

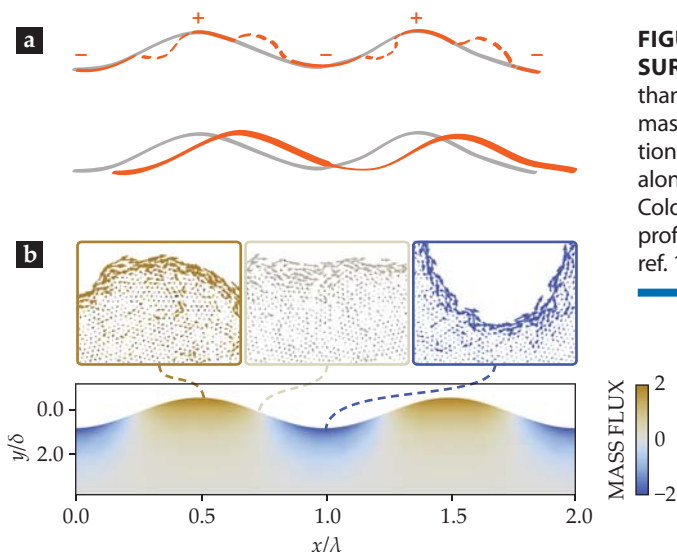


FIGURE 3. SURFACE WAVES PROPAGATE ON A CHIRAL FLUID'S FREE SURFACE. (a) In the presence of viscosity, fluid from regions with higher-than-average mass flux (+) gets pumped into regions with lower-than-average mass flux (-). The process propagates waves in the direction of particle rotation. **(b)** A sinusoidal perturbation (wavelength λ) generates a net mass flux along the fluid's free surface (height y , in an edge current of average depth δ). Color intensity indicates the relative strength of the flow. The inset velocity profiles show the microscopic origin of the mass flux variation. (Adapted from ref. 1.)

ward the flat wavefront; that motion leads to unidirectional wave motion. However, unlike the sand dune analogy, the surface motion is not an external force but a property intrinsic to the chiral fluid. The researchers dubbed the mechanism "edge-pumping."

That's odd

Surface waves in most fluids lose energy to their surroundings through viscous damping, which diminishes the waves' motion and flattens the fluid's surface. For the colloidal chiral fluid on the glass substrate, however, the observed damping rate resulted from the competition between surface tension and substrate friction. Surface tension flattens any curves, and substrate friction restricts any movement of the material.

To find out how damping arises when substrate friction is reduced, Soni, Bililign, and Magkiriadou placed droplets of the colloid suspension on an air-water inter-

face. The lower-friction situations also sustained surface waves. However, those waves did not flatten according to the equations that described their glass-substrate counterparts—the measured damping rates could no longer be explained by surface tension alone.

The researchers found their answer in a phenomenon called odd or Hall viscosity, a term coined in 1998 by Joseph Avron.³ Odd viscosity can be understood by decomposing the edge-current velocity into its tangential and perpendicular components.⁴ Whereas shear viscosity is a stress that acts on a fluid in the same direction as the flow, odd viscosity is a stress that acts on a fluid orthogonally to the direction of the flow. In the case of a chiral fluid, the odd viscosity gives rise to a flow perpendicular to an applied pressure and thus, perhaps counterintuitively, does not dissipate energy.

In Irvine's lab, the odd viscosity flattened the chiral fluid's surface waves in a manner similar to surface tension. For the glass substrate, damping could be fully accounted for with a zero value of odd viscosity. For the air-water interface, the magnitude of the odd viscosity was of the same order as the shear viscosity.

Although researchers at Leiden University had demonstrated in 1966 that odd viscosity could exist in a magnetized gas⁵ and researchers at the University of Manchester recently reported odd viscosity in a 2D electron gas,⁶ Irvine and colleagues have now provided the first measurement of it in a chiral fluid.

