been successfully detected with single-lattice-site resolution at Harvard University, once again using Raman sideband cooling[12]. One important aspect is the fact that, due to rapid light-assisted collision processes in multiply occupied sites, such quantum gas microscopes are only sensitive to the parity of the on-site atom number. Although this can be a severe limitation for bosonic systems, it is less a problem for ultracold fermions when they occupy a single lattice band because Pauli's exclusion principle forbids multiple occupancy on a single site.

All three Fermi gas microscope experiments achieved a very good fidelity in the distinction of empty and unity occupied sites after illumination times between one and two seconds in which approximately 1,000 photons per atom were collected. However, an excellent optical detection signal-to-noise ratio is not the only important feature of a useful quantum gas microscope. Equally important is a low atom loss and low hopping rate during the illumination time. Both require efficient cooling to confine the atoms to the lowest onsite energy levels during the time they scatter light. One way to quantify these rates is to take successive images of the same atomic cloud and to directly 'watch' the atoms disappear or hop. All three research teams performed these measurements and demonstrated that low rates (a few per cent) can be achieved and, thus, that high-fidelity imaging of strongly correlated fermions can be realized. The highest demonstrated reconstruction fidelity of the parity signal is 95% (ref. 12).

In the three experiments an optical resolution slightly better than the wavelength of the imaging light (671 nm for lithium and 770 nm for potassium) is required to detect the atoms with single-lattice-site resolution. This is achieved by using high numerical aperture (>0.8) imaging techniques, which need to be compatible with an ultracold atom experiment carried out in an ultrahigh vacuum environment. The groups use different strategies to accomplish this. Whereas the Strathclyde team works with a highly specialized custom-designed objective that combines a high numerical aperture with a large working distance above one centimetre, the teams at Harvard and MIT prepare their two-dimensional gas a few micrometres away from a hemisphere in optical contact with the vacuum window. In both approaches the depth of focus is limited, such that high-resolution quantum gas microscopes are at present restricted to the detection of a single two-dimensional plane.

These imaging techniques pave the way towards a new generation of quantum gas experiments with fermions. The next step is to achieve low temperatures of the two-dimensional quantum gases under the microscopes. Here, the state of the art in other experiments is around 5% to 10% of the Fermi temperature. This requires the combination of the best (evaporative) cooling strategies with the quantum microscope set-ups. Once such cold temperatures have been achieved, the microscopes can be used to probe strongly correlated fermionic quantum gases with unprecedented resolution at the single atom level.

Further developments include the implementation of single-site manipulation techniques. These are ideally suited to study the response of the system to local quenches or to project arbitrary potentials onto the atoms. Even the simultaneous detection of two spin states might be implemented in the future, making the technique even more powerful for the study of quantum magnetism. Finally, quantum gas microscopy can also be used to study small sufficiently dilute continuous systems with high precision. In this case the optical lattices can be ramped up suddenly to freeze the atomic position for the subsequent single-atom-sensitive detection. ❐

Christian Groß is at the Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany.
e-mail: christian.gross@mpq.mpg.de

References

1. Nelson, K. D., Li, X. & Weiss, D. S. *Nature Phys.* **3,** 556–560 (2007).
2. Bakr, W. S., Gillen, J. I., Peng, A., Fölling, S. & Greiner, M. *Nature* **462,** 74–77 (2009).
3. Sherson, J. F. *et al. Nature* **467,** 68–72 (2010).
4. Miranda, M., Inoue, R., Okuyama, Y., Nakamoto, A. & Kozuma, M. *Phys. Rev.* A **91,** 063414 (2015).
5. Endres, M. *et al. Science* **334,** 200–203 (2011).
6. Cheneau, M. *et al. Nature* **481,** 484–487 (2012).
7. Fukuhara, T. *et al. Nature Phys.* **9,** 235–241 (2013).
8. Simon, J. *et al. Nature* **472,** 307–312 (2011).
9. Schauß, P. *et al. Nature* **491,** 87–91 (2012).
10. Haller, E. *et al. Nature Phys.* http://dx.doi.org/10.1038/nphys3403 (2015).
11. Cheuk, L. W. *et al. Phys. Rev. Lett.* **114,** 193001 (2015).
12. Parsons, M. F. *et al. Phys. Rev. Lett.* **114,** 213002 (2015).

QUANTUM OPTICS

Jumping to hyperentanglement

A state-of-the-art source of hyperentangled photon pairs has been built and its quantum properties fully characterized.

