montane forests are immensely valuable, and not only because they host the source of the River Nile, mountain gorillas and ecosystems such as mysterious lichen-covered forests. They also store vast amounts of carbon, and thereby have a key role in tackling climate change. Of course, this immense intrinsic value does not preclude intense human exploitation of these ecosystems, which can lead to rapid degradation and deforestation. For instance, on the basis of satellite monitoring, Cuni-Sanchez and colleagues report that Mozambique lost nearly one-third of its montane forests between 2000 and 2018.

There is, however, the faint hope that putting a financial value on carbon, and the establishment of economic incentives to avoid deforestation in tropical countries, might help to check the flood of damage[5]. The aim is to reward African countries – for which montane forest sometimes constitutes the last remaining forests – for their conservation endeavours, and for renouncing efforts to access the timber and ore in these ecosystems, even when such resources are otherwise desperately lacking. By gathering the best-available data to provide precise, country-level estimates of average aboveground carbon content in African montane forests, Cuni-Sanchez and colleagues' study will add weight to such efforts – not least because the new estimates are, on average, two-thirds higher than the values reported by the Intergovernmental Panel on Climate Change[6].

The next step should be to extend measurements in these forests, particularly by continuing to support national forest-inventory efforts. These inventories target all vegetation types, rather than just the most intact forests, and all carbon pools, using standardized protocols and systematic sampling methods. Remote sensors, both in the sky and in space, should also be used to fully map the detailed spatial variation of forest diversity, structure and dynamics. But there is no excuse for delaying policymaking – we already know enough to justify immediate decisive action to preserve yet another of Earth's threatened treasures.

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Quantum technology

Single proton cooled by distant ions

Manas Mukherjee

Laser-cooled ions have been used to substantially lower the temperature of a proton located several centimetres away. This technique could be useful in ultraprecise measurements of the properties of antimatter particles. **See p.514**

On page 514, Bohman *et al.*[1] (the BASE Collaboration) report the cooling of a single proton by a cloud of laser-cooled beryllium ions. Remarkably, the ions were separated from the proton by a distance of about 9 centimetres – which is too far apart for the charges on the ions to have interacted with that of the proton. This means that the ions could not have exerted a direct cooling effect on the proton. Instead, the researchers used an indirect cooling process, mediated by an electric circuit that established an effective interaction. This approach has potential applications in studies of antimatter particles and in the field of quantum information.

A wealth of knowledge about nature's inner workings comes from studies of fundamental particles, such as electrons and protons. Currently, the most accurate theoretical model of the forces of nature is the standard model of particle physics, which describes how fundamental particles interact with each other and thereby build up the macroscopic world. The standard model has passed many stringent tests using various experimental tools, at particle energies that range from 10^{11} electronvolts in particle accelerators[2] to only about 0.0001 electronvolts in ion traps[3]. However, it is widely accepted that the standard model does not explain some natural phenomena, such as the fact that the Universe is made up of only matter. It also does not account for the existence of dark matter – the invisible and largely unaccounted for mass of the Universe.

High-precision measurements of fundamental particles and their corresponding antiparticles provide opportunities to verify the standard model, and maybe even to find evidence of new physics that goes beyond the currently accepted model[4,5]. Two conditions must be met to perform such measurements: the particles must be spatially confined; and they should be very nearly at rest (that is, the particles must be cooled to almost zero kelvin, to minimize their kinetic energy). The first of these requirements can be solved using a combination of static electric and magnetic fields in a device called a Penning trap.

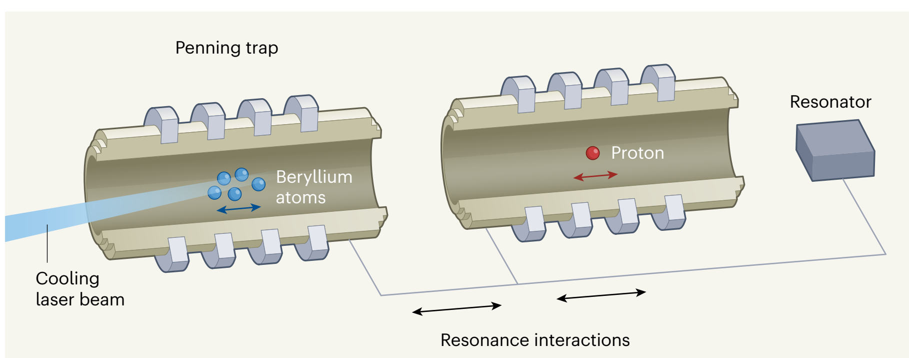

Figure 1 | Sympathetic cooling at a distance. Bohman *et al.*[1] used devices called Penning traps to capture a proton at 17 kelvin and a cloud of beryllium ions, which was continuously cooled by a laser to a much lower temperature. The traps were connected by a wire to a circuit known as a resonator. Oscillations (coloured arrows) of the proton and of the ions generate electrical currents (not shown) in the electrodes of their respective traps; these currents oscillate at the same frequency as the particles that generate them. If the natural oscillation frequency of the proton is the same as that of the ions and of the electrical current in the resonator circuit, a phenomenon called resonance allows the currents in the system to interact. The ions therefore cool the resonator, which, in turn, cools the proton. Such indirect cooling of the proton by the ions is called sympathetic cooling through the resonator.

