a user only from the statistics of the observed outputs of such processes, the verification procedure represents a black-box test of randomness.

Violations of Bell inequalities have been observed in numerous experiments over the past three decades[5], and their qualitative connection to randomness has been known for many years. However, quantum-information researchers have started to develop the tools to exploit this connection only in the past few years[6].

A key difficulty has been that most experiments that violate Bell inequalities are affected by loopholes, meaning that they cannot be considered as black-box demonstrations. For instance, the constraint that the two photons cannot exchange signals at subluminal speeds was not strictly enforced in the two previous demonstrations of randomness generation based on Bell inequalities[7,8]. In the past few years, loophole-free experiments have been carried out[9–11], but they remain a technological challenge. In particular, the magnitude of the Bell-inequality violations observed in these experiments, although sufficient to confirm the correlated behaviour of the photons, was too low to verify the presence of randomness of sufficient quality for cryptographic purposes.

Bierhorst and co-workers have improved existing loophole-free experimental set-ups to the point at which the realization of such randomness becomes possible. However, this threshold is barely reached. Every time a photon is measured in the authors' experiment, the randomness that is generated (expressed as bits; 0s and 1s) is equivalent to tossing a coin that has 99.98% probability of landing on heads.

Over many runs, the sequence of measurement outcomes should have accumulated enough uncertainty that truly random bits could be extracted through clever post-processing. However, no existing methods for analysing such sequences would have been efficient enough to reach this goal. Bierhorst *et al.* therefore introduced a powerful statistical technique, tailored to the weak Bell-inequality violations they observed, that achieved this aim. Ultimately, the authors were able to generate 1,024 random bits in about 10 minutes of data acquisition — corresponding to the measurement of 55 million photon pairs.

Bierhorst and co-workers' random-number generator represents the most meticulous and secure method for producing randomness that has ever been demonstrated. However, its generation rate is much lower than in more-conventional commercial quantum random-number generators, which can produce millions of random bits per second[12]. Nevertheless, improvements in the generation rate can reasonably be expected to the point at which this will no longer be a strong limiting factor.

More problematic is the size of the authors' random-number generator: it is comprised of measurement stations that are 187 metres apart to prevent subluminal signalling between the photon pairs. This distance might be reduced in the future, but it is hard to imagine how it could reach the dimensions of more-standard electronic hardware (at most, a few centimetres) using foreseeable technology.

Although Bierhorst and colleagues' study will therefore not directly lead to practical, consumer-grade random-number generators, it sets a new direction and ideal for the secure production of random bits. The authors' approach and theoretical methods could be adapted to much more practical and simple designs for random-number generators that potentially retain many of the conceptual and security benefits of their work. ■

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OPTICAL PHYSICS

Mirrors made of a single atomic layer

Researchers have demonstrated that atomically thin materials can be highly reflective, contrary to general thinking. This finding could have technological implications for nanophotonics, optoelectronics and quantum optics.

KIN FAI MAK & JIE SHAN

The discovery of a single layer of carbon atoms, known as graphene[1], led to great interest in 2D materials. Whereas graphene is highly transparent to visible light[2], 2D materials that are highly reflective could be used as lightweight mirrors in optical or optoelectronic systems. The existence of such materials has been questioned, but, writing in *Physical Review Letters*, Back *et al.*[3] and Scuri *et al.*[4] report that single layers of molybdenum diselenide can have high levels of reflectance.

The importance of the authors' work can be understood by considering the reflection of light from a homogeneous, free-standing thin film of material. When a wave of light of a particular colour — or, equivalently, frequency — hits the film, the oscillating electric field that is associated with the light wiggles the charged particles in the material. This drives the oscillation of electric dipoles (separations between positively and negatively charged particles) at the same frequency as that of the incident light (Fig. 1a).

The oscillating dipoles re-radiate light waves in both the forward and backward directions with respect to the direction of the incident wave. Whereas the latter occurrence gives rise to reflection, the former destructively interferes with the incident wave, producing transmitted light that has a lower intensity than that of the incident light. The material's response to an oscillating electric field is, in general, not uniform with respect to incident waves from across the electromagnetic spectrum. At a particular frequency, the dipoles have a large oscillation amplitude — a phenomenon known as resonance — which results in more reflection and less transmission of light than at any other frequency.

Like all oscillators in real physical systems, the oscillations of the dipoles are damped, which means that they die out if the event that drives them is stopped. There are two ways in which the energy that is stored in the dipoles can be lost: it can be re-radiated (as discussed previously) or it can be absorbed by the material and converted into heat. These processes are known as radiative and non-radiative damping, respectively. In most materials, both mechanisms of damping operate. The incident light is therefore partly reflected, partly absorbed and partly transmitted.

