dimensional ellipsoid would make such coulombic expansion reversible. One would simply need the right combination of external electric and magnetic fields to recompress the beam.

The idea was theoretically laid out for photocathode sources, but it applies to cold-atom sources equally well. And

in 2011 Scholten's group demonstrated such dynamic bunch shaping in the context of near-threshold photoionization.⁶ The trick was to tailor the incident laser pattern with a spatial light modulator to imprint a pattern on the charge distribution. The electron bunch subsequently retained its shape as it travelled away from the gas. Although the imprinted charge distribution wasn't ellipsoidal—in fact, the imprinting was done in two dimensions—the demonstration represents a promising path toward counteracting space-charge ef-

fects and stepping up the brightness of an electron beam.

Mark Wilson

References

1. R. J. D. Miller, *Science* **343**, 1108 (2014).
2. B. J. Claessens et al., *Phys. Rev. Lett.* **95**, 164801 (2005).
3. M. W. van Mourik et al., *Struct. Dyn.* **1**, 034302 (2014).
4. A. J. McCulloch et al., *Nat. Commun.* **4**, 1692 (2013); W. J. Engelen et al., *Nat. Commun.* **4**, 1693 (2013).
5. See, for example, F. O. Kirchner et al., *New J. Phys.* **15**, 063021 (2013).
6. A. J. McCulloch et al., *Nat. Phys.* **7**, 785 (2011).

Isotopes tell the story of lead in ancient Rome

The toxic element leached out of pipes into the water and left its record in harbor sediments.

At the beginning of the second century AD, Rome was not only the capital of a vast empire, it was also a city of perhaps a million inhabitants. Servicing such a population challenged the infrastructure of the day. A network of aqueducts and lead pipes distributed water from the Tiber River throughout the city. And the arrival of goods from the Mediterranean region was facilitated by the protected harbor of Portus, built around AD 112 at the mouth of the Tiber, 25 km from the city center.

Inspired by a 30-year-old hypothesis—though now largely discredited—that lead poisoning was responsible for the Roman Empire's demise, Hugo Delile, Francis Albarède (École Normale Supérieure de Lyon and Rice University), and colleagues measured lead isotope ratios of sediments in the Portus harbor.¹ From their data, the researchers not only estimated the level of lead in ancient Roman drinking water but also found evidence of changes in the aqueduct system's use and disuse over time.

Lead in the water

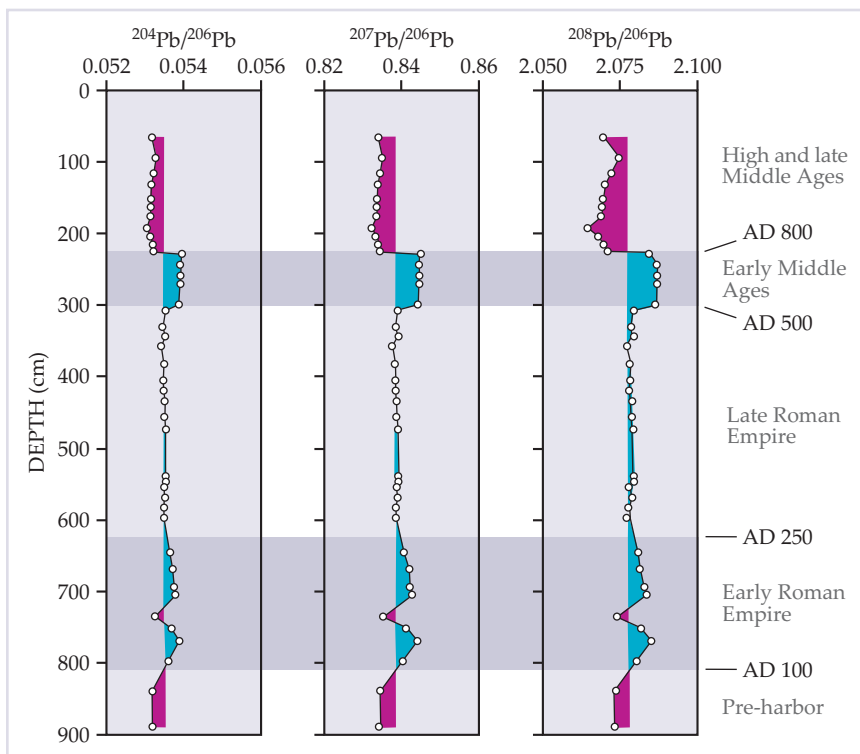
Three of the four stable isotopes of lead are radiogenic: Lead-206, lead-207, and lead-208 are the endpoints of the decay chains of uranium-238, uranium-235, and thorium-232, respectively. The relative abundance of those isotopes, and of the entirely primordial ²⁰⁴Pb, in a particular mining district depends on how much U and Th were originally present in the area. As a result, Pb isotope ratios can vary considerably from location to location. If the Pb used to build Rome's

