

and letting the particle fall. With the current setup, a freely falling wavepacket would have time to expand by only a factor of three before it decohered. Lowering the pressure to 10^{-11} mbar and the surrounding temperature below 130 K would preserve coherence for long enough, about 10 ms, for the wavepacket to expand to a size on the order of the particle radius.

Aspelmeyer's long-term vision is to apply his technique to particles that are large enough to produce a measurable gravitational field. In that regime, questions about how the gravitational field looks for an expanded wavepacket can be answered. But Aspelmeyer says those experiments are still a decade or two away.

Heather M. Hill

References

1. U. Delić et al., *Science* **367**, 892 (2020).
2. P. Horak et al., *Phys. Rev. Lett.* **79**, 4974 (1997); V. Vuletić, S. Chu, *Phys. Rev. Lett.* **84**, 3787 (2000).
3. U. Delić et al., *Phys. Rev. Lett.* **122**, 123602 (2019); D. Windey et al., *Phys. Rev. Lett.* **122**, 123601 (2019).
4. F. Tebbenjohanns et al., *Phys. Rev. Lett.* **124**, 013603 (2020).

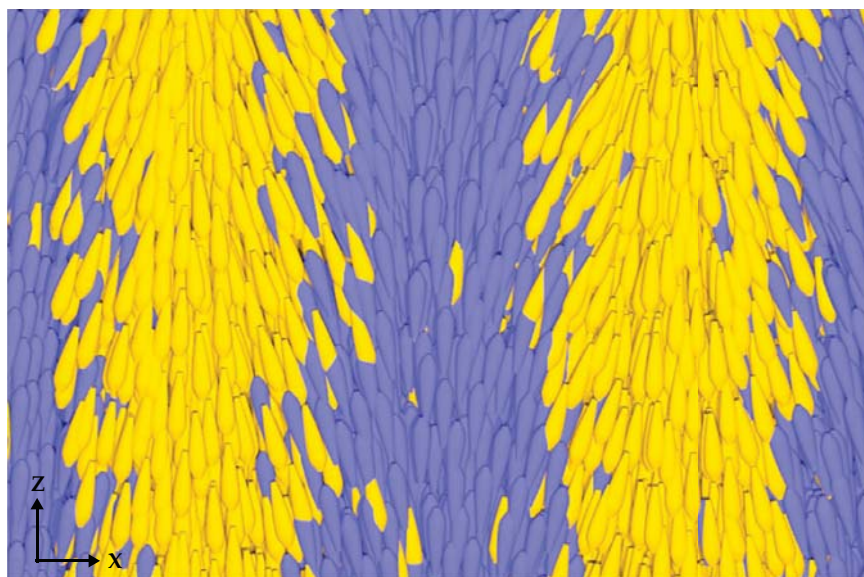
A novel liquid-crystal phase is ferroelectric

Molecular dipoles in a liquid don't usually spontaneously align. The secret to getting them to do so may be the molecules' shape.

Three years ago chemist Richard Mandle and colleagues at the University of York in the UK published a surprising observation.¹ They'd created a new organic molecule, now known as RM734. Because of its elongated shape and large electric dipole moment, they thought it might be useful in liquid-crystal applications.

Cooling a hot sample of RM734 molecules below 188 °C transformed it, as expected, from an ordinary isotropic liquid into a nematic liquid-crystal phase, characterized by its orientational order without positional order. But as the researchers cooled the liquid further and monitored its heat capacity, they saw the clear signature of a second phase transition, at 133 °C, that they were unable to explain. Above and below the transition temperature, the material looked exactly the same.

Now, in collaboration with Mandle and others, physicists Nerea Sebastián and Alenka Mertelj, both at the Jožef Stefan Institute in Ljubljana, Slovenia, have figured out what's going on.^{2,3} Through a combination of measurements, they found that the high-temperature phase is indeed the usual uniform nematic one, in which the asymmetric elongated molecules all align along, say, the z-axis, but with a homogeneous mix of molecules pointing in the +z and -z directions. The lower-temperature phase, however, is something that had never been seen before: It comprises a series of stripes, as shown schematically in yellow and blue



in figure 1, of +z- and -z-oriented molecules, respectively.

Because the RM734 molecules are slightly wedge shaped—a bit wider at one end than the other—the stripes are also splayed in alternating directions. And they're surprisingly wide, at several microns, or thousands of times the width of a single molecule.

