

approach called solar-radiation management. It has been proposed that, by using particles other than sulfuric acid, negative side effects such as ozone depletion and stratospheric warming could be bypassed or reduced¹². Solomon and colleagues' study underscores the possibility that various particle types, fresh or after chemical transformation in the stratosphere, might still promote ozone depletion for a few decades as stratospheric chlorine levels slowly decline. Any candidate material for stratospheric injection must, at a minimum, be studied carefully in the laboratory, under simulated conditions of the stratosphere.

The Australian bushfire season of 2019–20 was extreme, but large wildfires and the resulting pyrocumulonimbus clouds are likely to become increasingly frequent and intense as the climate changes. The resulting injections of smoke into the upper atmosphere might therefore slow or temporarily disrupt the recovery of the stratospheric ozone layer. In this context, Solomon and colleagues' findings emphasize the need for atmospheric chemists to better understand the properties and reactivity of common, but complex, atmospheric particle types, such as those produced from biomass burning, in the cold and dry upper atmosphere.

V. Faye McNeill is in the Department of Chemical Engineering and the Department of Earth and Environmental Sciences, Columbia University, New York, New York 10027, USA. **Joel A. Thornton** is in the Department of Atmospheric Sciences, University of Washington, Seattle, Washington 98195, USA. e-mails: vfm2103@columbia.edu; thornton@atmos.uw.edu

1. Li, M., Shen, F. & Sun, X. *Sci. Rep.* **11**, 12288 (2021).
2. Bernath, P., Boone, C. & Crouse, J. *Science* **375**, 1292–1295 (2022).
3. Solomon, S. *et al. Proc. Natl Acad. Sci. USA* **119**, e2117325119 (2022).
4. Solomon, S. *et al. Nature* **615**, 259–264 (2023).
5. Molina, M. J. & Rowland, F. S. *Nature* **249**, 810–812 (1974).
6. Solomon, S., Garcia, R. R., Rowland, F. S. & Wuebbles, D. J. *Nature* **321**, 755–758 (1986).
7. Molina, M. J., Tso, T.-L., Molina, L. T. & Wang, F. C.-Y. *Science* **238**, 1253–1257 (1987).
8. Brasseur, G. & Granier, C. *Science* **257**, 1239–1242 (1992).
9. Abbatt, J. P. D., Lee, J. K. Y. & Thornton, J. A. *Chem. Soc. Rev.* **41**, 6555–6581 (2012).
10. McNeill, V. F., Loerting, T., Geiger, F. M., Trout, B. L. & Molina, M. J. *Proc. Natl Acad. Sci. USA* **103**, 9422–9427 (2006).
11. Zobrist, B., Marcolli, C., Pedernera, D. A. & Koop, T. *Atmos. Chem. Phys.* **8**, 5221–5244 (2008).
12. Keith, D. W., Weisenstein, D. K., Dykema, J. A. & Keutsch, F. N. *Proc. Natl Acad. Sci. USA* **113**, 14910–14914 (2016).

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Condensed-matter physics

Hopes raised for ambient superconductors

ChangQing Jin & David Ceperley

A hydrogen-rich compound has taken the lead in the race for a material that can conduct electricity with zero resistance at room temperature and ambient pressure – the conditions required for many technological applications. **See p.244**

A superconductor is a metal that conducts electricity without resistance. In our increasingly electrified world, the implications of such a material are astounding – just imagine transmitting electrical power over thousands of kilometres with essentially no losses. But as promising as superconductivity might sound, this state has been achieved only at low temperatures¹ or very high pressures², both of which are unsuitable for many applications. For this reason, finding a material that can superconduct under ambient conditions has long been a focus of materials research. On page 244, Dasenbrock-Gammon *et al.*³ report possible evidence for remarkable progress in this search.

When a material is in a superconducting state, its electrons form bound pairs known as Cooper pairs. These pairs avoid further collisions, and therefore encounter less resistance, than do single electrons moving alone. In some materials, crystal-lattice vibrations enable these Cooper pairs to form because the movement of positive ions in the lattice draws the electrons together. Materials containing hydrogen are particularly amenable to this pairing mechanism because hydrogen is the lightest chemical element, which means it has the highest vibration frequency. According to theory⁴, this high frequency should increase the temperature at which a material can superconduct.

In 1968, physicist Neil Ashcroft predicted that pure hydrogen could superconduct at room temperature⁵. However, hydrogen becomes metallic only when H₂ molecules are dissociated at intense pressures of around 500 gigapascals (1 GPa is 10⁹ Pa)⁶. This is about five million times that of atmospheric pressure, and extremely difficult to achieve with current experimental techniques. Ashcroft later suggested that hydrogen-rich compounds could become superconducting at lower pressures than can pure hydrogen, owing to the chemical compression induced by the other elements⁷.