Thomas Powers, a physicist at Brown University, says, "The field of active matter is still a little theory and computation heavy, and there aren't that many clean experimental systems. This is a nice one with relatively new features." The chiral fluid provides the first platform for probing and designing materials with properties that arise from uniformly spinning particles. The model system could also help predict behaviors that may emerge in some plasmas or in charge carriers in 2D electronic materials.

Rachel Berkowitz

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Superconductivity is found in a nickel oxide

A long-sought structural and electronic analogue of the cuprate superconductors has finally been synthesized.

In 1986 Georg Bednorz and Alex Müller discovered superconductivity in an oxide of lanthanum, barium, and copper— $\text{La}_{1.85}\text{Ba}_{0.15}\text{CuO}_4$. The achievement won the researchers a Nobel Prize the following year (see PHYSICS TODAY, December 1987, page 17) and triggered an explo-

sion of research in condensed-matter physics. Although that oxide superconducts below a relatively low 30 K, the transition temperatures T_c of subsequent cuprates exceed those of any previously known superconductor by almost an order of magnitude. Yet despite 33 years of research since then, no consensus has emerged as to what causes their superconductivity.

Prospects appear brighter now that a new family of cuprate-like superconduct-

tors has been realized. Harold Hwang, his postdoc Danfeng Li, and their colleagues at SLAC and Stanford University have successfully synthesized neodymium strontium nickel oxide, $\text{Nd}_{0.8}\text{Sr}_{0.2}\text{NiO}_2$, which superconducts below 15 K.¹

Hwang's group did not stumble on the superconducting nickelates purely by serendipity. Rather, their quest was inspired by a theoretical prediction that was in turn informed by what experimenters and theorists have learned about cuprates

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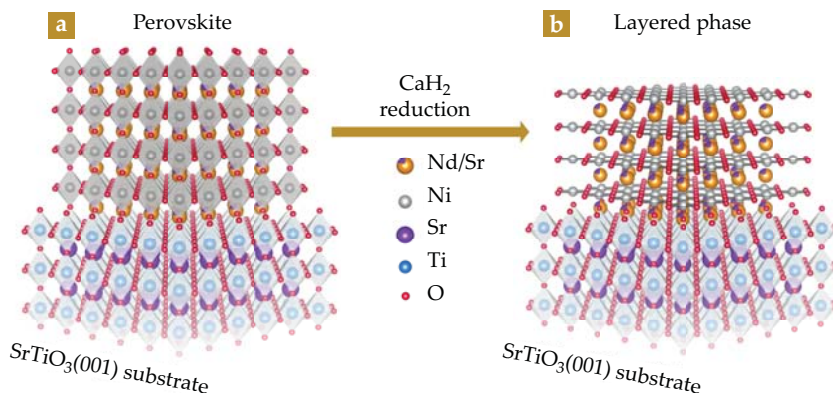


FIGURE 1. CHEMICAL TRANSFORMATION from a three-dimensional perovskite to a 2D layered phase. (a) The formation of superconducting $\text{Nd}_{0.8}\text{Sr}_{0.2}\text{NiO}_2$ starts with an epitaxially grown crystal of $\text{Nd}_{0.8}\text{Sr}_{0.2}\text{NiO}_3$ on a strontium titanate (SrTiO_3) substrate. (b) That phase is then reduced using calcium hydride, which strips off one-third of the oxygens to leave NiO_2 planes separated by a network of neodymium and strontium atoms. (Adapted from ref. 1.)

over the years. Despite their different chemistry, near the Fermi level Ni and Cu have an apparently similar electronic structure, which is dominated by a single $d_{x^2-y^2}$ orbital. The differences of detail between the families should shed light on the origins of superconductivity.