Olivier Pfister

Once considered a central oddity of quantum mechanics and the key to its incompleteness[1], entanglement is also the essential ingredient of quantum information. The most powerful quantum computing algorithms require entanglement between a large number of qubits, which can be implemented using optical modes. Furthermore, the generation of high-quality entanglement between two modes (bipartite) is still a key enabler of quantum technologies such as quantum cryptography, quantum teleportation and repeating, and quantum secret sharing.

Writing in *Nature Photonics*, Zhenda Xie and colleagues[2] demonstrate a significant experimental advance in the generation and verification of photonic bipartite hyperentangled states. Hyperentanglement[3] is the achievement of simultaneous entanglement that spans more than one degree of freedom, for example photon number, frequency and polarization (Box 1). It is an important resource for quantum information as its quantum (entangled) redundancy allows more flexibility in implementing essential Bell-state measurements as well as providing error-correction encoding features.

For their hyperentanglement experiment, Xie *et al.*[2] used a highly efficient type-II spontaneous parametric downconversion (SPDC) source comprising a long (1.6 cm) waveguide in a periodically poled potassium titanyl phosphate (PPKTP) crystal to produce orthogonally polarized photon pairs (Box 1). An optical cavity subsequently filtered the broadband 245 GHz frequency output to 17 discrete GHz bins, spaced by the free spectral range of the filter

© 2015 Macmillan Publishers Limited. All rights reserved

Box 1 | Principles of hyperentanglement.

Bipartite hyperentanglement can be illustrated and obtained as follows. First, consider a perfectly entangled state of light created by two-photon emission into two well-defined optical modes, 1 and 2:

$$\sum_{n=0}^{\infty} |n\rangle_1 |n\rangle_2$$

where n is the photon number. This state is actually a perfect Einstein–Podolsky–Rosen state[13], good approximations of which can be generated by stimulated parametric downconversion in an optical parametric oscillator[14]. Here, the emission will be spontaneous parametric downconversion in a nonlinear medium in which photons from a narrowband pump field of frequency ω_p are annihilated to create pairs of signal photons at frequencies ω and $\omega_p - \omega$. Because such emitters usually have rather broad bandwidths, there can be a wide distribution of the signal photon frequency, yielding (still paying no heed to realistic normalization)

$$\int d\omega \sum_{n=0}^{\infty} |\omega; n\rangle_1 |\omega_p - \omega; n\rangle_2$$

This state is entangled both in the photon number and frequency, or hyperentangled. We can up the ante by adding polarization entanglement to the mix:

$$\sum_{\varepsilon \in \{H,V\}} \int d\omega \sum_{n=0}^{\infty} |\varepsilon, \omega; n\rangle_1 | \varepsilon_\perp, \omega_p - \omega; n\rangle_2$$

and so on, where ε is the polarization direction along the horizontal (H) or vertical (V) direction. In the case that interests us here, only photon pairs are emitted, which restricts the sum over n to $n = 1$:

$$\sum_{\varepsilon \in \{H,V\}} \int d\omega |\varepsilon, \omega; 1\rangle_1 | \varepsilon_\perp, \omega_p - \omega; 1\rangle_2$$

cavity, thereby yielding about four bits of encoding space per photon. Moreover, the temporal dependence of the transmitted light assumed a periodic, 'mode-locked' character as the filtered modes, being resonant in the filter cavity, must be temporally separated by the roundtrip time of 66 ps.

Xie *et al.* then proceeded to thoroughly characterize the source properties by making use of the well-known arsenal of quantum interference effects discovered by Hong, Ou and Mandel[4], and Franson[5].

In Hong–Ou–Mandel interference, two single, identical photons impinging separately on each input port of a balanced beamsplitter always exit together from the same output port, more precisely in a quantum superposition of both output ports. For this to happen the input photon wavepackets must, of course, arrive at the same time and overlap at the beamsplitter and any temporal delay of one with respect to the other yields the famous Hong–Ou–Mandel dip of the coincidence signal at the beamsplitter output, which provides a clear signal of the absence of the distributed photon output.

In the case of the mode-locked biphoton frequency comb used by Xie and colleagues, the Hong–Ou–Mandel quantum interference can actually happen at all time-differences equal to the pulse spacing, that is, the filter cavity roundtrip time. These 'revivals' of the Hong–Ou–Mandel dip, which could also be called recursive Hong–Ou–Mandel dips, occur as the time delay is scanned, as first predicted by Shapiro[6]. This was first observed by Ou's group[7], albeit with a less sophisticated set-up that only gave a 50%, rather than a 100%, dip depth. In the work by Xie and colleagues[2], a 96.5% Hong–Ou–Mandel dip is obtained, which constitutes the first complete observation of such recursion. In an absolute sense, a near-100% Hong–Ou–Mandel dip depth is important beyond the mere quantitative aspect because it rules out all classical explanations of the observed interference (dip).