Long molecules with large electric dipole moments, like RM734, don't usually seek out such parallel, ferroelectric arrangements in the liquid phase. Rather, they energetically prefer to form antiparallel pairs. So as useful as a ferroelectric liquid might be—its spontaneous polarization could enable molecular orientations to be switched quickly and with low power—ferroelectricity in liquid crystals has until now been limited to smectic phases, which, because of their partial positional order, aren't fully fluid.

It's not yet clear exactly what makes RM734 different. The researchers are still

FIGURE 1. THE SPLAY NEMATIC PHASE in a liquid crystal is made up of polar wedge-shaped molecules. Aligned along the z-axis, the molecules segregate into slightly splayed stripes of molecules with their narrower end pointing toward +z (yellow) and -z (blue). (Adapted from ref. 2.)

working to get a handle on which specific molecular features give rise to the ferroelectric phase, in the hope of being able to tune properties such as the stripe width and the transition temperature. But from what they've seen so far, they've concluded that a subtle interplay is at work between the molecule's charge distribution and its shape. Apparently, neither one alone is enough to produce the unusual molecular arrangement, but together they are.

Bend and splay

The polarity-shape interaction is related to the flexoelectric effect, a phenomenon

first described in liquid crystals by Robert Meyer half a century ago.⁴ Similar to the piezoelectric effect in solids, in which mechanical strain produces an electric potential or vice versa, the flexoelectric effect is the coupling between an electric potential and a strain gradient.

Figure 2 illustrates two ways it can work. The top panel shows a liquid crystal of banana-shaped molecules with electric dipole moments perpendicular to the molecular length. In the normal nematic phase, shown on the left, all the molecules align horizontally, but with the dipole moments pointing in random directions. But when the liquid-crystal layer is bent, the molecules reorient so their curves conform to the bend, and the dipoles align.

The bottom panel shows a similar reorientation of wedge-shaped molecules with dipoles parallel to their length. This time, the dipoles are aligned by a splay strain gradient: squeezing the liquid crystal at one end and stretching it at the other.

Flexoelectricity is not ferroelectricity; external forces are required to align the dipoles. But in 2001 Ivan Dozov showed theoretically that molecules might align spontaneously under some circumstances, at least over small length scales.⁵ Specifically, in a liquid crystal of banana-shaped particles, if the mechanical resistance to bending strain were to somehow go to zero, the molecules would tend toward the bent configuration all by themselves.

However, it's impossible for a uniformly bent arrangement of curved molecules to fill three-dimensional space: Even in a thin bent layer, the curvature is tighter on the inner surface than the outer one. Dozov proposed that the molecules could overcome that problem by adding a twist—by arranging into loosely wound helical structures that look locally like the bent configuration. Because the helix is turning every few nanometers, there's no large-scale ferroelectric alignment of molecular dipoles. Still, when the twist-bend nematic phase was experimentally discovered, a decade after Dozov's prediction, it took the liquid-crystal world by storm.⁶ It was the first new kind of nematic phase to be discovered in almost a century.

Wide stripes

Mandle and colleagues weren't thinking about the flexoelectric effect, or about the

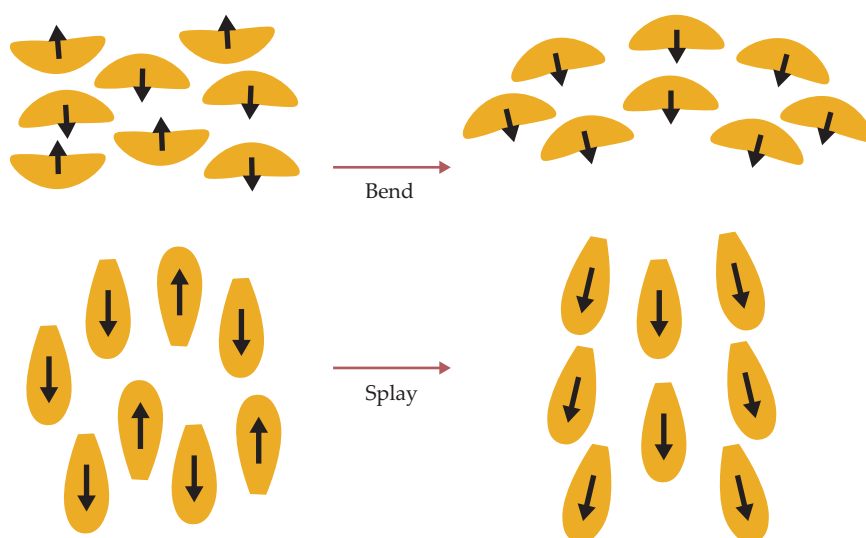


FIGURE 2. THE FLEXOELECTRIC EFFECT in a nematic liquid crystal describes the coupling between molecular dipoles (black arrows) and strain gradients. Banana-shaped molecules are polarized by an applied bending strain, and wedge-shaped molecules by splay strain. (Courtesy of Nerea Sebastián.)

