

provide the best of both worlds: the accuracy of ion clocks and the stability that comes from using many atoms, without the uncertainty that stems from multi-atom interactions in present-day neutral-atom clocks.

Whether or not two-valence-electron atoms will prove to be superior to alkali atoms for quantum simulation and computing remains to be seen. Experiments have already demonstrated high-quality measurements of the quantum state of single strontium atoms¹². The outlook for corresponding advances in Rydberg gates for computation is less certain, because the properties of Rydberg states in two-valence-electron atoms are more complex,

and less-well studied, than those in alkali atoms. More work is required to accurately characterize these properties before a definite conclusion can be drawn. Nevertheless, the availability of arrays of single strontium and ytterbium atoms will provide a crucial experimental tool for such studies. ■

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MATERIALS SCIENCE

Refrigeration based on plastic crystals

Materials called plastic crystals have been found to undergo huge temperature changes when subjected to small pressures near room temperature. Such materials could form the basis of future refrigeration technologies. [SEE LETTER P.506](#)

CLAUDIO CAZORLA

Materials known as plastic crystals are composed of molecules that interact through weak long-range forces. As a result, these materials are highly compressible and can be deformed in a reversible manner — hence the adjective ‘plastic’. Under certain pressure and temperature conditions, molecules in plastic crystals can start rotating almost freely around their centres of mass. The centres of mass remain localized at well-defined and ordered positions in the crystal lattice, but the rotation leads to orientational disorder. On page 506, Li *et al.*¹ report that the phase transition between molecular order and disorder in plastic crystals can be used for cooling purposes through the application of small pressures.

Conventional refrigeration technologies are based on cycles in which greenhouse gases are alternately compressed and expanded. One kilogram of a typical refrigerant gas contributes as much to the greenhouse effect in our planet’s atmosphere as two tonnes of carbon dioxide, which is the equivalent of running a car uninterruptedly for six months (see go.nature.com/2ffbqvt). In addition, current cooling technologies cannot be scaled down to the dimensions of microchips, which hinders the development of faster and more-compact computers and portable electronic devices. There is therefore a pressing need to find eco-friendly and highly scalable cooling methods for improving many crucial technologies, as well as for protecting the environment.

Solid-state cooling is an environmentally friendly, energy-efficient and highly scalable technology that could solve most of the problems associated with current refrigeration methods. It relies on applying cycles of external magnetic, electric or mechanical fields

to compounds called caloric materials. These compounds undergo temperature variations as a result of field-induced phase transitions that involve large changes in entropy — a measure of disorder.

Examples of caloric materials include ferroelectrics², organic–inorganic hybrid perovskites³ and fast-ion conductors⁴. However, most known caloric materials are not ideal. Some have only modest refrigeration performances, for example, or operate at temperatures different from ambient conditions. And for others, durability and cycling rate can be affected by material fatigue and phase-transition hysteresis — in which the conditions required for completing a phase transition depend on the direction of the transition. Consequently, progress in solid-state cooling has been limited.

Li and colleagues’ work offers exciting

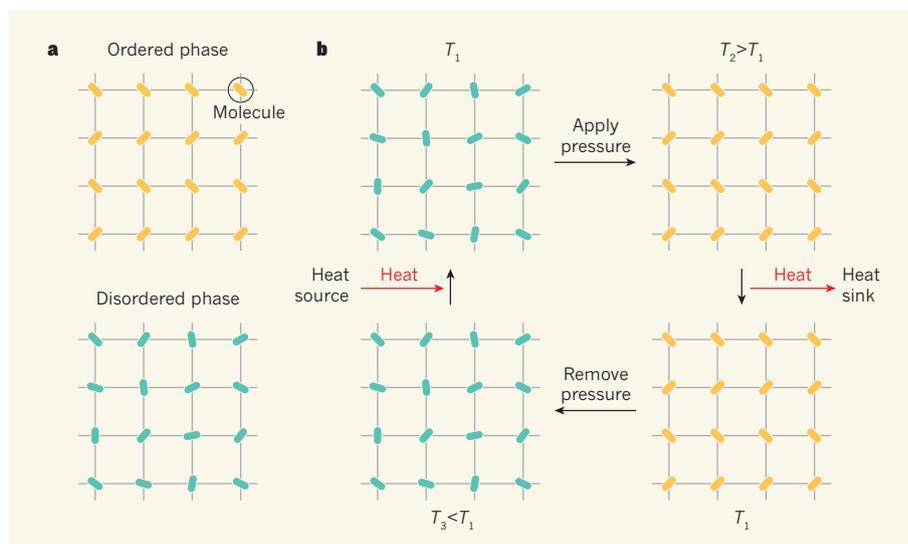


Figure 1 | Phases and potential cooling application of plastic crystals. **a**, In materials known as plastic crystals, the orientations of the molecules can be either ordered or disordered. **b**, Li *et al.*¹ demonstrate that these materials could be used for refrigeration. In this simple, four-step refrigeration cycle, a plastic crystal is initially in the disordered phase at a temperature T_1 . First, pressure is applied to the crystal, which causes the ordered phase to be stabilized and the crystal’s temperature to increase to a value T_2 . Second, a heat sink absorbs heat from the crystal and the crystal’s temperature returns to its initial value. Third, pressure is removed from the crystal such that the disordered phase is recovered and the crystal’s temperature decreases to a value T_3 . Fourth, the crystal absorbs heat from a heat source and returns to its initial temperature, thereby cooling the heat source.

prospects for the field of solid-state cooling. The researchers discovered extremely large entropy changes associated with the molecular order–disorder phase transitions that occur in plastic crystals (Fig. 1a). Moreover, they found that these transitions could be triggered near room temperature by applying small pressures (about 10–100 megapascals), and so could be used for refrigeration purposes (Fig. 1b).

