

Martin, Cantalupo, and their coworkers identified the newly found filament as a perfect target for the CWI. “We knew it would be interesting and bright enough to say a lot about,” says Martin. They were right: Attached to the filament was a giant protogalactic disk, 400 000 light-years across.

The disk and filament are shown in figure 2 with the positions of QSO UM287 marked A, another nearby quasar marked B, and two star-forming regions within the disk marked C and D. By analyzing how the redshifts vary along the disk, the group deduced that the disk is rotating. They then fit the protogalaxy’s velocity profile to a rotating disk model and obtained good agreement with a gas disk embedded in a dark-matter halo of some 10^{13} solar masses.

The researchers also ran computer simulations, with the disk’s thickness and brightness as inputs, to estimate the protogalaxy’s baryonic mass. Baryons, the stuff of conventional matter, make up only about 1% of the protogalaxy—well below the cosmic average baryon component of 17%. Apparently, suggest Martin and company, the baryons have lagged behind the collapse of the dark-matter halo and will continue to accrete in the future.

Cold flow

The velocity of the gas in the extended filament is constant and matches that of the upper end of the disk where the two meet. The astronomers speculate that gas flowing down the filament imparts angular momentum to the disk, consistent with the so-called cold-flow model of galaxy formation. Martin likens the filament to a hose streaming water into one side of a circular tub. “The water will spiral down into the drain,” he explains. The group’s modeling indicates a gas temperature of about 30 000 K, much cooler than the plasma of the dark-matter halo and again consistent with the cold-flow model.

The standard model of galaxy formation posits that when a dark-matter halo collapses gravitationally, the conventional matter embedded in the halo heats to high temperatures and then slowly cools to form stars. Any additional gas that falls into the nascent galaxy would also be shock heated to high temperatures. In that picture, galaxies formed slowly in the early universe.

In the alternative cold-flow model, cool gas ready for star formation flows directly from filaments of the cosmic web into galaxies, as seen in figure 3. That scenario has galaxies build up rap-



Figure 3. A snapshot from a cosmological simulation shows relatively cool gas flowing into two rotating protogalactic disks (magenta) from filaments (gray-green) of the cosmic web. Hot ionized gas at temperatures greater than 10^6 K is shown in red. (Courtesy of Philip Hopkins/Caltech.)

idly from large gas disks connected to the cosmic web, much like the one discovered by Martin, Cantalupo, and their colleagues. (See the article by Jeremiah Ostriker and Thorsten Naab, *PHYSICS TODAY*, August 2012, page 43.)

An intrigued Jason Tumlinson of the Space Telescope Science Institute explains that hydrodynamic simulations of galaxy formation show such filamentary inflows of cool gas. He adds, “Detecting them has been a key goal. This one looks filamentary and looks real.”

Martin and his colleagues have considered alternative interpretations of their data—for example, as arising from a galactic merger involving one or both quasars (A and B in figure 2) in the neighborhood. But given the distance between the disk and QSO UM287 (at least 32 000 light-years), the large size of the disk, and the lack of any signs of tidal disruptions, they say those explanations are unlikely.

Tumlinson says the new results are just as interesting for demonstrating a new technique for observing the intergalactic medium. “It’s a pretty heroic measurement,” he remarks. Martin and coworkers are already busy surveying other quasars in search of more giant protogalactic disks.

In addition, the Caltech group is commissioning an improved version of the CWI at the Keck Observatory. And a similar instrument, the Multi Unit Spectroscopic Explorer, is being tested on the European Southern Observatory’s Very Large Telescope. Both new instruments are set to make similar observations but on telescopes larger than the one on Mount Palomar.

Sung Chang

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Freestanding solids get stretched

Engineering a phase transformation to proceed in just the right way creates a material that’s permanently under tension.

Negative absolute pressures, though much investigated in liquids (see *PHYSICS TODAY*, January 2011, page 14), have been thought to be impossible to sustain in solids. Informally, materials under negative pressure are said to be under tension. But more specifically, that tension must be isotropic; thin films produced by strain-engineering techniques that stretch them in just one or two dimensions, though useful, don’t qualify.

