A New Twist for Electron Beams

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linear evolution is consistent with models for continental growth in which new continental crust is continuously generated along destructive plate margins (*1*, *10*). Relatively few zircons (<2%) plot between the depleted mantle and the new crust curves (*1*), which suggests that incorporation of preexisting crustal material into the mantle source of the pristine continental crust has been a long-standing feature, at least since the onset of plate tectonics and the development of supercontinents around 3.0 billion years ago (*11*).

Model ages calculated from the composition of the new crust are up to 300 million years younger than model ages traditionally calculated from the depleted mantle. As a result, new crust ages are generally more consistent with the geological record, which opens new perspectives in crustal evolution studies based on radiogenic isotopes.

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PHYSICS

A New Twist for Electron Beams

Rodney Arthur Herring

Passing an electron beam through carefully prepared holograms creates electron vortex beams that improve resolution and allow samples to be manipulated.

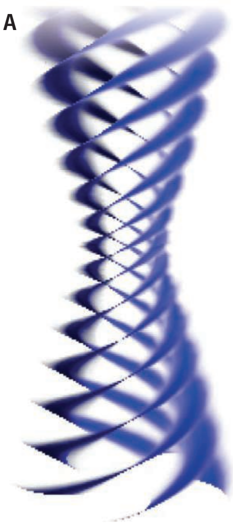
The transmission electron microscope (TEM) has primarily been used by physical and life scientists for imaging structures and compositions ranging in size from atoms to cells. New applications are likely to emerge from recent demonstrations that it is possible to change the nature of the primary electron source used to create images. Normally, an electron is emitted from its source in a TEM as a plane wave. However, as shown on page 192 of this issue by McMorran *et al*. (*1*) as well in recent studies by Verbeeck *et al*. (*2*), passing the electron plane wave through a hologram that contains a dislocation causes it to undergo diffraction and split into an electron vortex beam. This type of electron beam can be used to create higher-resolution images and to manipulate the structure and properties of the sample.

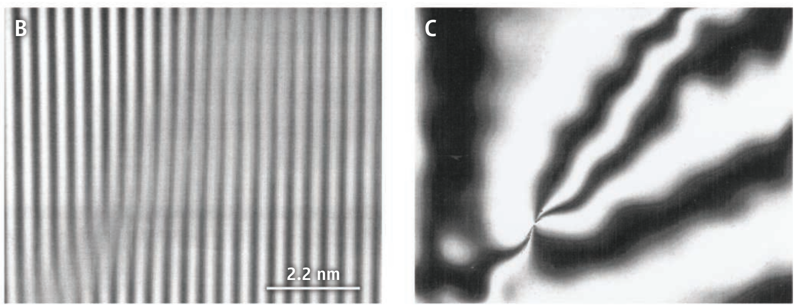
When an electron beam diffracts from these holograms, it has a singularity in the quantum mechanical phase along the center of the beam; the phase is not well defined. Interference effects cause the central beam intensity to vanish, creating instead a vortex of twisted beams spiraling around this node that passes through the microscope (see the figure, panel A). The absence of intensity at the beam center can be used to improve the resolution of the scanning mode of electron imaging, because resolution is determined by the beam's spot size, and the central beam is the most difficult to focus.

Another useful property of these vortex electron beams is that they have an associated orbital angular momentum (OAM). Like an ice dancer doing a spin, the spiraling wavefront of the electron vortex beam carries OAM. However, the electron beams are charged, so the OAM can couple with electrons, electrostatic charges, and magnetic potentials in the sample. Electron vortex beams could be used to induce currents in superconductors, apply magnetic fields at the nanoscale, and make or break electronic bonds. New types of electron beam lithography may enable the building of three-dimensional nanostructures in which atoms are picked up, moved, and set in place rapidly and accurately.

The singularity at the center of the electron vortex also has a topological charge of m that is a measure of the number of the twists per electron wavelength. Here, m increases with the higher-order diffracted beams and enables greater coupling with the atomic structures. The holograms are nanofabricated gratings with a dislocation where one or more lines are added to half of the grating. A dislocation core that adds one line (one grating line forks into two) produces $m = 1$ for the first diffracted beam, $m = 2$ for the second diffracted beam, and so forth. McMorran *et al*. created a hologram with 25 lines added at the dislocation that has $m = 25$ for the first diffracted beam, $m = 50$ for the second diffracted beam, and up to $m = 100$ for the fourth diffracted beam. However, this higher topological charge comes at a price—the intensity of the diffracted beam is lower, and may be too low for adequate coupling with some types of structures.

These limitations aside, an immediate application of electron vortex beams is to produce new types of communication and





Crystal defects underlie new microscopy tools. (**A**) Electron beams that pass through a hologram containing a dislocation form a vortex of diffracted beams. A simulation by McMorran *et al*. of a higher-order diffracted beam illustrates the helical structure of the wavefronts. (**B**) A hologram is created from a GaAs crystal bearing a dislocation by the interference of the 000 beam (a plane wave) with a diffracted beam (an electron vortex beam) (*6*). (**C**) The reconstructed phase image of the hologram (amplified by a factor of 8) shows a singularity at the position of the dislocation core.