twist-bend phase, when they designed RM734. “We were interested in molecules with large electric dipole moments,” explains Mandle. “But our only motivation to make them wedge shaped was to reduce the material’s melting point”—a molecule that’s bulkier at one end than the other would have a harder time organizing into an ordered, solid crystal lattice—“and make it easier to study.” When they saw the unexpected phase transition, though, they were immediately reminded of the twist-bend phase. So was Mertelj, when she heard about the work at a conference and offered to study the unusual liquid crystal in her lab.

The exact relationship to the twist-bend phase, however, was far from clear. “Initially we believed that the second nematic phase was due to the formation of antiparallel pairs of molecules,” says Mertelj, “and unconnected to the material’s mechanical properties.” Later she and her colleagues wondered whether they might be seeing a version of the twist-bend phase itself—but the bend elastic constant showed no unusual behavior at the phase transition. The splay elastic constant, on the other hand, dropped sharply at the transition temperature. “That was a big surprise,” says Mertelj. “We had to remeasure it several times to be certain of what we were seeing.”

Just like the bent arrangement of banana-shaped molecules, though, the splay arrangement of wedge-shaped molecules can’t uniformly fill space. If the RM734 molecules were spontaneously splaying, there had to be something more to the phase structure to compensate.

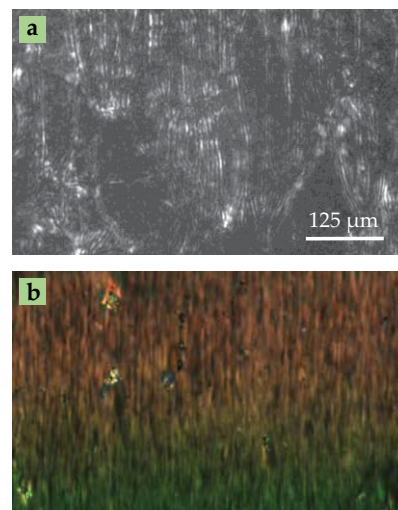


FIGURE 3. THE STRIPE MODULATIONS shown in figure 1 are visible in (a) second harmonic generation microscopy and (b) polarized optical microscopy. Although the schematic in figure 1 depicts stripes on the order of 10 molecules wide, the observed stripe widths, at 4–5 μm , are thousands of times the width of a molecule. (Panel a adapted from ref. 3; panel b courtesy of Nerea Sebastián.)

With a little more detective work, the researchers arrived at the modulated structure—the alternating stripes—shown in figure 1.

At first, they supposed that the modulation period, or width of the stripes, would be on the order of nanometers, similar to the pitch of the helices in the twist-bend phase. The splayed phase was optically identical to the ordinary nematic phase, so any structural features seemingly had to be smaller than the wavelength of visible light. And if the phase transition was driven purely by molecular shape, as it seemed to be, the modulations couldn't be much larger than the dimensions of the molecule itself.

But second harmonic generation (SHG) microscopy told a different story. SHG can occur only in structures that lack inversion symmetry. The interfaces between stripes don't qualify because they contain about as many molecules pointing one way as the other. But the interior of each stripe, where all molecules point in the same direction, is potentially visible in SHG imaging. "In fact, as we cooled the sample through the phase transition, the signal was so strong that we nearly burned out our detector," says Mertelj. The SHG image, seen in figure 3a, shows clearly delineated stripes 4–5 μm wide at the phase transition.

As it turns out, the stripes show up in optical images too, such as the one in figure 3b. Mandle and colleagues hadn't seen them before because they're visible only at the cusp of the phase transition. Below the transition temperature, the phase structure reorients, so the modulation direction (the x -axis in figure 1) is perpendicular to the imaging plane, and the stripes are rendered invisible to both SHG and optical microscopy.

Ferroelectric potential

The stripe modulations are too wide to arise from the mechanical effects of molecular shape, but what else could be causing them? If the phase transition was driven by molecular polarity, it would be revealed in the material's dielectric susceptibility—similar to the critical behavior of the magnetic susceptibility at a ferromagnetic phase transition. But labs equipped for broadband dielectric spectroscopy measurements on liquid crystals are scarce, and Mertelj's isn't one of them.