Now Nava Setter (Swiss Federal Institute of Technology, Lausanne), her former student Jin Wang (currently an

assistant professor at the Tsinghua University Graduate School at Shenzhen, China), and their colleagues have developed a method to create freestanding crystalline nanomaterials stretched in all three dimensions.¹ The researchers synthesized lead titanate nanowires in the material’s so-called PX phase—a low-density, metastable crystal structure shown in figure 1a—and induced them to transform into the denser, stable perovskite phase shown in figure 1b. Because of the dynamics of that transformation, the perovskite nanowires form with their surfaces under positive

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"A clever trick"

The discovery was serendipitous. Setter's research centers on ferroelectrics: materials that spontaneously acquire a bulk electric polarization when cooled below a certain critical temperature. All ferroelectrics are necessarily both piezoelectric and pyroelectric—that is, the polarization is responsive to both pressure and temperature—so their applications include ultrasound transducers, actuators, and temperature sensors.

Wang's PhD work, conducted in the late 2000s, was on nanowires of lead zirconate titanate ($\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$, or PZT), one of the most important classes of ferroelectrics, of which perovskite-phase PbTiO_3 is a member. He wanted to investigate size effects: whether ferroelectric behavior differed in nanowires of different thicknesses. In the course of those experiments, he and Setter noticed some unusual phenomena, including spherical nanopores marring many of the wires. "At the time, we were disappointed," says Wang, "because it seemed like an imperfection in the sample." Amazingly, though, the "imperfect" wires showed enhanced ferroelectric properties: sharply higher transition temperatures and dramatically stronger spontaneous polarization.

Over the following years, the negative-pressure picture gradually emerged. The transformation from the PX phase to the perovskite phase is initiated by catalytic oxygen—O atoms absorbed from the environment and released when the transformation is

complete—so it must begin at the wire's surface. As the structural change works its way inward, the outer layer forms a rigid high-density shell around the remaining PX-phase nanowire. That shell encloses a volume 13% greater than the perovskite nanowire would normally fill.

Some of that excess volume is taken up by nanopores; the rest produces tensile stress of up to a few gigapascals. As the cross-sectional images in figure 2a show, the size and number of the pores depend on the wire's diameter; as the numerical simulations in figure 2b show, so does the magnitude of the negative pressure at the wire's center. For diameters greater than 500 nm, the tension becomes too strong for the material to accommodate and the wires crack.

The enhanced ferroelectric properties are consistent with a 2003 theoretical prediction.² Spontaneous polarization arises when a ferroelectric's metal ions break the lattice's inversion symmetry by moving away from the centers of the O-ion cages that contain them. Stretching the material enlarges the cages and gives the ions more room to move. "In the theory community we've often joked about improving properties using negative pressure," says Nicola Spaldin of ETH Zürich. "It's easy for us to do on the computer, but we never imagined such a clever trick for achieving it in reality."

The trick is not limited to PbTiO_3 . Setter, Wang, and colleagues have already found that it works for some other materials in the PZT family and are working to extend it to other ferroelectrics. Perovskite materials—anything with the chemical formula ABX_3 and the ground-state crystal structure shown in

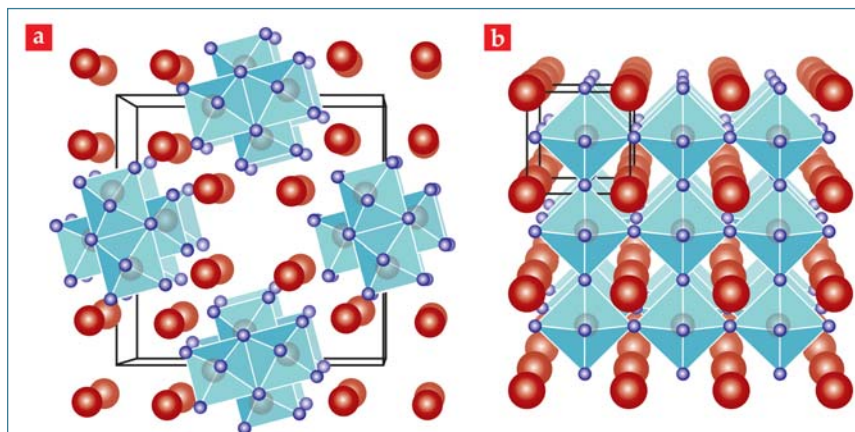


Figure 1. Crystal structures of lead titanate. (a) The PX phase is metastable and low density. **(b)** The perovskite phase, the material's ground-state structure, is 13% denser than the PX phase. Lead atoms are shown in red, oxygen in dark blue, and titanium inside the semitransparent light-blue octahedra. Unit cells are shown in black. (Adapted from ref. 1.)