Mott insulators

At room temperature the cuprates are such poor conductors that they barely qualify as metals. Their stacks of closely spaced CuO_2 planes are separated by charge reservoirs. Each unit cell in the CuO_2 plane has an odd number of electrons, and their states are so well localized that it takes a large amount of energy for an electron to hop from one lattice site to another. Indeed, the cuprates are materials whose single-particle band structure tells you should be metals but are, in fact, Mott insulators because of electron-electron repulsion that creates a traffic jam.²

The magnetic moments of the material's nearly filled $\text{Cu}^{2+} 3d^9$ shell arrange themselves in a two-dimensional checkerboard with strong antiferromagnetic interactions between neighboring spin- $\frac{1}{2}$ Cu ions, each separated by an O ion. The usual approach to studying the cuprates' peculiar superconductivity is to modify the charge-carrier concentration in the CuO_2 planes through chemical doping. (For instance, one could introduce holes by substituting Ba^{2+} for La^{3+} .) Hole doping suppresses the antiferromagnetic order, and superconductivity sets in at a critical doping concentration.

Soon after the cuprates were discovered, Princeton University's Philip An-

derson argued that their superconductivity is somehow inherited from the properties of a doped Mott insulator. One strategy for gaining further insight was to look for superconductivity in solids that incorporate similar structural, magnetic, and electronic features—a 2D lattice, spin- $\frac{1}{2}$ ions, and d - and p -orbital hybridization among them. Replacing Cu with another transition metal was an obvious path.³ Nickel sits next to Cu in the periodic table, and theorists Vladimir Anisimov, Danil Bukhvalov, and Maurice Rice predicted in 1999 that if Ni could be synthesized in the unusual +1 oxidation state in a lanthanum nickelate lattice, it would have the same electronic configuration as Cu^{2+} in the cuprates.⁴ Each would have a single hole in its $3d$ shell.

By partially substituting strontium for neodymium in NdNiO_2 , Hwang's group finally found a superconducting analogue. Although the transition temperature of 15 K is meager by cuprate standards, the achievement has generated enormous enthusiasm. Just four weeks after the researchers' publication,¹ more than a dozen theory papers had appeared on arXiv.org.

Long time coming

Several groups have made LaNiO_2 compounds as powders and thin films. The first synthesis was done in the early 1980s, before Bednorz and Müller's award-winning cuprate work. Nickelates ordinarily prefer an octahedral coordination—a network of Ni atoms surrounded by four oxygens in one plane and two "apical" oxygens above and below it. In

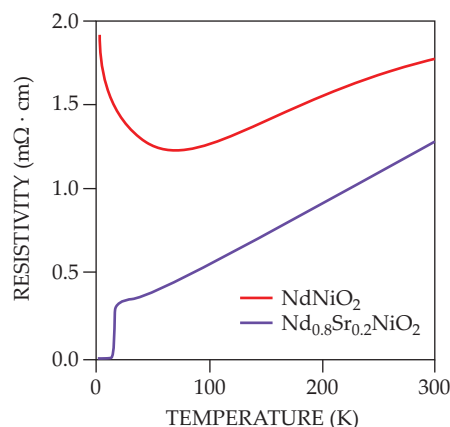


FIGURE 2. UNDOPED NEODYMIUM NICKELATE (red) exhibits metallic temperature dependence at high temperature, with a resistive upturn below 70 K. By contrast, strontium-doped nickelate (blue) behaves like a metal down to a superconducting transition that begins at 15 K and drops to zero resistance at 9 K. (Adapted from ref. 1.)

1983 chemists Michel Crespin, Pierre Levitz, and Lucien Gatinéau realized they could start with that phase—a 3D perovskite LaNiO_3 —and expose it to hydrogen gas to reduce it into LaNiO_2 with a 2D planar geometry.⁵

In the perovskite phase, planes of LaO alternate with those of NiO_2 . Reducing the perovskite strips out about a third of the oxygens (the apicals) while leaving the NiO_2 framework, whose planes are then separated only by La atoms. The layered structure (LaNiO_2) that remains has both the square-planar geometry and a transition-metal oxidation state present in the cuprates.