However, in a material in which radiative damping dominates, the absorption losses would be negligible, and all of the incident electromagnetic energy would be re-radiated. Furthermore, the re-radiation in the forward direction would perfectly cancel out the incident light, through destructive

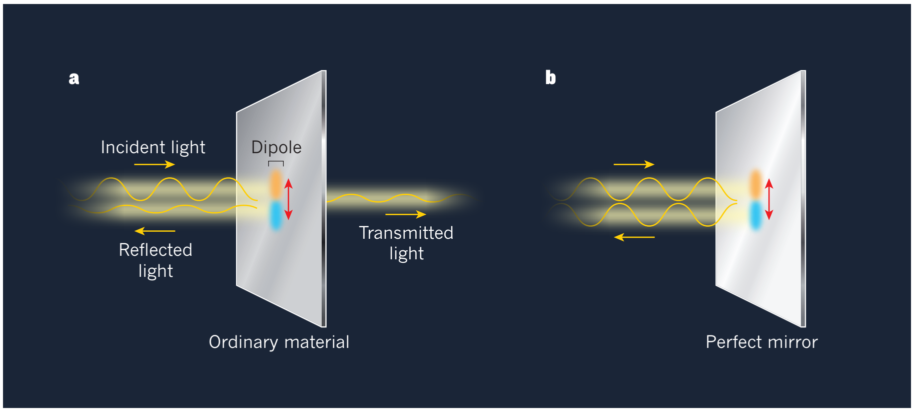

Figure 1 | A conventional material versus a perfect mirror. **a**, When a wave of light hits a thin film of an ordinary material, it produces electric dipoles — separations between positively charged (orange) and negatively charged (blue) particles. These dipoles oscillate (red arrow) at the same frequency as that of the incident light. They re-radiate light waves in both the forward and backward directions, which gives rise to transmission and reflection, respectively. **b**, By contrast, in a hypothetical perfect mirror, there is no absorption or transmission, and the incident light is reflected entirely. Back *et al.*[3] and Scuri *et al.*[4] report near-perfect mirrors made of a single layer of the material molybdenum diselenide.

interference. Owing to conservation of energy, the incident light would be reflected entirely, and the material would act as a perfect mirror (Fig. 1b). This holds true even when the material comprises a single layer of atoms, provided that the oscillating dipoles are being driven at their resonance frequency.

Although theoretical studies have suggested that such conditions could be realized in a 2D array of ultracold atoms[5,6], the authors demonstrate near-perfect mirrors in a solid-state system. They use a single layer of molybdenum diselenide, which is a semiconductor and belongs to a family of materials known as the transition-metal dichalcogenides. In such materials, the oscillating dipoles generated by the incident light are excitons[7] — bound pairs of an electron and a hole (the absence of an electron). The more tightly bound the excitons are, the larger the radiative damping will be, and the more perfectly the mirror will behave. Previous experimental work has shown that the exciton binding in single-layer transition-metal dichalcogenides is extremely strong[8–10], which results in a rate of radiative damping that is much greater than that of conventional semiconductors.

Back *et al.* and Scuri *et al.* fabricated high-quality samples of single-layered molybdenum diselenide by encapsulating the material in atomically thin, inert films of hexagonal boron nitride, and then carried out their experiments at a low temperature (4 kelvin). Under these conditions, the authors show that radiative damping of the excitons is the dominant process. They demonstrate mirrors that can reflect a considerable proportion of the incident light — up to 85% in Scuri and colleagues' study — at the exciton resonance frequency of the material.

Although the authors' near-perfect mirrors work only in light from a narrow range of the electromagnetic spectrum (in the vicinity of the resonance frequency), the two studies open up intriguing possibilities for the fields of nanophotonics and quantum optics. For instance, quantum nonlinear optics requires strong interactions between photons at the single-photon level, which is difficult to achieve in conventional materials. The authors' work shows that quantum nonlinear optics could be realized in single-layer transition-metal dichalcogenides because of the extremely strong light–matter interactions that can be achieved[11].

The authors also demonstrate that the application of a voltage causes the mirrors to switch from being highly reflective to highly transparent. Such mirrors could therefore be used as light modulators, or as other reconfigurable components, in optical and optoelectronic systems. Moreover, the excitons in single-layer transition-metal dichalcogenides have a feature known as the internal-valley degree of freedom[7], which might enable the mirrors' reflectance to be controlled purely by varying the polarization of the incident light.

About a decade ago, during the early stages of research on 2D materials, many scientists were asking whether a single layer of atoms could be highly reflective. Thanks to Back *et al.* and Scuri *et al.*, we now know that the answer is yes. ■

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This article was published online on 9 April 2018.

PLANT BIOLOGY

Peptide signal alerts plants to drought

It is thought that plants sense water availability in the soil as a way of anticipating drought. The identification of a peptide expressed when water is scarce offers a chance to unravel the underlying molecular mechanism. SEE LETTER P.235

ALEXANDER CHRISTMANN & ERWIN GRILL

Because plants cannot move to escape unfavourable conditions, they must continuously monitor environmental cues to survive when conditions change. Plants can sense interactions with other organisms, such as bacteria, and can monitor light conditions across the spectrum, from ultraviolet to far red. The molecular mechanisms that facilitate those capacities are well understood. But how plants sense drought, cold and salt has remained an enigma[1]. On page 235, Takahashi *et al.*[2] report the identification of a peptide that is generated in response to a water deficit in plants.

Drought, cold or salty conditions can affect a plant's water status. Such conditions result in the synthesis[3] of the hormone abscisic acid (ABA), which can regulate the plant's water levels. Stomatal pores in leaves enable plants to take up the carbon dioxide required for photosynthesis, but water vapour can escape through them. ABA can trigger a reduction in