

uncertainty from having a discrete spacetime has been reduced by a factor of three. This correspondingly reduces the error on extrapolating from the unphysical lattice world to the real world.

Until now, this uncertainty has been a problem for the charm quark because its relatively large mass gives it a short-wavelength quantum field that can 'see' the lattice spacing. This improvement also helps for light quarks: the pion and kaon decay constants calculated by Follana *et al.* have uncertainties of 1.5% and agree with experiment. In another significant check, which was not possible previously, the computed masses, with no free parameters, of the D meson and the D_s meson (charm quark, anti-strange quark) also agree with experiment.

The LQCD calculation of f_D agrees with the experimental result⁷ from the CLEO- c 'charm factory' — within the errors of about 8% for experiment and 2% for theory. However, there is a

fly in the ointment. For the D_s meson, the most precise measurement^{6,7} of its decay constant, f_{D_s} (analogous to f_D), sits about three standard deviations above the calculation by Follana and colleagues¹. The discrepancy is a surprise. Follana *et al.* are checking their calculation by computing other related quantities that have already been well measured. CLEO- c will have an updated result from a larger data set by the summer. Then we will be in a better position to judge: either the discrepancy will disappear, or it will have been established with greater statistical significance.

What could be causing it? If the discrepancy is real, it could be due to new physics. If a particle exists that is not in the standard model but couples predominantly to leptons (electrons, muons and taus) and charm quarks, but not to down quarks, then the decays of the D^+ meson would be unaffected by it; but the decays of D_s mesons would. The D_s decays could be

more sensitive to new physics than any other process explored so far⁸. On the other hand, if the discrepancy disappears and the data validate the LQCD calculation of f_{D_s} , this would inspire confidence in LQCD calculations of f_B . The result would be improved measurements of the sides of the unitarity triangle, and hence an increased sensitivity in CP-violation experiments to new physics. It's a win-win situation, just what particle physicists like best.

References

1. Follana, E. *et al.* (HPQCD and UKQCD Collaborations) *Phys. Rev. Lett.* **100**, 062002 (2008).
2. Davies, C. T. H. *et al.* *Phys. Rev. Lett.* **92**, 022001 (2004).
3. Shipsey, I. *Nature* **435**, 185–187 (2005).
4. Aubin, C. *et al.* (MILC Collaboration) *Phys. Rev. D* **70**, 114501 (2004).
5. Artuso, M. *et al.* (CLEO Collaboration) *Phys. Rev. Lett.* **95**, 251801 (2005).
6. Pedlar, T. K. *et al.* (CLEO Collaboration) *Phys. Rev. D* **76**, 070002 (2007).
7. Ecklund, K. M. *et al.* (CLEO Collaboration) *Phys. Rev. Lett.* (in the press); preprint at <<http://arXiv.org/abs/0712.1175>> (2007).
8. Dobrescu, B. A. & Kronfeld, A. S. Preprint at <<http://arXiv.org/abs/0803.0512v1>> (2008).

GRAVITATIONAL WAVE DETECTORS

Squeezing up the sensitivity

Gravitational wave detectors based on laser interferometry have reached an incredible level of sensitivity. But to develop to the level needed to explore the Universe, the next generation of detectors will probably need to use squeezed light.

Roman Schnabel

is at the **Institute for Gravitational Physics, Leibniz Universität Hannover and the Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute), 30167 Hannover, Germany.**

e-mail: roman.schnabel@aei.mpg.de

Future gravitational wave detectors will need to be more than a hundred times more sensitive than current devices if they are to enable us to gather information about the fundamental nature of the Universe and the behaviour of the largest, most energetic, and possibly electromagnetically dark, astrophysical objects within it. Reaching this level of sensitivity will require a host of techniques that have been developed in the field of quantum optics. Of these, the ability to generate so-called squeezed light — in which the noise of one of light's degrees of freedom is reduced to less than that usually dictated by the Heisenberg uncertainty principle at the expense of increasing the noise of another — is likely to be the first

to be put into practice. Although the use of squeezed light for improving the sensitivity of interferometers built using fixed mirrors on a mechanically stable optical bench has been demonstrated, the real test is whether similar performance can be achieved on a practical gravitational wave detector using suspended mirrors. On page 472 of this issue¹, Goda and colleagues demonstrate the successful completion of just such a test, in a 40-m prototype detector.