Fortunately, the lab where Sebastián had done her PhD—with María Rosario de la Fuente at the University of the Basque Country in Bilbao, Spain—specializes in just such dielectric measurements. Sebastián took a sample of RM734 back to Bilbao, measured the susceptibility, and found that it diverged at the phase transition. It was a clear signature of ferroelectricity.

From the dielectric measurements and stripe widths, the researchers concluded that the mysterious phase transi-

tion is driven primarily by molecular polarity, with shape playing only a bit part. But it must play some role, because most polar liquid-crystal molecules don't tend toward ferroelectric order. The nature of the polarity-shape interplay is not yet understood.

There's still a lot of work to do. Experiments so far have focused on the immediate vicinity of the phase transition, and little is known about how RM734 behaves as it's cooled deeper into the splay nematic phase. Do the stripes, although



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reoriented, stay more or less the same? Or do more complicated textures form? And how does the behavior change when the molecular features are subtly altered?

An eventual goal is to design a molecule that forms a homogeneous ferroelectric phase: all the molecular dipoles pointing in the same direction, without

any splay or stripes. “We strongly believe it is likely that such a material can be found,” says Mertelj. “Everything is possible.”

Johanna Miller

References

1. R. J. Mandle, S. J. Cowling, J. W. Goodby, *Phys. Chem. Chem. Phys.* **19**, 11429 (2017);

Chem. Eur. J. **23**, 14554 (2017).

2. A. Mertelj et al., *Phys. Rev. X* **8**, 041025 (2018).
3. N. Sebastián et al., *Phys. Rev. Lett.* **124**, 037801 (2020).
4. R. B. Meyer, *Phys. Rev. Lett.* **22**, 918 (1969).
5. I. Dozov, *Europhys. Lett.* **56**, 247 (2001).
6. M. Cestari et al., *Phys. Rev. E* **84**, 031704 (2011); K. Adlem et al., *Phys. Rev. E* **88**, 022503 (2013); V. Borshch et al., *Nat. Commun.* **4**, 2635 (2013).

Barbs of a feather lock together

When a bird extends its wings in flight, microscopic fasteners stick to each other to prevent gaps between the feathers and improve the bird’s macroscopic maneuverability.

Airplane wings trade off some of their efficiency for stability. Their shape is fixed and rigid except for the flaps and slats that pilots can tune during take-offs and landings to attain the desired level of lift and drag. Birds approach flying a bit differently: They take off, glide, turn, and land more efficiently and nimbly than airplanes by changing the shape of their flexible wings to various configurations (see *PHYSICS TODAY*, June 2007, page 28).

The feathers that make such morphing possible are made of a few basic parts. Each feather consists of a central shaft that’s lined with branching barbs. The many hook-like barbules on each barb easily fasten together to form an individual feather with a pliable and gapless surface. Based on several detailed observational studies, biologists have assumed for decades that simple friction causes feathers to cling together during flight.¹

Scientists could use computational fluid dynamics simulations to test, in principle, whether frictional forces are strong enough to keep feathers together. But the research is complicated by the morphable wings, which deform as they interact with air. More recently, engineers have begun applying dynamical systems analysis to better understand how individual structures in bird anatomy, including the neuromuscular and sensory systems, integrate to control wing shape and flight.²



FIGURE 1. THIS BIOHYBRID ROBOT combines mechanical parts with pigeon feathers. During real-world flight tests with high and low turbulence, PigeonBot controlled the position of its 40 feathers using four wing-mounted motors. The feathers’ fasteners prevented any gaps in the wings from forming that would have otherwise limited the robot’s mobility. (Lentink Lab/Stanford University.)

A group of biologists and engineers that recently teamed up has now uncovered the biophysical mechanism that makes morphing feasible. Graduate student Laura Matloff, her adviser David Lentink (both at Stanford University), and their colleagues determined that adjacent feathers on the wings of common rock pigeons are held together by microstructures similar to barbules.³ Field tests with a biohybrid flying robot, shown in figure 1, confirm that the microstructures fasten together in one direction and unlock in the other to pre-

vent wings from getting bent out of shape in flight.

Prime mover

The researchers first measured the skeletal kinematics of pigeon wings and their relative flight positions using cameras and microcomputed tomography scanning. They couldn’t observe each configuration of the bird’s fingers, arms, and wrist bones in an active, living bird, so three pigeon cadavers were used for the experiment. The wings of each cadaver were positioned in various