GRAVITATIONAL-WAVE DETECTION

# Entanglement at work

The Einstein–Podolsky–Rosen type of quantum entanglement can be used to improve the sensitivity of laser interferometer gravitational-wave detectors beyond the quantum limit.

Raffaele Flaminio

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen published the famous paper describing the EPR paradox, with the aim to challenge the basis of quantum mechanics. However, the paradox turned out to be a real effect and quantum entanglement is now recognized as an essential part of quantum mechanics. Writing in *Nature Physics*, Yiqiu Ma and colleagues[1] propose a way of taking advantage of this quantum entanglement to improve the sensitivity of gravitational-wave detectors.

In 2016 the LIGO and Virgo collaborations announced the first direct detection of gravitational waves, emitted by the coalescence and merger of binary black holes[2]. This ground-breaking discovery is the result of over fifty years' worth of efforts by three generations of scientists. Nowadays, kilometre-scale Michelson laser interferometers are used to detect the tiny variation of the spacetime geometry produced on Earth by the most powerful phenomena in the Universe, such as the merger of black holes and the explosion of massive stars. Thanks to the progress in basic research and technology, these gigantic detectors are able to measure variations of the interferometer mirror positions of the order of $10^{-18}$ m. At this level of sensitivity the detectors are limited by the quantum nature of the light used to sense their mirror's positions.

Indeed, the proper quantum description[3] of a Michelson interferometer shows that its sensitivity is limited by the quantum vacuum fluctuations entering from the output port of the interferometer. These fluctuations have two effects. On one hand, they add to the laser beam entering the interferometer, limiting the precision with which the phase of the field exiting the interferometer — and therefore the interferometer mirror positions — can be measured. The importance of this effect tends to decrease as the laser power injected into the interferometer increases. On the other hand, the superposition of the vacuum fluctuations with the laser field produces varying radiation pressure on the mirrors, which instead increases with the injected power. We are therefore dealing with a kind of 'Heisenberg microscope', where more injected power improves the measurement up to the point where a further increase starts perturbing the system and thus the measurement. Indeed, it is ultimately the Heisenberg uncertainty relation that limits the detector sensitivity.

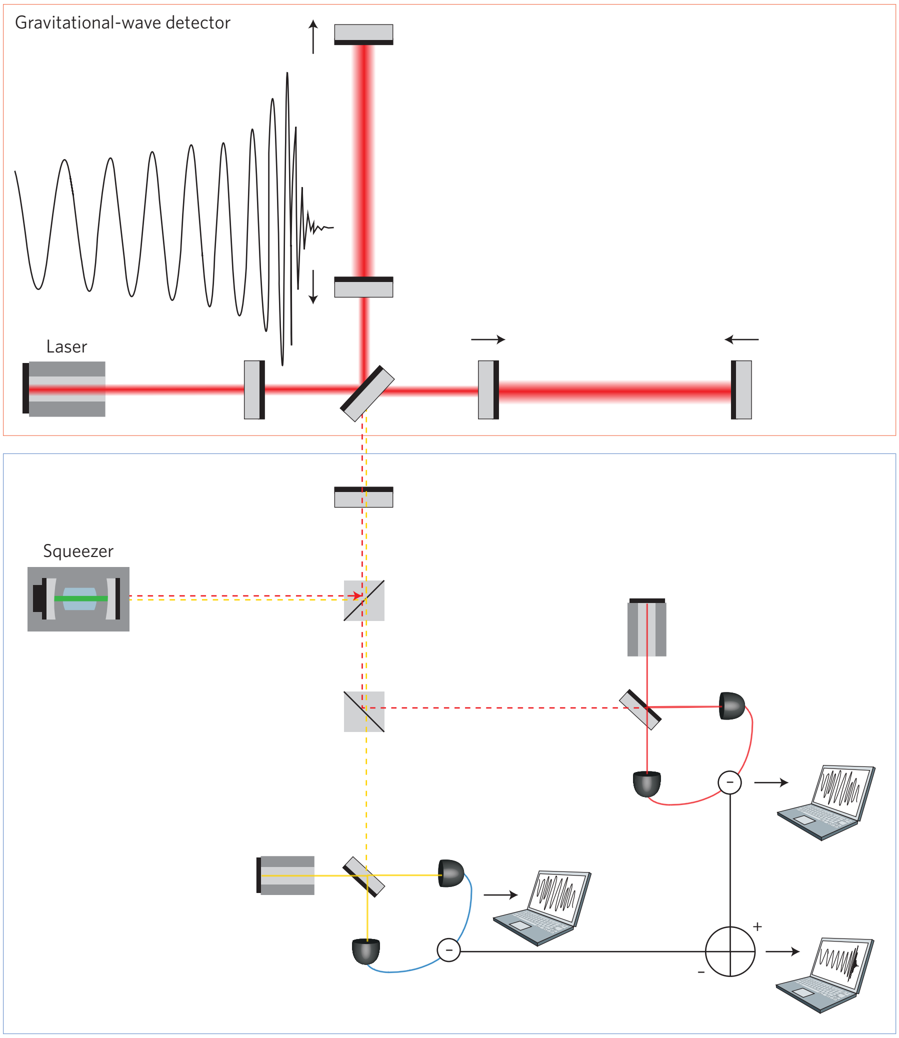


**Figure 1 |** In the lower panel, two entangled beams (yellow and red) are injected into the output port of a laser interferometer gravitational-wave detector (upper panel). The beams reflected by the interferometer are detected separately. Thanks to their quantum correlations, the combination of the two output signals reveals the gravitational wave enveloping the interferometer and hidden by the quantum noise.