Experiments have since shown that several polyhydride compounds transition

to a superconducting state at temperatures higher than 200 kelvin (some 93 K below room temperature). These compounds include sulfur hydride², rare-earth hydrides^{8,9} and alkaline-earth hydrides^{10,11}. But the pressures required are still very high – typically, hundreds of gigapascals.

Other materials exhibit a state of 'unconventional' superconductivity induced by lattice vibrations, as well as other physical processes that set these systems apart from their conventional counterparts^{12,13}. A process called doping, in which impurities are deliberately added to a material, can induce, modify or enhance superconductivity in these materials – changing a non-superconducting state into a high-temperature superconducting state.

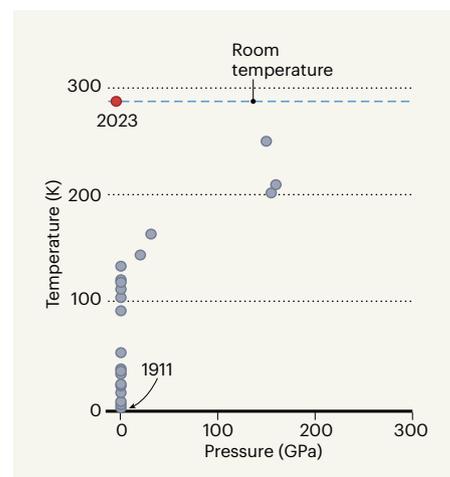


Figure 1 | The road to high-temperature superconductors. Researchers have been trying to achieve a superconducting (zero electrical resistance) state at ambient temperatures and pressures for more than a century. Several superconductors have been reported, albeit at very low temperatures. In 1968, it was predicted that pure hydrogen could superconduct at room temperature⁵. Dasenbrock-Gammon *et al.*³ provide possible evidence that a hydride compound superconducts at 294 kelvin and 1 gigapascal (10⁹ Pa), close to ambient conditions. (Adapted from Fig. 1 of ref. 20, with extra data from refs 10, 11.)

Dasenbrock-Gammon *et al.* obtained evidence for near-ambient superconductivity by replacing some of the hydrogen in a lutetium hydride compound with nitrogen, which increased the number of charge carriers. The authors fabricated the compound at a pressure of 2 GPa. They then lowered the pressure to 1 GPa and measured a superconducting phase with a maximum transition temperature of 294 K. This is the highest temperature recorded at such low pressures (Fig. 1).

The sample underwent a striking visual transformation as it transitioned through different phases with changing pressure. When the non-superconducting metal was compressed, its colour changed from blue to pink, coincident with the onset of the superconducting regime at 171 K and 0.5 GPa. Then, when the authors compressed the sample to more than 1 GPa, the sample became non-superconducting again and its colour changed to a vivid red. It is intriguing that the superconducting state appeared only in the pink phase marked by intermediate pressures.

Dasenbrock-Gammon *et al.* made various measurements to show that this phase was indeed superconducting. They measured electrical resistance, and looked at how the voltage across their sample depended on the current through it. They also measured the temperature dependence of magnetic susceptibility (how easily a sample can be magnetized) and of a thermodynamic quantity called specific heat.

These measurements were all consistent and comprehensive. However, the authors' discovery will no doubt be controversial, because researchers from the same team previously retracted a report¹⁴ of high-temperature superconductivity in carbonaceous sulfur hydride¹⁵. Independent measurements of the material, its properties and fabrication process will help to assuage any doubts about the results.

The authors suggest that hydrogen's high vibration frequency and the extra charge carriers from the nitrogen both contribute to the high-temperature superconducting state they measured. To determine whether this is indeed the case, more needs to be known about the composition and structure of the material. Dasenbrock-Gammon *et al.* used a technique called X-ray diffraction to show that the lutetium formed a closely packed crystal lattice, in an arrangement known as a face-centred-cubic structure, in some of the phases they detected. However, the locations of the hydrogen and nitrogen atoms could not be detected with X-rays. Future work is required to understand their distribution, which could be measured, for example, using neutron-diffraction methods.

The concentrations of hydrogen and nitrogen are also unknown. Dasenbrock-Gammon and colleagues' structural model holds that the distance between hydrogen atoms is 2.19 Å. This is surprisingly large

—almost twice that of other hydrides exhibiting high-temperature superconductivity^{16–18}—and suggests that there is relatively little hydrogen present in the authors' samples compared with in similar superconducting compounds.

