ceased in 1975. Attempts to restore the pre-agricultural ecosystem were futile until both the invasive trees and the fertilized agricultural soil were removed[15–17]. For phosphorus-limited lake ecosystems, reduction of phosphorus inputs can be insufficient for lake recovery if excess phosphorus inputs from agriculture are retained and recycled[18].

These cases suggest that both reduction of nutrient inputs and removal of any large stores of accumulated nutrients may be required for restoration of native ecosystems. Some terrestrial restorations also require liming to overcome soil acidification, and seed addition when formerly abundant plant species are absent[2,11,13]. However, it is not yet clear how the magnitude of increases in nitrogen stores influences the recovery of grassland diversity after nitrogen addition decreases or ceases[3,19,20].

The insights from the Park Grass experiment, together with results from earlier studies, show that biodiversity can recover even after chronic high rates of nutrient pollution, and suggest that this recovery may be hastened by, or perhaps require, management practices that reduce accumulated nutrient stores. Moreover, it suggests that haying, a much gentler practice than destructive removal of both vegetation and soil, may reduce nutrient stores sufficiently to allow grassland diversity to recover. Finally, Storkey and colleagues' work demonstrates the great value that long-term studies can provide in identifying solutions to environmental problems. ■

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QUANTUM PHYSICS

Entanglement beyond identical ions

Control of quantum particles has been extended to enable different types of ion to be entangled — correlated in a non-classical way. This opens up opportunities for the development of new quantum technologies. **See Letters p.380 & p.384**

TOBIAS SCHAETZ

Entanglement is a peculiar phenomenon that causes two or more particles to share one common state, such that each particle can no longer be described independently. In this issue, Tan *et al.*[1] (page 380) and Ballance *et al.*[2] (page 384) report entangled pairs of ions consisting of two different atomic species — the first time that this has been achieved. They used the resulting systems to test the puzzling predictions of quantum mechanics with unprecedented accuracy. This in turn allowed them to benchmark trapped ions as an experimental platform for quantum technology, and to assess the platform's prospects to further exploit quantum effects for applications such as atomic clocks and quantum computation.

Quantum mechanics requires objects to be able to exist in two states simultaneously, even if the states are mutually exclusive. To picture such a superposition, imagine the magnetic needle of a hypothetical quantum compass pointing north and south at the same time. A measurement that determines the state of the needle will project it into one of its two possibilities at random — the result is not just unknown, but not determined before the measurement.

If there are two quantum magnetic needles, they can become entangled. For entangled objects, a measurement on one object that produces a completely random output instantaneously determines the potential result of the second object (or vice versa). The effect of the measurement is immediate and is independent of the distance between the objects.

Einstein was one of the founding fathers of the theory of quantum mechanics, but he and his colleagues realized that the consequences of entanglement severely violate intuition and logical conclusions based on the classical interpretation of nature. Einstein and others therefore proposed some seminal experiments[3] that could be used to show that their theory was far from complete. But because the practical

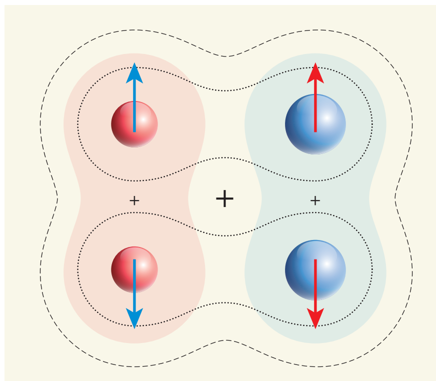

Figure 1 | Entangling two different ions. Individual ions can exist in one of two quantum 'spin' states: spin up (↑) and spin down (↓). Quantum mechanics also allows ions to form a superposition state (↑+↓) in which both the ↑ and ↓ states coexist. Tan *et al.*[1] and Ballance *et al.*[2] have prepared entangled pairs of ions consisting of two different atomic types — either different elements or different isotopes of an element. Each ion seems to be in a ↑+↓ state (shaded regions), but entanglement generates a correlated state (↑↑+↓↓, bounded by dashed lines; dotted lines indicate spin correlations), which means that a measurement of one of the two ions instantaneously affects the state of the other — that is, the two formerly independent ions have to be considered as a whole.

prerequisites for the experiments seemed to exceed the capabilities of any researcher, even in the future, they called their proposals *Gedankenexperimente* ('thought experiments').

Tan *et al.* and Ballance *et al.* report that quantum mechanics is accurate even when non-identical objects are entangled. Tan and colleagues entangled a beryllium-9 ion ($^{9}Be^{+}$) and a magnesium-25 ion ($^{25}Mg^{+}$), whereas Ballance and co-workers used two isotopes of calcium, $^{40}Ca^{+}$ and $^{43}Ca^{+}$. To describe how both groups created entanglement, consider the ions in each pair as magnetic needles that can point in one of two directions. This behaviour is analogous to that of a particle that has a spin value of +½ or −½; discrete spin values are a quantum form of angular momentum. Applying appropriate optical fields generated by laser beams, or microwave fields, mediates a ferromagnetic interaction that aligns the spins. In other words, if the first ion is prepared and kept in the 'northward-pointing' spin-up (↑) state, then the interaction puts the second spin into a ↑ state too.

