Gaussian noise through amplitude noise on one of the beams[5] and through phase noise on both beams[6], respectively. The two groups have different ways of detecting information for the gatekeeper and for the post-selection of the data, but in both cases they verify that the degree of entanglement of the distilled information stream is close in quality to that of the unperturbed pair of beams.

These proof-of-principle demonstrations show that the proper protocols can make use of entanglement in practical situations. There are many ways of generating the pairs of entangled beams, and the influence of the environment has to be analysed carefully and the distillation protocol has to be adapted to the individual situations. We will not find a universal solution that is optimal for all cases, but the impressive technical progress reported by Dong *et al.*[5] and Hage *et al.*[6] can give us confidence that optical entanglement will be useful in practical applications.

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OPTICAL LATTICE CLOCKS

Keeping time in three dimensions

The demonstration of an optical clock in which individual atoms are confined in a three-dimensional optical lattice moves us closer to the atomic clockmaker's dream: tens of thousands of isolated atoms that work in parallel.

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Optical atomic clocks are rapidly moving from being clocks of the future to present-day devices, mainly thanks to advances in laser cooling, laser stabilization and optical frequency combs[1]. Benefiting from their high oscillation frequencies, the best optical atomic clocks are now ten to a hundred times more precise than their microwave counterparts, which have traditionally been the workhorse for precision-timing applications such as global positioning systems[2,3]. On page 954 of this issue, Tomoya Akatsuka, Masao Takamoto and Hidetoshi Katori report an important advance in this field, in which the most promising approach for a neutral-atom optical clock has been realized in full for the first time[4]. They have designed and demonstrated a three-dimensional lattice whose micrometre-sized compartments contain at most one atom (see Fig. 1), thereby suppressing contaminating atom–atom interactions.

At the heart of every optical atomic clock is a stabilized laser — ticking at 10^{15} times per second — whose frequency is locked to that of an atomic transition[1]. Clocks differ in the choice of transition and how the atoms are prepared. Historically there have been two main approaches to building atomic clocks: those based on trapped ions and those based on clouds of neutral atoms. For making the most accurate clocks, single trapped ions are attractive because they can be well isolated from external effects that perturb the intrinsic atomic (or ionic) frequency. Already two different ion clocks have achieved uncertainties an order of magnitude below that of the best existing microwave clocks[2]. Neutral atoms on the other hand hold great appeal because they can be trapped and cooled in large numbers, offering the possibility of a high signal-to-noise ratio that can produce an extremely precise clock. Clouds of neutral atoms, however, have the troublesome property for clockmakers of causing unwanted frequency shifts when individual atoms get too close together (that is, when they collide).

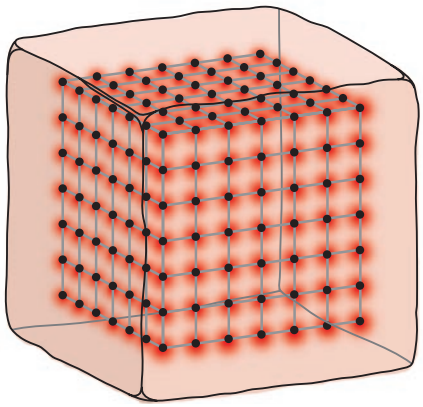

Figure 1 Kept in isolation. Akatsuka *et al.*[4] have built a clock consisting of some 100,000 atoms trapped at separate sites of an optical lattice (red), preventing signal-deteriorating collisions between them.

In 2001, Katori and his co-workers proposed a solution to this problem by identifying optical transitions that could make use of the features of atoms confined in an optical lattice, which is an array of egg-carton-like potential wells formed by intersecting laser beams[5–7]. In this way one could hope to have large numbers of atoms confined in an ion-like environment. Several groups jumped on this idea, and today there exist more than half a dozen lattice clock experiments around the world. This research has removed the main doubts about whether the lattices themselves could be engineered by appropriately controlling their wavelength and polarization, so as not to perturb the clock transition. And future prospects look extremely promising[8,9]. However, experiments thus far have used one-dimensional (1D) standing-wave light fields that provide submicrometre confinement in only one dimension. In this geometry, there are typically tens of atoms confined in each of several hundred disks, so the possibility of collision shifts still exists.

