https://doi.org/10.1038/s41563-024-02103-8

Cooler than cool

Improved thermoelectric refrigeration at cryogenic temperatures may lead to enhanced technologies and better research capabilities.

Mastery of heat is a fundamental part of the human toolkit, with evidence for cooking fires dating back to at least 780,000 years ago[1]. Yet, exploiting refrigeration to cool things down is far newer. The first liquefaction of a gas was achieved by Louis Clouet and Gaspard Monge in 1780, where they used a combination of compression and a mixed refrigeration bath of ice and salt to obtain liquid SO_2 (ref. 2). Later, aided by better compressors and improved refrigeration baths, as well as a much-improved understanding of thermodynamic cycles, chemists were able to liquify atmospheric gases, furthering exploration of the physical chemistry of these substances. The usage of vapour compression or Joule–Thompson techniques eventually allowed production of liquid hydrogen and helium, the production of which has, in turn, enabled discoveries of fundamental effects that manifest at cryogenic temperatures, such as superconductivity. Thermoelectric solid-state cooling has the advantages of compactness, no moving parts, durability and scalability to low power levels. However, application at cryogenic temperatures is difficult. This is because the coefficient of performance zT, where $z = S^2\sigma / \kappa$, and S is the Seebeck coefficient, σ the electrical conductivity, κ the thermal conductivity and T the temperature, is temperature-dependent and so reduced at cryogenic temperatures.

In this issue of *Nature Materials*, we present two studies that demonstrate improved performance for thermoelectric cooling at cryogenic temperatures, and demonstrate pathways to improved devices.

Given the temperature dependence of zT, for cryogenic applications it is necessary to increase z. Topological materials possess robust and topologically protected states with linear band dispersion that can enable high electrical conductivity as well as small bandgaps. Moreover, they tend to consist of heavy elements that lead to a lower thermal conductivity. This combination of properties will increase z. In an Article by Yu Pan and colleagues, the thermoelectric properties of a homogeneous single crystal of the topological material $Bi_{88}Sb_{12}$ are investigated. The authors found that at temperatures below 200 K a modest zT of approximately 0.5 was obtained, but applying a magnetic field of 0.7 T increases zT to approximately 1.7 at 180 K. This is due to a magneto-Seebeck effect, the application of magnetic field enhancing S and so zT. A magnetically enhanced zT has been observed before in this material; however, the zT obtained was much lower and in addition was achieved under a much higher magnetic field[3]. Here Pan and colleagues theoretically demonstrate that the large magneto-Seebeck effect is due to the linear band dispersion and the sensitivity of these bands to a magnetic field, a splitting of the linear bands into two pockets occurs with each pocket then contributing to the Seebeck coefficient, increasing this parameter. In the related Research Briefing the authors note that precise tuning of the Fermi level could enable Landau localization, and so even further enhance zT.

More efficient cooling technologies can enable easier gas liquefactions, as shown here for nitrogen.

For practical applications, the n-type crystal studied by Pan and colleagues needs to be complemented with a p-type material to enable cooling using the Peltier effect, complicating device fabrication. An electrically induced cooling in the bulk was first predicted by Thomson in the 1850s[4]; however, the Thomson effect is usually negligible when compared with the Peltier effect. In a Letter by Yanzhong Pei and colleagues it is shown that the Thomson effect can lead to improved cooling properties with a simple device geometry, and demonstrate >5 K cooling at 38.4 K.

For substantial Thomson cooling, a material must have a sizeable difference between the Seebeck coefficients at the hot and cold sides, this means the Seebeck coefficient must vary exponentially with temperature. Noting that $YbInCu_4$ demonstrates an electronic phase transition, where the 4*f* electrons of Yb transition from an itinerant to a localized state, Pei and colleagues measure a substantial change in the Seebeck coefficient around the transition temperature. Moreover, a device outperforms standard BiSb alloys, calculated as a percentage temperature change compared to the hot-side temperature. In a related News & Views article, Kornelius Nielsch and Ran He note that the performance is highly dependent on the temperature of the material, with device operation away from the phase transition temperature causing a notable reduction. As they also remark, there is no roadmap for identifying high-value Thomson cooling materials, but several effects could enhance this effect, including metal–insulator transitions, or phonon or magnon drag. In addition, graded materials, where composition varies across a device, could be used to vary the Seebeck coefficient in the required exponential-like way with temperature.

Improved cryogenic cooling technologies, of which these are but a few examples, could enable scientific discovery of exotic quantum effects that present at cryogenic temperatures. Moreover, as quantum effects become stronger at lower temperatures, improved cooling technologies may be of interest for applications such as quantum computation, of topical interest as 2025 is the International Year of Quantum Science and Technology (https://quantum2025.org/en/). It seems that research on cooling technologies will continue to heat up.

Published online: 3 January 2025

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