The typical field-induced entropy changes measured in archetypal caloric materials are of the order of 10 joules per kilogram per kelvin. By comparison, those found by Li *et al.* in plastic crystals are of the order of $100 \text{ J kg}^{-1} \text{ K}^{-1}$. For instance, the entropy change reported for the representative plastic crystal neopentylglycol near room temperature is about $390 \text{ J kg}^{-1} \text{ K}^{-1}$, which leads to a large temperature change (roughly 50 K).

The molecular mechanisms that underlie the colossal pressure-induced entropy changes in plastic crystals can be understood intuitively. When pressure is applied to the disordered (high-entropy) phase, the molecular rotations are geometrically frustrated; that is, competing interactions between the molecules limit their possible orientations. As a result, the ordered (low-entropy) phase is stabilized. The accompanying reduction in entropy is huge — similar in magnitude to the entropies typically associated with the melting of a crystal. Conversely, when pressure is removed, the molecules resume their rotations and the disordered phase is re-established, causing an equally large increase in entropy.

Previous studies have already reported giant temperature changes associated with pressure-driven order–disorder phase

transitions in caloric materials. For example, in fast-ion conductors, such effects accompany the transition from a normal phase to a superionic phase, in which the conductivity of ions is extremely high^{5–7}. However, plastic crystals are quite different from other caloric materials, and not just because of their huge entropy changes near room temperature: they are cheap and easy to produce, lightweight, non-toxic and flexible. They therefore seem to be especially well suited for the integration of solid-state cooling in electronic devices and mobile applications.

Nevertheless, plastic crystals are not perfect caloric materials. For instance, given their organic nature, they have relatively low melting points (typically about 300–400 K)⁸, which is not desirable for refrigeration applications. In addition, the properties that make plastic crystals highly deformable mean that these materials lack the mechanical resilience to endure many refrigeration cycles. Perhaps most importantly, hysteresis and phase-coexistence effects are likely to weaken the cooling performance of plastic crystals. These technical issues will need to be analysed, and solutions found, if we are to pursue the use of plastic crystals in commercial refrigeration.

Li and colleagues propose combining external pressure and electric fields as a way of avoiding the hysteresis problems associated with plastic crystals. A similar strategy has been demonstrated to work well for compounds called magnetocaloric materials, in which mechanical and magnetic fields have been combined to remove unwanted hysteresis effects⁹.

However, the fact that most molecules in plastic crystals are polar does not guarantee that applying electric fields to these materials will eliminate the effects of hysteresis. The reason is that incredibly large electric fields (about 1,000 kilovolts per centimetre) might be needed to induce any effect on the molecular rotations, as has been shown theoretically for organic–inorganic hybrid perovskites¹⁰. A possible solution to this problem might be to find or engineer ferroelectric plastic crystals, in which the ordered phase already exhibits collective polar order¹¹. Despite these challenges, Li and colleagues' work represents a step towards finding other caloric materials that have advantageous properties. ■

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STRUCTURAL BIOLOGY

Lipopolysaccharide transport ratcheted up

A protein complex that moves molecules called lipopolysaccharides between the two cell–wall membranes of certain bacteria is a target for drugs. Structures reveal how this complex delivers its load irreversibly. SEE ARTICLE P.486 & LETTER P.550

RUSSELL E. BISHOP

Many bacteria that cause infections are surrounded by two distinct membranes, which form part of their protective cell wall. The surface of the outer membrane includes a tightly packed layer of glycolipid molecules known as lipopolysaccharides (LPSs), which provide a barrier against harmful detergents and antibiotics. The LPSs are synthesized in the inner membrane, before being transported and assembled in the outer membrane¹ — the molecules are

extracted from the external layer of the inner membrane and shuttled across a bridge to the outer membrane, before emerging on the cell surface. Two papers^{2,3} in this issue now provide long-awaited details of the molecular processes that drive LPS transport.

The structures of six of the seven components of the LPS transport apparatus (known as LptA–G) have been fully characterized^{1,4}. They reveal that a portal for LPS molecules forms from the LptD and LptE subunits in the outer membrane, and is connected to a pump in the inner membrane (formed from LptF, LptG and two LptB

subunits) by a bridge, which includes one or more LptA subunits (Fig. 1). The pump is driven by the binding and hydrolysis of cytoplasmic ATP, the cell's energy-carrying molecule, but how it binds to LPSs from the inner membrane and pumps them only in the outward direction was unknown. A full-length structure of the inner-membrane protein LptC was needed to complete the puzzle and to explain how the pump is connected to the bridge.

Li *et al.*² (page 486) and Owens *et al.*³ (page 550) have resolved this issue. Li *et al.* report structures of the LptB₂FGC complex from the bacterium *Escherichia coli*, produced using cryo-electron microscopy (cryo-EM). These structures show how the complex binds to LPS molecules, and the conformational rearrangements of the complex that occur when LPSs are captured and extruded onto the bridge. Owens *et al.* present X-ray crystal structures of LptB₂FGC from two other bacteria (*Vibrio cholerae* and *Enterobacter cloacae*), which show how LPSs are transported irreversibly towards the outer membrane.

In structural-biology studies, membrane proteins are often extracted from the