If the nitrogen doping is indeed partly responsible for the superconducting state, its role in achieving such a high transition temperature is yet to be determined. Further research will be needed to confirm that Dasenbrock-Gammon and co-workers' material is a high-temperature superconductor, and then to understand whether this state is driven by vibration-induced Cooper pairs—or by an unconventional mechanism that is yet to be uncovered.

Regardless of the mechanism, the prospect of a material that superconducts under ambient conditions is tantalizing. Superconducting materials make powerful magnets that are used, for example, in magnetic resonance imaging (MRI)—a technology that has had a profound impact on medical diagnostics since it first appeared half a century ago¹⁹. Such magnets can also be used to levitate objects, and this ability has inspired the idea of a high-speed train that would optimize energy consumption by minimizing friction.

But standard MRI systems currently require expensive refrigeration in the absence of high-temperature superconducting components. And trains that travel as fast as aircraft on a fraction of the power are still a thing of the future. Perhaps Dasenbrock-Gammon and

colleagues' hydride compound will bring us a step closer to such technologies becoming a reality.

ChangQing Jin is at the Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China. **David Ceperley** is in the Department of Physics, University of Illinois Urbana-Champaign, Urbana, Illinois 61801, USA.
e-mails: Jin@iphy.ac.cn; ceperley@illinois.edu

1. Chu, C. W. *Physica C* **482**, 33–44 (2012).
2. Drozdov, A. P., Erements, M. I., Troyan, I. A., Ksenofontov, V. & Shylin, S. I. *Nature* **525**, 73–76 (2015).
3. Dasenbrock-Gammon, N. *et al.* *Nature* **615**, 244–250 (2023).
4. Bardeen, J., Cooper, L. N. & Schrieffer, J. R. *Phys. Rev.* **108**, 1175–1204 (1957).
5. Ashcroft, N. W. *Phys. Rev. Lett.* **21**, 1748–1749 (1968).
6. McMahon, J. M., Morales, M. A., Pierleoni, C. & Ceperley, D. M. *Rev. Mod. Phys.* **84**, 1607–1653 (2012).
7. Ashcroft, N. W. *Phys. Rev. Lett.* **92**, 187002 (2004).
8. Drozdov, A. P. *et al.* *Nature* **569**, 528–531 (2019).
9. Somayazulu, M. *et al.* *Phys. Rev. Lett.* **122**, 027001 (2019).
10. Li, Z. *et al.* *Nature Commun.* **13**, 2863 (2022).
11. Ma, L. *et al.* *Phys. Rev. Lett.* **128**, 167001 (2022).
12. Keimer, B., Kivelson, S. A., Norman, M. R., Uchida, S. & Zaanen, J. *Nature* **518**, 179–186 (2015).
13. Ishida, K., Nakai, Y. & Hosono, H. *J. Phys. Soc. Jpn* **78**, 062001 (2009).
14. Snider, E. *et al.* *Nature* **586**, 373–377 (2020).
15. Snider, E. *et al.* *Nature* **610**, 804 (2022).
16. Duan, D. F. *et al.* *Sci. Rep.* **4**, 6968 (2014).
17. Peng, F. *et al.* *Phys. Rev. Lett.* **119**, 107001 (2017).
18. Wang, H., Tse, J. S., Tanaka, K., Iitaka, T. & Ma, Y. *Proc. Natl Acad. Sci. USA* **109**, 6463–6466 (2012).
19. Lauterbur, P. C. *Nature* **242**, 190–191 (1973).
20. Gao, G. *et al.* *Mater. Today Phys.* **21**, 100546 (2021).

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Plant sciences

A protein entry path into chloroplasts

Takashi Hirashima & Toshiya Endo

Structures of the machinery for importing proteins into chloroplast organelles of algae, determined using cryo-electron microscopy, have opened a new chapter in efforts to understand how chloroplasts are built. **See p.349**

Chloroplasts are organelles, found in plants and algae, that house hundreds of different proteins responsible for photosynthesis, a process essential for life on Earth. Most chloroplast proteins are encoded by the nuclear genome, are made in the cytosol and contain a chloroplast-targeting signal. To be imported into the chloroplast, such proteins must cross the outer and inner envelope membranes (OEM and IEM, respectively) that surround the organelle. Protein complexes on the OEM (called TOC) and IEM (called TIC) form the intricate machinery that

mediates protein transport across the two membranes^{1–3}. On page 349, Liu *et al.*⁴ report the cryo-electron microscopy (cryo-EM) structures of the TOC–TIC supercomplex from the unicellular green alga *Chlamydomonas reinhardtii*. This and another such structure reported in *Cell* by Jin *et al.*⁵ are the first high-resolution structures of the TOC and TIC complexes—they provide surprises and insights, but also raise many questions.

Chloroplast-destined proteins are recognized and move from the cytosol across the OEM with the aid of the TOC complex. Previous