they could run for tens of thousands of model years. For the first 200–800 years of each simulation, they introduced a thermal forcing in the ocean to drive melting at the coast. Then they removed the forcing and tracked the basin's evolution for the next 25 000 years. In some simulations, the basin collapsed; in others, it remained intact.

Comparing all their simulations, the pair found that the basin collapsed if and only if a specific chunk of ice—which they termed the "ice plug"—melted during the forcing period. If part or all of the plug remained intact, so did the basin. The plug has a mass of about 30 trillion tons, equivalent to about 80 mm of sea-level rise. "It's a lot of ice," says Levermann, but it pales in comparison to the whole basin—which could raise sea levels by 3 m or more—let alone all of East Antarctica.

Although the simulations required at least 200 years of forcing to melt the plug, there's no guarantee that it couldn't happen faster. If glacial melting altered ocean currents, the water temperature at the grounding line could rise by even more than the 2.5 °C that Mengel and Levermann used in their most extreme simulations. And their model didn't consider the possibility of calving, or ice breaking off in chunks, which could remove parts of the plug even faster.

The models of Thwaites and Pine Island Glaciers and the Wilkes Basin don't explicitly address the effect that those regions' collapse could have in destabilizing neighboring ice, but there must be some impact. As Levermann puts it, "You can't just have a hole in East Antarctica." The entire West Antarctic ice sheet has enough ice to raise sea levels by about 3 m; East Antarctica, more than 50 m. (About two-thirds of East Antarctic ice lies on bedrock above sea level, though, so it's less susceptible to instability.)

The coming sea-level rise will take many generations to play out. Levermann likens the situation to the consequences of nuclear waste: The harm is done on a similar time scale, and although sea-level rise is not as deadly, its effects will be global. Joughin asks, "Is it okay to trigger such an event and leave our great, great grandchildren to take the brunt of it?"

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Ultrafast electron diffraction from an ultracold source

Femtosecond electron bunches extracted from a laser-cooled gas cloud could become a powerful tool for macromolecular studies.

For decades, x-ray and electron diffraction have resolved the atomic-scale details of matter. Extending such techniques to the ultrafast time scales at which chemical reactions occur is a more recent achievement.[1] Thanks to recent advances in accelerator technology this past decade, x rays from free-electron lasers can now probe the structural dynamics of molecules at femtosecond resolution (see PHYSICS TODAY, April 2011, page 13, and for background on FELs the article by William Colson, Erik Johnson, Michael Kelley, and Alan Schwettman, PHYSICS TODAY, January 2002, page 35). And for the past few years, a handful of groups have been working to extend electron sources to that time regime as well—no big-machine physics required. The essential ingredients can all fit on a tabletop.

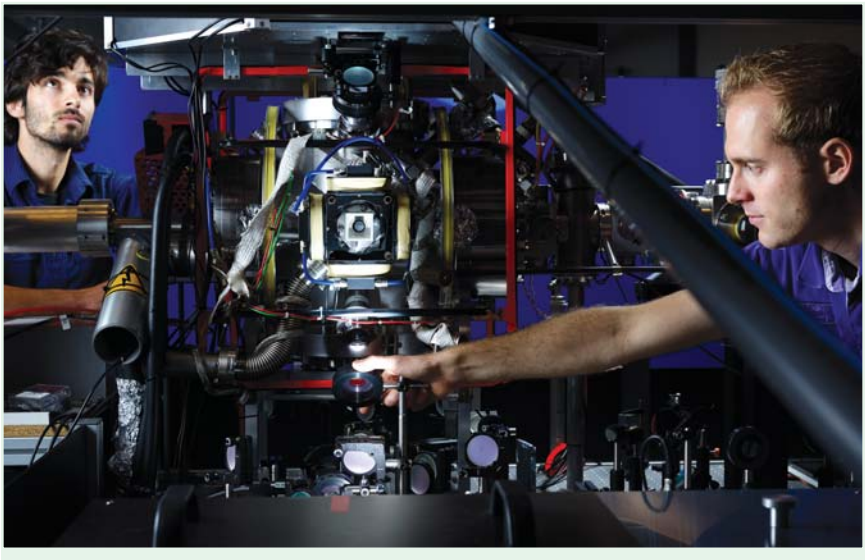
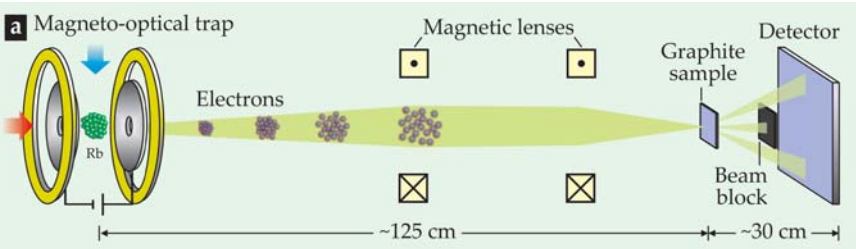


Figure 1. A magneto-optical trap (center) holds an ultracold gas of rubidium atoms that are ionized to generate a 100-fs pulse of electrons. Those electrons are then accelerated and travel to the right in a diffraction experiment. Doctoral students Martin van Mourik (left) and Peter Pasmans (right) adjust the setup. Cooling and trapping laser beams pass from an optical table (foreground) through the quarter-wave plate in Pasmans's hand, and ionization laser pulses are reflected into the trap after passing through the upward-directed black pipe. (Image courtesy of Bart van Overbeeke Fotografie.)