Laser-cooling methods were first reported[6,7] in 1975, and have since been widely developed to reduce the motion of particles. This approach works well for atoms, but not for particles that do not absorb light, such as protons. Scientists have therefore invented other cooling methods, such as resistive cooling[8] (in which ions dissipate their energy by inducing a current in a cold electric circuit) and synchrotron cooling[9] (in which fast-rotating particles with low mass radiate energy by emitting electromagnetic radiation). However, the lowest particle temperatures achieved using those approaches are roughly 1,000 to one million times higher than those of laser-cooled atoms.

An interesting alternative is to cool a charged particle by bringing it close to another, colder charged particle[10] — an approach commonly known as sympathetic cooling. For example, consider a positively charged atomic ion that is being continuously laser-cooled to one-thousandth of a kelvin, and which is then brought close to a proton that is initially at 4 K in an ion trap. The proton and ion will repel each other within the confinement of the ion trap, effectively transferring kinetic energy from the proton to the ion. Because the ion is constantly being laser-cooled, the repulsive interactions will eventually chill the proton to the same temperature as the ion, even though the proton is not being cooled directly.

Sympathetic cooling works well, but the nearby presence of an ion would be undesirable when making ultraprecise measurements of a proton's properties. Furthermore, the method requires that the particle and the ion have charges of the same polarity, to provide the necessary repulsive interactions. Bohman and colleagues' work provides a potential solution to these issues.

The authors used separate Penning traps to confine a cloud of beryllium ions and a proton in an ultrahigh vacuum, and continuously laser-cooled the ions (Fig. 1). The proton and the ions were then set up to 'talk' to an electrical resonator circuit, which enables the two trapped-particle systems to interact only when the natural oscillation frequencies (the resonance frequencies) of the two systems match exactly. Bohman *et al.* demonstrated the influence of the ions on the proton using an established technique, in which electrical 'noise' in the resonator circuit is analysed to directly determine the temperatures of the two systems.

To further ensure that the proton cooling is indeed caused by the ions, the authors fixed the oscillation frequency of the proton, and then varied the oscillation frequency of the ions. They observed that cooling interactions occurred only when the ions' natural oscillation frequency matched that of both the proton and the resonator circuit, as expected. Furthermore, the researchers found that numerical simulations of the cooling set-up matched the observed experimental result, confirming the ions' proton-cooling influence.

Impressively, Bohman *et al.* show that the proton temperature can be reduced by 85%, which would be a substantial amount in an ultraprecise measurement of a fundamental particle. The authors' technique opens up the possibility of being able to cool any charged particle by 'wiring it up' to laser-cooled ions, with any distance between the particle and the ions.

The results also have implications for research in quantum information. A goal for this field is to exchange single bits of quantum information between spatially separated quantum systems. However, it is challenging to do this using a conducting wire. Bohman and colleagues' findings suggest a possible solution to this problem, but it will first be necessary to broaden our understanding of how single quanta of energy are exchanged over large distances, and to greatly improve the rate of energy exchange between the separated systems.

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Cancer

A persistent look at how tumours evade therapy

Karen Gomez & Raul Rabadan

Understanding how resistance to chemotherapy occurs could lead to better anticancer treatments. Persister cells in tumours can contribute to this resistance. A method to characterize these cells in detail sheds light on their origins. **See p.576**

Cancer can recur when a subset of tumour cells, called persister cells, survive chemotherapy. Most of these persisters are non-dividing (quiescent) in the presence of the therapeutic drug, but a rare subpopulation can re-enter the cell cycle during treatment, which enables them to proliferate. Much research has focused on the genetic mechanisms underlying such resistance to treatment. However, emerging data suggest that non-genetic mechanisms (such as changes to the complex of DNA and protein called chromatin) might also have a role in the development of a persistent state. On page 576, Oren *et al.*[1] examine the cellular lineages and gene-expression profiles of persister cells by using a method called DNA barcoding to trace tumour cells and their descendants. Their findings illuminate the role of non-genetic, reversible mechanisms in resistance to chemotherapy for a range of tumours from different tissues.

The authors analysed cell divisions in human lung cancer cells grown *in vitro* that have a mutation in the gene encoding the epidermal growth factor receptor (EGFR). The cells were treated with osimertinib, an inhibitor of this receptor. Oren and colleagues tracked the outcomes for cellular lineages of the tumour cell line and found that 8% of the lineages gave rise to persister cells after 14 days, and 13% of the persisters resumed the cell cycle and proliferated to form cell colonies. These results show that these cycling and non-cycling persisters arise early during the course of treatment, and that they evolve from separate cell lineages.

To characterize the molecular mechanisms associated with cycling and non-cycling persister cells, the authors developed a system that they call Watermelon, to simultaneously trace each cell's lineage, proliferation status and transcriptional state (Fig. 1). To determine whether the persister state was due to a genetic, irreversible property of the persister cells, the authors re-exposed the persister cell population to osimertinib after a pause in treatment. They found that cells from both cycling and non-cycling populations reacquired drug sensitivity, suggesting that