Xie *et al.* explicitly tested the frequency correlations in the biphoton comb, which confirmed the expected symmetrical distribution with respect to the half-frequency of the SPDC pump. They then performed Franson interferometry[5], an elegant nonlocal quantum interference effect under conditions where classical coherence is lost, and thus classical interference is impossible. Franson interferometry provides a time–energy Bell inequality test, and thus a rigorous test of entanglement, as the photons are correlated in time and anticorrelated in energy. Each photon of an emitted pair is sent to a separate Mach–Zehnder interferometer whose two arms have a path difference that is much longer than the single photon coherence length. The quantum probability amplitudes for both photons taking the short interferometer arm, and for both taking the long interferometer arm, and then interfering, are measured (both long paths do not differ by more than the single photon coherence length). The interference visibility in the experiment was a very good 97.8%.

Although the observation by Xie *et al.*[2] that Franson fringes do, indeed, recur at every multiple of the roundtrip time of the filter cavity may not be very surprising, it is in fact the first observation of such an effect. The authors also observed a degradation of the fringe visibility, consistent with the theoretical expectation from the linewidth of each mode of the filter cavity.

Having convincingly established the time–frequency entangled nature of their biphoton comb, the authors proceeded to generate hyperentanglement by adding polarization entanglement. They then tested for hyperentanglement by conducting combined Bell measurements on polarization entanglement and on time–frequency entanglement, showing the violation of Bell-type Clauser–Horne–Shimony–Holt inequalities at levels near the maximum allowed by quantum mechanics.

Because they used a long nonlinear waveguide, the authors demonstrated a very high brightness for their source of hyperentangled photons, and their careful experiments demonstrated quantum interference effects with consistently high visibilities.

Where do we go from here? Xie *et al.*[2] mention that one next step could be to increase the brightness of their source by placing the waveguide inside a resonator, say, by surrounding it with Bragg mirrors. This is not yet possible because the waveguide has non-negligible levels of propagation loss (typically of the order of 0.1 dB cm^{-1}) and so further work on low-loss integrated nonlinear optics is therefore very worthwhile.

Another possibility would be to improve the system detection efficiency, which is of the order of 1% in this work. Because coincidence detection is used, the final results are post-selected and the adverse effects of this low detection efficiency, as well as of phase-mismatched SPDC emission background[8] and losses in the PPKTP waveguide, can be completely circumvented at the expense of a reduced probability of success for the coincidence measurement. This powerful redeeming method has been, justifiably, a workhorse of numerous (though not all) photonic implementations of quantum information. However, the approach hinders scalability exponentially, and scalability will be important in practical applications, as one would reasonably expect to have to resort to a multitude of quantum repeater stages, which use entangled channels, to reliably send quantum information across large distances.

Another consequence of the current coincidence set-up, besides decreasing

© 2015 Macmillan Publishers Limited. All rights reserved

the information flux, is to limit quantum processing to single-photon states. Overcoming these limitations with high-efficiency photon-number-resolved detection techniques[9] will allow one to address the Fock basis in earnest, giving access to more general protocols, such as quantum state tomography by photon counting[10,11] and the generation of non-Gaussian states of light[12]. ❒

Olivier Pfister is in the Department of Physics at the University of Virginia, 382 McCormick Road, Charlottesville, Virginia 22904-4714, USA.
e-mail: opfister@virginia.edu

References
1. Einstein, A., Podolsky, B. & Rosen, N. *Phys. Rev.* **47,** 777 (1935).
2. Xie, Z. *et al. Nature Photon.* **9,** 536–542 (2015).
3. Kwiat, P. G. *J. Mod. Opt.* **44,** 2173–2184 (1997).
4. Hong, C. K., Ou, Z. Y. & Mandel, L. *Phys. Rev. Lett.* **59,** 2044 (1987).
5. Franson, J. D. *Phys. Rev. Lett.* **62,** 2205 (1989).
6. Shapiro, J. H. in *Technical Digest of Topical Conference on Nonlinear Optics* (ed. Sawchuk, A.) FC7 (Optical Society of America, 2002).
7. Lu, Y. J., Campbell, R. L. & Ou, Z. Y. *Phys. Rev. Lett.* **91,** 163602 (2003).
8. Kleinman, D. A. *Phys. Rev.* **174,** 1027 (1968).
9. Calkins, B. *et al. Opt. Express* **21,** 22657–22670 (2013).
10. Wallentowitz, S. & Vogel, W. *Phys. Rev. A* **53,** 4528 (1996).
11. Banaszek, K. & Wódkiewicz, K. *Phys. Rev. Lett.* **76,** 4344 (1996).
12. Ourjoumtsev, A., Tualle-Brouri, R., Laurat, J. & Grangier, P. *Science* **312,** 83–86 (2006).
13. van Enk, S. J. *Phys. Rev. A* **60,** 5095 (1999).
14. Ou, Z. Y., Pereira, S. F., Kimble, H. J. & Peng, K. C. *Phys. Rev. Lett.* **68,** 3663 (1992).