Unlike photons from a laser, though, electrons emitted from a photocathode don't usually hang together well: Thermal drift and Coulomb repulsion spread them apart. And the resulting transverse momentum spread—or, more precisely, its inverse multiplied by Planck's constant, a figure of merit known as the transverse coherence length—determines the sharpness of the Bragg peaks in any electron diffraction experiment.

In 2005 Jom Luiten and his colleagues from Eindhoven University of Technology in the Netherlands proposed a bold scheme to ameliorate the spreading without resorting to apertures, which sacrifice the brightness of a beam. The idea, which his and other groups later implemented, was to liberate bunches of electrons not from a



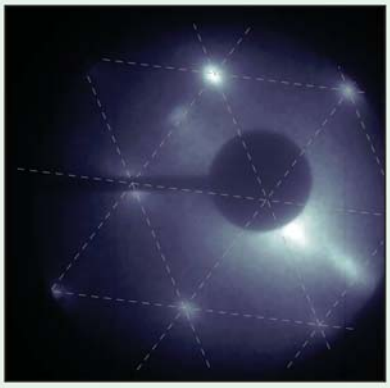


Figure 2. The diffraction experiment. Rubidium atoms in a magneto-optical trap **(a)** are ionized by two spatially and temporally overlapping laser pulses. A 780-nm pulse (red) excites the electrons and a second pulse (blue) at a wavelength of 480 nm or shorter raises a few hundred of them to the ionization threshold. The electron bunch is then accelerated downstream by a local electric field and focused, as shown by the green path, using magnetic lenses onto a 20-nm-thick graphite flake. **(b)** A diffraction pattern taken with 10-K electrons illustrates graphite's hexagonal lattice. Focusing the beam onto the sample enlarges the first-order Bragg peaks for clear comparison of experiments. (Adapted from ref. 3.)

photocathode but from a cloud of laser-cooled atoms held in a magneto-optical trap.[2] According to simulations, the atoms, when excited just above their ionization threshold, would emit electrons at temperatures as cold as 10 K. The coherence length, which scales inversely with the square root of temperature at low charge densities, would thus be more than an order of magnitude greater than that of electrons released at thousands of kelvin, the temperature typical of a photocathode.

After nearly a decade of exploring the properties of their ultracold electron source, the Eindhoven researchers have now put it to work: By adding magnetic lenses they projected a 100-Hz pulsed electron beam onto a thin graphite flake. The resulting diffraction patterns offer a proof-of-principle demonstration,[3] "an important technical step in our field," says the University of Melbourne's Robert Scholten. "Diffraction is ordinarily put in the service of revealing details about a poorly understood sample. But that procedure is here turned on its head: Diffraction patterns of a well-known crystal may reveal insights for optimizing a new and unusual source."

Spots and sizes

Preparing the electron beam is a multistep process. The Eindhoven researchers first load some 100 million rubidium atoms into the cold trap, shown in figure 1. To strip out electrons, they overlap two coincident laser beams—a red pulse that excites the atoms from a 5*s* to 5*p* hyperfine state and a 100-fs blue pulse that ionizes those excited atoms. The ionizing pulse imprints the electron bunch with its ultrashort duration and is tunable around a central wavelength. A local electrostatic field then accelerates the bunch downstream toward the graphite, about a meter away, as illustrated in figure 2a.

At first glance, one might expect the broad bandwidth of a 100-fs pulse to spoil the coherence because of hot electrons ejected by the shorter wavelengths. But last year Scholten's and Luiten's respective groups published independent accounts proving that wasn't the case.[4] The excess kinetic energy does not get redistributed evenly among all degrees of freedom but rather mostly contributes to the electrons' longitudinal motion. That's because the trap's applied electrostatic field, which pulls electrons downstream, also lowers, via the Stark shift, the atoms' ionization potential in that direction, effectively squeezing liberated electrons transversely at the expense of their longitudinal spread.

The combination of the applied field and the ionization laser pulse determines the kinetic-energy distribution of the released electrons, and thus their effective temperature. By varying the ionizing laser's wavelength in a series of runs,

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 effects and stepping up the brightness of an electron beam.

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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 ^{204}Pb, 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.