Akatsuka and colleagues[4] investigate two solutions to this problem. The first is to continue the use of 1D lattices, which are comparatively easy to handle, but to load them with ultracold fermionic atoms, which, by the laws of quantum statistics, are

forbidden from colliding when prepared and excited identically. Akatsuka *et al.* excite the atoms more uniformly than has been achieved in previous experiments, which should suppress density-dependent shifts to a higher degree. The second solution is to construct a 3D lattice that spatially separates the individual atoms from one another. They have achieved the formidable task of creating and loading a 3D optical lattice, while preventing multiple atoms from gathering at one lattice site. In this case Akatsuka *et al.* claim that bosons — the quantum statistical counterpart to the fermions — are preferable, as they are less sensitive to the complicated light polarization that exists in a 3D lattice. Thus they use bosonic strontium-88 in their 3D setting, despite the increased magnetic field-based frequency shift that accompanies its use[8].

As part of the demonstration, the authors make a comparison between the frequencies of 1D and 3D versions of the non-interacting lattice clock. The total fractional uncertainty for each of the two clocks is one to two parts in 10^{15}, which, although impressive, falls short of the best evaluations of other state-of-the-art optical atomic clocks[2,3]. Because of the uncertainty, they have found it hard to verify to a high degree how well the 1D clock suppressed the collision shifts. The measurement uncertainties, however, were not due to fundamental limitations, and should be considerably reduced in the near future.

This demonstration represents an important milestone towards the ultimate lattice clock, but several questions remain. In particular, the question of whether fermions or bosons are ultimately better suited for 3D lattice clocks is still open and could have important experiment consequences (bosonic isotopes may require more stable lasers and more stable magnetic fields). Additionally, it is still not clear what will be the ideal 3D lattice apparatus. A lattice geometry based on separate laser beams for each of the dimensions — Akatsuka *et al.*[4] use a single, multiply reflected laser — could be used to evaluate ideas such as the use of multiple lattice frequencies and/or different configurations for the polarization. Several multi-beam lattices are already under development, so expect rapid advances in answering these and other important questions, leading to the realization of a 3D lattice clock with predicted uncertainties of below one part in 10^{17}. At this level of clock performance new applications emerge, including setting new limits on possible drifts of fundamental constants[2] or even a new type of relativity-based geodesy[10], as well providing a fascinating quantum-atomic system in its own right.

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ULTRACOLD MOLECULES

The coldest polar region

Polar diatomic molecules, consisting of potassium and rubidium, have been created with density and temperature close to the regime of quantum degeneracy.

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The ability to produce ultracold atoms has had a revolutionary impact across many areas of science. An ultracold sample of polar molecules — that is, molecules that when fixed in space possess a net electric dipole moment — promises similar but distinctly different payoffs. Cooled molecules open up a new realm of physics as a result of their complex internal structure, which gives rise to the rotational and vibrational motions that are absent in atoms. However, this same complexity has made it difficult to cool molecules to the ultracold regime. Now, Kang-Kuen Ni and co-workers[1] have created a gas of diatomic molecules that is ultracold in all its degrees of freedom, both translational and internal. The sample of polar molecules is at a temperature and density near the conditions for quantum degeneracy. Possible applications are in areas as diverse as quantum simulation of strongly correlated systems, quantum information processing, quantum chemistry and precision measurements.

Ni *et al.* use a multi-step method to produce ultracold potassium–rubidium (KRb) polar molecules (Fig. 1). Co-located gases of K and Rb are simultaneously laser-cooled, optically trapped and evaporatively cooled to a high phase-space density. Next, pairs of atoms from this mixed-species cloud are joined into very weakly bound molecules. This is accomplished by using a magnetic field to adjust the energy of the unbound atoms (which are in a particular pair of hyperfine sublevels) into resonance with the energy of a bound pair of the same atoms (but in a different hyperfine configuration). By slowly sweeping the field through this so-called Feshbach resonance, the atoms are adiabatically transformed into the bound configuration.

This process of 'magneto-association' has become a workhorse in ultracold-atom physics. For example, it has previously made possible the formation of Bose–Einstein condensates of homonuclear molecules[2]. However, although molecules in these types of states have been of great interest, they would not be familiar to most chemists: they are bound by only about 10^{-5} eV or less; the atoms reside tens of ångströms or more apart; and they have about 0.5 eV of vibrational energy. In fact, for these weakly bound states, the electron orbitals of the two atoms barely hybridize. Therefore even heteronuclear molecules, such as KRb, possess virtually no molecular electric dipole moment here. Moreover, the enormous vibrational energy can be released in inelastic collisions, leading to rapid heating in a dense sample.

To remove the molecular internal energy, Ni *et al.* applied a pair of laser pulses. The