Luckily, this quantum limit is not the ultimate bound as long as one is interested in measuring only one of the two quadratures of the electric field while disregarding the other, as is the case in a gravitational-wave interferometric detector. By using an optical squeezer it is possible to generate vacuum states characterized by smaller fluctuations along one of the field quadratures, at the cost of larger ones in the other. The proper injection of such a squeezed vacuum state into the interferometer output port allows for the reduction of the fluctuations in phase with the gravitational-wave signal. This technique was successfully implemented in the GEO600 and LIGO interferometers to improve their sensitivities in the kHz frequency region. But the way these fluctuations affect the overall interferometer sensitivity depends on the interferometer response. Below ~100 Hz, the suspended mirrors are displaced by the larger fluctuations in the other phase of the field, thus increasing the so-called radiation pressure noise. To overcome this effect, it has been proposed to use frequency-dependent squeezed vacuum — a vacuum state whose squeezed phase depends on the frequency. Such a solution has the potential to decrease both phase noise and radiation pressure noise without violating the Heisenberg relation. So far scientists have been pursuing the use of 100-m-scale low-loss optical cavities to imprint the proper frequency dependence on a squeezed vacuum state. But Ma and colleagues now suggest taking advantage of the EPR quantum entanglement to produce such a frequency-dependent squeezed vacuum.

An optical squeezer requires a nonlinear crystal. When this is properly pumped with a laser beam, it generates a squeezed vacuum by producing entangled virtual photons at half the pumping frequency. By choosing the pumping frequency equal to twice the interferometer's main laser frequency, the entangled photons will be right at the desired wavelength. But in the design proposed by Ma *et al.*, the nonlinear crystal is pumped at a frequency slightly shifted from that value. As a result, the two entangled beams will have slightly different frequencies and, once injected into the interferometer, they will undergo different frequency-dependent phase shifts. The fluctuations that the two entangled beams will generate once superposed with the main laser will be correlated so that, as in the EPR paradox, the measurement of fluctuations in one of the beams will allow the prediction of fluctuations in the other (Fig. 1). By properly separating the two beams and measuring the fluctuations of each, the authors show that it will be possible to reduce the fluctuation of the proper combined output at all frequencies and thus reduce the effect of quantum noise over the entire detector bandwidth.

The remarkable advantage of this proposal is that no long low-loss optical cavities will be required. The price to pay is the detection of two beams instead of one, with the consequent reduction by a factor of $\sqrt{2}$ of the quantum noise that one can achieve given an initial vacuum-squeezed level. As it is often the case, more investigations are needed to understand the impact that various sources of optical losses will have on the ultimate performance. But the idea of using Einstein's most famous (mistaken) paradox to improve the sensitivity of gravitational-wave detectors, enabling new tests of his general theory of relativity, is certainly intriguing. Einstein's ideas — whether wrong or right — continue to have a strong influence on physics and astronomy. ❐

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## References

1. Ma, Y. *et al. Nat. Phys.* **13,** 776–780 (2017).
2. Abbott, B. P. *et al.* (LIGO Scientific and Virgo collaborations) *Phys. Rev. Lett.* **116,** 061102 (2016).
3. Caves, C. M. *Phys. Rev. D* **23,** 1693–1708 (1981).

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QUANTUM SIMULATION

# Probing information scrambling

Quantum information encoded in one of many interacting particles quickly becomes scrambled. A set of tools for tracking this process is on its way.

Monika Schleier-Smith

Quantum information can never be entirely lost, but it can be exceedingly well hidden. In interacting systems of many particles, information encoded in a given particle can quickly become diluted among all the degrees of freedom like a drop of dye in the sea — each dye molecule soon to be found everywhere with equal probability. Understanding how quantum information spreads may have wide-ranging implications, from elucidating the information paradox in black holes[1,2] to imposing fundamental limits on transport properties of strongly correlated materials[3]. Writing in *Nature Physics*, Martin Gärttner and colleagues present a powerful set of tools for directly probing the 'scrambling' of quantum information in an experiment using laser-cooled ions[4].

Scrambling is intimately related to chaos[5], a concept that is tricky to define in the framework of quantum mechanics. Classically, a hallmark of chaos is the sensitivity to initial conditions. But, consider two slightly different quantum states of a system, $|\psi_1\rangle$ and $|\psi_2\rangle$, governed by a Hamiltonian $H$, and compare their time evolution under the Schrödinger equation. A one-line derivation reveals that the overlap $\langle\psi_2(t)|\psi_1(t)\rangle$ is a constant, so two states that are initially similar will remain similar for all time. What, then, does it mean for the Hamiltonian $H$ to be chaotic?

Paraphrasing the famous analogy of chaos theory, how can the flap of a quantum butterfly's wing in Brazil trigger a tornado in Texas[6]? The answer is easiest to formulate in the Heisenberg picture of quantum mechanics, in which states are constant, but operators evolve in time. A chaotic system is then one where an initially localized operator — say $W$, the wing that flaps in Brazil — rapidly extends its influence throughout Hilbert space, affecting the vorticity of the air in Texas. As a result, the operator for the vorticity $V$, initially commuting with $W$, no longer does so at