The existence of gravitational waves is a direct consequence of Albert Einstein's theory of general relativity. They propagate with the speed of light and are produced when masses are accelerated. The Universe should be filled with gravitational waves originating from the big bang, supernova explosions, black hole binaries and possibly from objects that we do not even know about yet. Gravitational waves stretch the very fabric of spacetime, which should be detectable as a change in the distance between free-falling objects. Back on Earth, gravitational waves are expected to

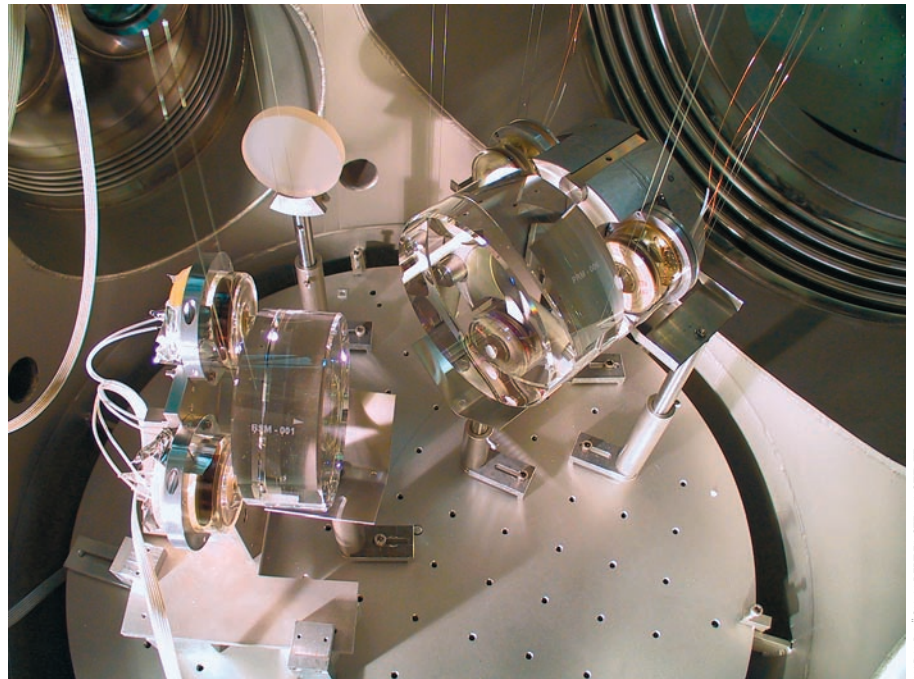
be extremely small, and Albert Einstein assumed that they might never be observed directly. However, the possibility of opening up a new window to the Universe, and to establish a new type of astronomy, has been a strong source of motivation in the development and construction of instruments with superlative sensitivity.

Recent decades have seen the invention of numerous new detector technologies, many of which are being implemented in ground-based, kilometre-scale laser interferometers^{2–5} (GEO600, LIGO, TAMA300, VIRGO). These detectors are based on Michelson interferometers whose mirrors are suspended from multiple pendula. Over short timescales, corresponding to operational detection band frequencies from tens of hertz up to several kilohertz, the mirrors are quasi-free in the free-falling horizontal directions of the propagating laser beams. In these directions the mirrors act as test masses of spacetime, and by measuring changes in their relative displacement it should be possible to detect

the propagation of a gravitational wave passing between them. But this is only possible if all sources of detector noise are reduced to an absolute minimum.