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memory devices at the nanoscale (for example, altering spin states for memory applications). For imaging, the spiral phase of their wavefront will enhance phase contrast microscopy of the edges of samples with low absorption contrast, such as unstained biological specimens, macromolecules, carbon nanotubes, and polymers. For analytical microscopy, electron vortex beams will provide new capabilities for electron energy loss spectroscopy, which can provide information about atomic composition. For structural microscopy, they will provide new crystallographic information of the specimen in the electron diffraction mode. For measurements of the specimen properties, they will provide new optical, electronic, and magnetic information.

The development of these electron vortex beams builds on a number of previous observations. First, it was realized that linearly polarized light beams carry OAM (*3*). Soon thereafter, the trapping and rotation of particles in the vortex produced by diffraction from a hologram containing a dislocation was demonstrated (*4*). The rotation could be reversed by changing the sign of the OAM, either by turning over the hologram or by using the opposite of diffracted beams from the hologram that rotate in the opposite direction. The same method was proposed for electrons in which the hologram consisted of a very thin crystal with a dislocation (*5*). The thin grating provided by a crystal's atomic planes separate the electron vortex beams because the wavelength of high-energy electrons is small, only a few picometers.

A few years ago, Uchida proposed an experiment to my group in which a strained gallium arsenide (GaAs) crystal containing dislocations would be used to create holograms. This kind of experiment had previously been shown possible by diffracted beam holography (see the figure, panels B and C) (*6*). We performed the experiment with Koh Saitoh and his group at Nagoya University but failed in recording the images. However, Uchida and Tonomura (*7*) proved the concept using a stacked, thin film of graphite flakes that produced a semihelical electron vortex beam.

Using helical-phase plates poses several challenges. They are difficult to fabricate with nanometer precision, they create unwanted internal Bragg and diffuse scattering of the electron beam, and surface contamination distorts their shape. Verbeeck *et al*. (*3*) and McMorran *et al.* came closer to Uchida's proposed crystal hologram by exploiting fabrication of defect holograms with focused ion beam (FIB) methods. A drawback of FIB-made holograms is their coarse grating relative to that of atomic planes, which results in shallower angles of diffraction of the electron vortex beams. However, an advantage that is not available with the crystal hologram is the production of dislocation cores having multiple half gratings. These structures induce large topological charges, as shown by McMorran *et al*.

Researchers should rapidly exploit the new capabilities of electron vortex beams. They are simple to implement, requiring merely the insertion of a dislocated hologram into the condenser aperture of the electron microscope. This capability should enable researchers to image in new ways, make new types of measurements, and manipulate the electrons and atoms in material in a manner never before possible.

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PALEOCLIMATE

Northern Meltwater Pulses, CO_2, and Changes in Atlantic Convection

Detailed evidence of how the North Atlantic Meridional Overturning Circulation behaved after the last ice age.

Michael Sarnthein

Global climatic and oceanic conditions underwent fundamental transformations after the last ice age ended about 19,000 years ago. In the North Atlantic, for example, the deglaciation was marked by major changes in the Meridional Overturning Circulation (MOC), which carries warm and highly saline surface water north to cooler regions, where it sinks and creates "deep water" that eventually cycles back to the surface. This process plays a substantial role in regulating climate and levels of atmospheric carbon dioxide (CO_2), and understanding how it operated in the past is important to understanding how it may influence climate in the future. On page 202 of this issue, Thornalley *et al*. (*1*) provide impressive and detailed evidence of how the North Atlantic MOC behaved after the Last Glacial Maximum (LGM), between 19,000 and 10,000 years ago. In particular, they show that the MOC experienced a series of abrupt changes that lasted from decades to centuries, and that some of the water masses involved were far older—and may have stored and released more carbon—than once believed.

Thornalley *et al*.'s findings are based primarily on measurements of the ratio of carbon-14 to carbon-12 ($^{14}C/^{12}C$) in the shells of small marine organisms, called foraminifera, obtained from four marine sediment cores collected south of Iceland in waters between 1200 and 2300 m deep. These isotopic measurements, together with data from Greenland ice cores (*2*) that helped calibrate the ages of the cores, enabled the authors to reconstruct the apparent "ventilation age" of the water masses in which the foraminifera once lived, or roughly how long it had been since the water was near the surface and in equilibrium with the atmosphere. In addition, the authors used another isotopic signature, the ratio of carbon-13 to carbon-12 ($\delta^{13}C$) in benthic (bottom-dwelling) foraminifera, to help reveal the different histories of masses of deep and intermediate water.

Today, intensive convection in the North Atlantic quickly transfers surface waters to depth, and newly formed deep water typi-

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