In a similar way, the authors prepared the first spin in a superposition state (↑+↓) by switching off the spin-rotating microwave or laser fields after 90° of rotation. The researchers then induced the ferromagnetic interaction described above. This orients the second spin into an entangled superposition state of ferromagnetic order (↑↑+↓↓); the ↑ part of the first ion's superposition state rotates the second ion into ↑, and the ↓ part rotates the second ion into ↓ (Fig. 1). The quantum nature of the created correlation became evident when the researchers took measurements of only the first ion's spin. The outcome was completely random but instantaneously determined the outcome of a subsequent measurement of the second spin — the outcome of the second measurement was almost always identical to that of the first.

Some correlation of measurements of classical objects is possible, and this is potentially enhanced in the presence of unknown or hidden (but classical) variables. The maximal possible correlation by classical means can be derived mathematically in the form of an inequality, known as a Bell inequality. In the current experiments, the variety concerned is called the CHSH Bell inequality, and its upper bound for classically achievable correlations is 2. Entanglement requires quantum correlations that enable this upper bound to be exceeded — that is, the Bell inequality can be violated up to a maximum value of approximately 2.828. When such violations are measured experimentally, the results show that entanglement is necessary to describe nature.

In 1982, the first experimental tests were done[4], and demonstrated that entanglement does indeed seem to be necessary. Since then, any potential shortcomings in the experiments used to find violations of Bell inequalities have been ruled out[5,6], albeit within statistical error limits. Tan and colleagues report a violation of up to 2.70, with a residual uncertainty that essentially rules out any classical description of nature — their result is equivalent to being about 40 standard deviations away from the value obtainable using classical explanations. When preparation and readout errors in Ballance and co-workers' study are accounted for, the theoretical maximum of the Bell inequality is 2.236; the authors report a violation of 2.228, with an uncertainty that means that the value differs by 15 standard deviations from any classical description.

The results emphasize that science and engineering at the level of individual quanta can reveal and characterize quantum mechanics with unprecedented accuracy, at close to 100% detection efficiency. But they also impressively demonstrate how the total quantum performance of a system can be benchmarked — the proximity of the experimentally determined violations to their theoretical limits quantifies the quality, performance or fidelity of the quantum operations in a single number.

The findings substantially improve the prospects for designing and realizing devices that use superposition states and entanglement as reliable resources, based on trapped ions or related systems. Different tasks in a common experimental protocol can now be allocated to the atomic species best suited for the chosen purpose — such as quantum memory, performance of logic operations with negligible effects on any nearby quantum memory elements, and generating links to devices based on other technological platforms, such as photonic or solid-state devices. This paves the way for precise spectroscopy, ultra-accurate clocks and simulators of quantum systems. It might even enable the development of universal quantum computers capable of running a superposition of many correlated tasks in parallel, offering much better performance than is currently available using conventional computers, such as exponentially higher speeds for dedicated applications. ■

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REPRODUCIBILITY

Experimental mismatch in neural circuits

The finding that acute and chronic manipulations of the same neural circuit can produce different behavioural outcomes poses new questions about how best to analyse these circuits. SEE ARTICLE P.358

THOMAS C. SÜDHOF

In 1949, Walter Rudolf Hess shared the Nobel Prize in Physiology or Medicine for his work using acute electrical stimulation to study neural circuits. Modern neuroscience is dominated by a newer, more sophisticated technique for acute circuit manipulation: optogenetics, in which light-sensitive ion-channel proteins are engineered to activate or inhibit select neurons[1]. However, a nagging doubt pervades the field — do the behavioural effects of acutely activating or silencing specific neurons reflect the normal functions of these cells? On page 358 of this issue, Otchy *et al.*[2] systematically address this question. Their findings are bound to excite lively discussion.

If acute inactivation of a particular neural circuit alters an animal's behaviour, the seemingly logical conclusion is that the circuit controls the behaviour. But the brain's circuits are densely interconnected, so how can we be sure that these behavioural effects are not caused by changes to other, connected, circuits that normally do not participate in the targeted behaviour but are affected by the manipulation? Otchy *et al.* used a brilliant study design to test this idea. They reasoned that, if the effects of acute manipulation are directly caused by the manipulated neurons, then chronically manipulating those neurons, for example by permanently impairing (lesioning) them, should have the same effect. The authors compared the effects of chronic and acute neural manipulations in rats and in zebra finches. They examined behavioural tasks that were learnt before the manipulations, but that were not repeatedly practised afterwards, avoiding the confounding effect of relearning a task after an experimental manipulation.

First, Otchy *et al.* demonstrated that, in rats that had learnt a complex lever-pressing task, acute silencing of neurons in the brain's motor cortex using the drug muscimol profoundly impaired task performance. Acute optogenetic activation of motor-cortex neurons produced a similar effect. The same research group had shown previously[3] that surgical ablation of the motor cortex blocked the initial learning of the lever-pressing task, but had no significant effect on the ability of rats to perform the task if it had been learnt before surgery. Thus, acute and chronic manipulations produce discrepant results in this circuit (Fig. 1a).

In a second set of experiments, Otchy and colleagues used muscimol to inactivate song neurons in a brain region called the sensorimotor nucleus interface (Nif) in zebra