The current generation of interferometers are designed to measure strains in spacetime of about one part in 10^{21} , corresponding to a distance change of 10^{-18} m for a 1-km-long interferometer. This value sets the upper limit for the sum of all noise contributions that might change, or appear to change, the relative positions of an interferometer's mirrors, and puts stringent requirements on the operational tolerances of the entire set-up. The suspended mirrors used in these devices (see Fig. 1) are made from high-quality fused silica and designed such that the thermally excited internal motions of the mirrors' surfaces with respect to their centres of mass do not result in excessive thermal noise in the detection band. In the GEO600 detector the suspension fibres are made from fused silica, have 250 μm thickness and are monolithically attached to the mirrors, all in order to keep the thermal noise floor as low as possible. But whereas thermal noise is linked to brownian motion and therefore can in theory be made arbitrarily small by cooling the mirrors, there is another source of noise that is, from some perspective, more fundamental. That is, quantum-mechanical noise.

During its operation, an interferometer's output laser field is measured by a photoelectric detector giving results in the form of counting statistics. For highly stabilized, coherent laser light, the uncertainty in these statistics is governed entirely by quantum mechanics and called shot-noise. This noise corresponds to an apparent distance change of the interferometer mirrors, and therefore masks weak gravitational wave signals. The most straightforward way of reducing the impact of this shot-noise is to use a stronger laser, which improves the signal-to-noise ratio. But this approach has its drawbacks. Stronger lasers generate greater photon pressure on the mirrors of an interferometer, which in turn introduces back-action noise that requires the use of heavier mirrors. Current detectors use ultrastable, high-power laser sources with operational powers approaching 10 kW at the central beam splitter (using power-recycling cavities), and mirror masses of up to 10 kg. But although there is nothing fundamental to stop these parameters from being increased still further, the higher they are pushed the more expensive the detectors become.



HARALD LOCK, ALBERT-LUENIGER-INSTITUT

Figure 1 View into a gravitational wave detector. Laser light that is reflected between suspended mirrors is used to measure changes in spacetime caused by remote astrophysical events. The photograph shows the power-recycling mirror of the GEO600 detector, which retro-reflects laser light back towards the central beam splitter to increase the effective laser power.

Squeezed light represents a potentially more cost-effective alternative to increasing the sensitivity of gravitational wave detectors. In an interferometer operated with squeezed light, the quantum noise is reduced below the shot-noise of the natural counting statistic, without lowering the signal strength. Squeezed light relies on the existence of quantum correlations between the arrival times of photons at the detector. Owing to the quantum nature of these correlations, squeezed light is susceptible to a range of decoherence processes, such as optical loss and phase diffusion, that destroy these correlations. For this reason, its use had been considered by many to be too technically involved to be implemented in a practical detector. But with developments in the performance of the nonlinear optical materials and components that generate and process squeezed optical fields, the prospects for their use are improving. Squeezed states of light were demonstrated recently in the complete detection band of ground-based gravitational wave detectors⁶. And now, Keisuke Goda and colleagues successfully extend this with a successful prototyping of the squeezed light technique in a quasi-suspended gravitational-wave-detector arrangement¹, enabling them to

increase the sensitivity of their detector by 44%.

The degree of quantum noise reduction achieved in the current demonstration is limited by optical losses in the authors' system, which includes the imperfect quantum efficiency of the photo detectors used. With further development, it seems reasonable to expect that such losses could be reduced in large-scale detectors to bring about further improvements in sensitivity of up to 100% — equivalent to simply increasing the power of the lasers used by a factor of four. Regardless of what laser power is actually used in the detector, this effectively increases the volume of the Universe that can be explored by a factor of 8 (the sensitivity improvement factor cubed). In doing so, the successful prototype test by Goda and colleagues represents an important step, and paves the way towards an implementation of squeezed light techniques in full-scale gravitational wave detectors.

References

1. Goda, K. *et al. Nature Phys.* **4**, 472–476 (2008).
2. <http://geo600.aei.mpg.de/>
3. http://www.ligo.caltech.edu/cit_local.html
4. <http://tamago.mtk.nao.ac.jp/>
5. <http://www.virgo.infn.it/>
6. Vahlbruch, H., Chelkowski, S., Danzmann, K. & Schnabel, R. *New J. Phys.* **9**, 371 (2007).