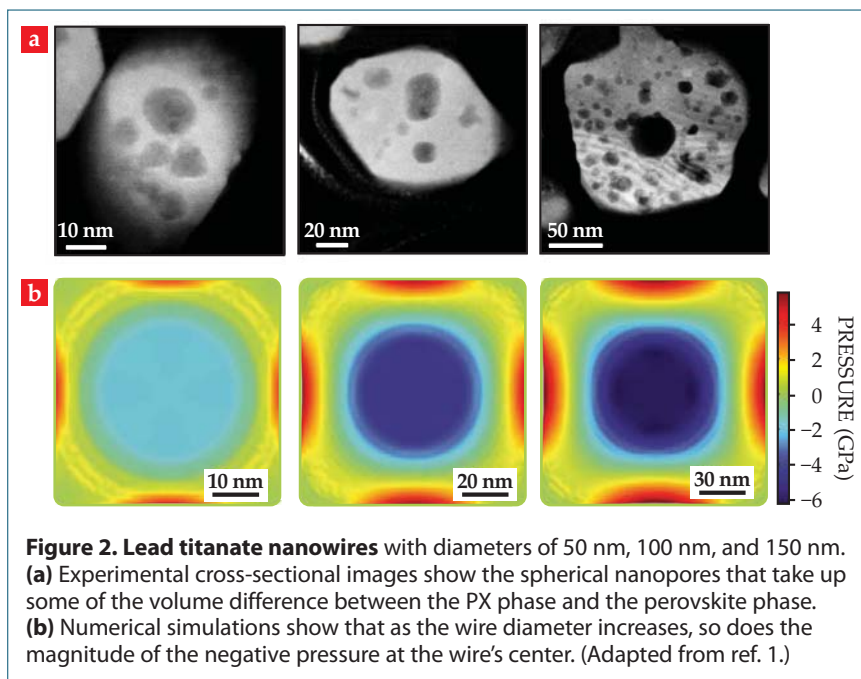


Figure 2. Lead titanate nanowires with diameters of 50 nm, 100 nm, and 150 nm. (a) Experimental cross-sectional images show the spherical nanopores that take up some of the volume difference between the PX phase and the perovskite phase. (b) Numerical simulations show that as the wire diameter increases, so does the magnitude of the negative pressure at the wire's center. (Adapted from ref. 1.)

figure 1b—are numerous and abundant, their applications are diverse, and many have low-density metastable phases similar to the PX structure. Setter speculates that many nonperovskite materials could also be made to undergo density-increasing transformations that start at the surface and proceed inward—and that extending the negative-pressure technique to different materials could enhance useful properties in ways theorists haven't yet explored.

Indeed, a similar method is already widely used to make tempered glass. Rapidly cooling a piece of hot glass causes it to contract to produce a material whose surface is under compression and whose core is under tension. Those stresses are responsible for tem-

pered glass's advantageous mechanical properties, including fracture toughness and shattering behavior.

Although Setter, Wang, and company's individual PbTiO_3 nanowires are tiny, the total quantity of material can readily be upscaled. The PX-phase wires are easy to make, and the conversion to perovskite is as simple as heating the wires in air. "I foresee bulk applications" for negative-pressure nanomaterials, says Setter, "in powder form, as paints, or as composites."

Johanna Miller

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The universal statistics of random searches

The time it takes a random walker to find all the targets in a given domain can be determined from the average time it takes to find just one of them.

How efficient can an exhaustive search be? Whether the goal is to locate every mushroom in a forest, say, or specific sequences on a DNA strand, the cover time τ —defined as the time it takes for a random walk to find all the targets in a spatial network—can quantifiably answer that question. But despite τ 's relevance to a broad range of situations, from animals foraging for

food to diseases spreading through a city, analytical results have been scarce and mostly limited to regular random walks—those involving moves between nearest neighbors in Euclidean geometry.

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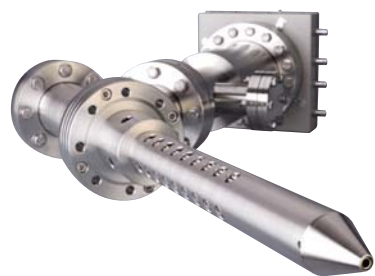
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