water pipes was brought in from elsewhere in Europe, the Pb that leached out of the pipes would probably differ in isotopic composition from the Pb naturally present in Tiber River water.

Albarède and colleagues excavated two cores from different parts of the Portus harbor; the first 700–800 cm of each consisted of sediment deposited in the harbor over the past two millennia. Using carbon-14 dating of organic matter in the cores, they established the relationship between depth and age, accurate to within 100 years. Then they measured the Pb isotope ratios as a function of depth. As shown in the figure for one core, those ratios rose and fell in concert.

In fact, all of the Pb samples could be neatly characterized as a sum of two components: a natural component, corresponding to unpolluted river water, and an anthropogenic component. When the researchers sampled several surviving first- and second-century Roman water pipes, they found that their isotopic composition matched the anthropogenic component exactly. “That was a wonderful surprise,” says Albarède.

The pipes' isotopic composition shed some light on where the Pb might have come from. Similar isotope ratios have been found in Pb deposits in the British Isles, parts of modern-day France and Germany, and southwestern Spain. Notably, the pipes couldn't have come from southeastern Spain, near modern-day Cartagena, which had been a major mining center of the ancient world.



Lead isotopes in sediments from Portus, the harbor that served ancient Rome. Higher isotope ratios, shaded in blue, represent higher levels of anthropogenic Pb leached into the water from Rome's water pipes. The dates along the right edge of the figure are derived from radiocarbon dating of organic matter and are accurate to within 100 years. (Adapted from ref. 1.)

At the times of the highest Pb pollution—the early Roman Empire and early Middle Ages—the anthropogenic component accounted for between 50% and 75% of the Pb in the harbor water. At the height of the Roman Empire, an estimated 3% of the Tiber's flow was diverted through Rome's water distribution system; it follows that the water in the pipes had 40–100 times more lead than the unpolluted river water. Explains Albarède, “We concluded that although lead excesses were significant, they were unlikely to have created a major health issue in antique Rome.”

Decline and fall

Over the history of the harbor, anthropogenic Pb levels dropped, rose, and dropped again in a way that can be tentatively related to events in Roman history. The ultimate fall of the Roman Empire, as marked by the overthrow of the last emperor in AD 476, was preceded by a long period of decline, which may have included a drastic decrease in urban population and a deterioration of infrastructure. The exact trajectory of Rome's population during that period remains uncertain. But the gradual

decrease in anthropogenic Pb around AD 250 suggests that the water distribution system was falling into disuse.

In the middle of the sixth century, the Byzantine Empire conquered the short-lived Gothic kingdom that had replaced the Roman Empire on the Italian peninsula. Byzantine repairs of the Roman aqueducts have been historically documented, and they're consistent to within Albarède and colleagues' error bars with the spike in anthropogenic Pb around AD 500. The sharp drop in anthropogenic Pb around AD 800 could be related to the sack of Rome by Arab raiders in AD 846 or to major flooding in AD 856.

Geochemical analysis of more cores in more locations will help to refine the timeline and to link the data to recorded and unrecorded historical events. Albarède and colleagues are currently working on cores taken from the harbor of the ancient religious center of Ephesus, in modern-day Turkey (see *PHYSICS TODAY*, March 2014, page 24).

Johanna Miller

Reference

1. H. Delile et al., *Proc. Natl. Acad. Sci. USA* **111**, 6594 (2014).

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