The 1983 synthesis and most others that followed produced polycrystalline powders. The large surface-to-volume ratios and random orientations of the crystals complicated the reduction chemistry: Reactions sometimes introduced Ni-metal inclusions and other defects or led to decomposition. A major step forward was to replace H_2 gas with a metal-hydride reducing agent, which turned out to be safer and more reliable.⁶ But it wasn't until 2009 that Kyoto University's Masanori Kawai and coworkers epitaxially grew the reduced planar structure as a single-crystal thin film.⁷ With the film grown on a strontium titanite (SrTiO_3) substrate, the reactions became more tractable.

Hwang, Li, and their colleagues used the Kyoto group's recipe as a springboard. They improved it in key ways: First, they swapped out La for Nd to make the material more conductive. Nd ions are smaller than La ions, and they shrink the nickelate's in-plane lattice constant. The Stanford group also chemically doped the starting perovskite material with holes by substituting 20% of the Nd^{3+} ions with Sr^{2+} . Earlier groups had doped the nickelate or reduced it, but not both. (An unpublished account of a doped, reduced sample was re-

ported in Oxford University chemist Mike Hayward's 1999 thesis, but no superconductivity was reported.)

The sequence also mattered. Only after the group had grown the Sr-doped NdNiO_3 lattice at the high temperature—600 °C—needed for it to crystallize atop SrTiO_3 did they reduce it. That step took place at a much lower temperature, 280 °C, and produced the layered phase shown in figure 1. The resulting samples measure $2.5 \times 5 \text{ mm}^2$.

In search of a mechanism

Resistivity measurements of the doped nickelate revealed a superconducting transition, shown in figure 2. But establishing superconductivity is just the start. Although the nickelate's lattice matches that of the SrTiO_3 substrate, the reduction process compresses the material. As Hwang points out, he and his colleagues faced the unusual situation in which the substrate that stabilizes the growth of the nickelate also strains it. Straining a superconductor's lattice, either by applying pressure or substituting atoms of a different size, often changes T_c .

The Stanford team has yet to fully optimize the growth parameters and doping levels. X-ray diffraction revealed that if the precursor compound is reduced for too long a time or at too high a temperature, the film decomposes and diffraction peaks disappear. "The superconducting phase appears stable," says Hwang, "but only if not pushed beyond the sought-after Ni^{1+} oxidation state."

Studying the differences between cuprate and nickelate superconductors could provide needed clues to the mechanism of unconventional superconductivity. According to the Bardeen-Cooper-Schrieffer theory of the late 1950s, lattice phonons mediate the Cooper pairing of electrons in conventional noncuprate superconductors such as aluminum or lead. But that interaction is thought to be too weak for Cooper pairs to survive much above 30 K at ambient pressures.

And whereas conventional superconductors have isotropic, s -wave symmetry, the superconducting wavefunction in the cuprates has d -wave symmetry—that is, it changes sign upon rotation by 90°. Many theorists now believe that the emergence of Cooper pairs in the vicinity of magnetism and other forms of electronic order is central to the cuprates' unconventional superconductivity.²

Once one starts doping a cuprate, the charge carriers delocalize because of hybridization between Cu $3d$ and O $2p$ orbitals. But what prompts the material at some critical doping to superconduct remains unknown. A magnetic origin for the pairing mechanism could arise from so-called superexchange, in which spin fluctuations in the antiferromagnetic interactions between neighboring Cu sites are mediated by O atoms that separate the Cu atoms.

In the cuprates, the energy of the Cu $d_{x^2-y^2}$ orbital is nearly degenerate with that of the O $2p$ orbitals, which makes the hybridization—and thus the spin fluctuations—particularly strong. By contrast, the energy levels of Ni and O orbitals are much different, which weakens the spin fluctuations. Indeed, according to neutron-diffraction studies, no sign of magnetic order appears in NdNiO_2 down to 1.7 K.

What should researchers make of the fact that superconductivity has now been found in a compound whose spin fluctuations may be so far less pronounced than in the cuprates? Answering that question will likely require answering others. For example, what happens at various levels of hole doping and on various substrates? And what is the role of rare-earth $5d$ electrons? Some theories advocate that they screen the Ni $3d$ spins—perhaps explaining why magnetism is suppressed.

Mark Wilson

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