NANOPHOTONICS

Liquid quantum photonics

Researchers have observed light propagation in which photons glide smoothly along a one-dimensional chain of electrons known as a Luttinger liquid — a many-body interacting quantum system held within a single-walled carbon nanotube.

Mark Tame

Most materials that guide light are simply described by the Lorentz model — a classical theory introduced by Hendrik Lorentz at the turn of the twentieth century. In this model, electrons are bound to atoms and form a dipole that responds to light by producing its own light field[1]. The combined fields of all the atoms in the material and that of the incoming light constitute the total field as it is guided along. The Lorentz model has played a pivotal role in the advancement of optical science in the decades since being introduced.

With rapid progress currently being made in nanofabrication, researchers are now trying to understand how to control and guide light at the nanoscale. New kinds of materials have been explored to realize compact integrated optical circuitry that can bypass the so-called diffraction limit — a limit that forbids the confinement of light to dimensions significantly smaller than its wavelength. A breakthrough came in 1997 when Junichi Takahara and colleagues[2] showed that metals are able to confine light to scales well below the diffraction limit. At an interface of a metal with a dielectric medium the light can be guided in the form of a surface plasmon polariton — a joint state of a photon coupled to an electron charge density wave. This discovery and impressive advances in metal nanostructure fabrication have resulted in intense interest in plasmonic systems from researchers keen to build high-speed optical devices for controlling light at the same scale as conventional electronics[3].

In plasmonics, the Lorentz model is superseded by the widely used Drude–Lorentz model[4], where the outer electrons of atoms are no longer bound, and move freely through the metal allowing it to conduct. This is again a classical model where the electrons are treated as a non-interacting gas with Maxwell–Boltzmann statistics. To model the electrons quantum mechanically, one should take into account their fermionic nature, in particular, the Pauli exclusion principle. To do this, the Drude–Sommerfeld model[4] can be used, where the electrons are treated as a non-interacting Fermi gas with Fermi–Dirac statistics. However, one of the main drawbacks of this description is that electron–electron interactions are not included, and these can have a big impact on the behaviour of the metal when guiding light.

To correctly model quantum electron behaviour in metals, Fermi–Landau liquid theory is needed[4]. A problem arises, though, when the electrons are confined to metallic structures that are narrow relative to their wavelength. In this case, the interacting electron system reduces to a one-dimension system and Fermi–Landau liquid theory completely breaks down. To correctly explain this one-dimensional system a Luttinger liquid model — a fully quantum mechanical theory — is required[5]. One of the hallmarks of this unusual many-body electron system is spin–charge separation, where spin waves and charge density waves propagate independently. The formation of charge density waves, or plasmons, in a Luttinger liquid is fundamentally quantum mechanical in origin, due to treating the electrons as a many-body interacting quantum system. The unique properties of Luttinger liquids have recently been observed in several impressive experiments[5], most notably in carbon nanotubes. However, there has not been any direct observation of Luttinger liquid plasmons in these systems, or their coupling to light as surface plasmon polaritons. This has been an outstanding challenge for well over a decade.

Writing in *Nature Photonics*, Zhiwen Shi *et al.*[6] now report the first observation of Luttinger liquid plasmons using metallic single-walled carbon nanotubes. Using near-field infrared nanoscopy, they show that the Luttinger liquid plasmons in a one-dimensional system behave qualitatively different from plasmons in two or three-dimensions, with 'quantized' velocities and coupling with light to form a new type of low-loss broadband optical mode that has extraordinary field confinement.

The plasmon optical mode in the Luttinger liquid is very different to previously studied plasmons in carbon nanotubes, which are simply considered to be rolled up sheets of graphene with the Drude–Lorentz model employed[7]. In the work by Shi and colleagues[6], the optical modes of the Luttinger liquid plasmons are based on a careful treatment of many-body quantum interactions between the electrons in one-dimension[8]. The work opens up new possibilities for designing some rather exotic nanoscale photonic waveguides based on interacting electronic systems. Whereas Shi *et al.*[6] have probed their metallic carbon nanotubes in the infrared, Luttinger liquid plasmons are expected to persist to visible

© 2015 Macmillan Publishers Limited. All rights reserved