Quantum physics

Spaced-out electrons

John C. H. Spence

In a stream of photons, the particles tend to bunch together, but electrons in a beam do the opposite. At last, this quantum effect for free electrons — the Hanbury Brown–Twiss anticorrelation — has been seen experimentally.

Like the gentle patter of raindrops, we expect photons, the quanta of sunlight, to arrive at Earth at random intervals, their arrival times distributed in just the same, natural way that customers arrive at a box-office to buy tickets for a play. A histogram of the number of people or photons arriving per unit time follows what is known as the Poisson distribution. But in 1909, in the first clear evidence for wave–particle duality, Einstein pointed out[1] that the width of this distribution for sunlight contains both the Poisson contribution of random arrival times, and a second 'wave-noise' contribution, which causes the photons to arrive in bunches.

An experiment performed by Kiesel *et al.*[2], reported on page 392 of this issue, shows that the same principle applies to a beam of coherent electrons — but with the opposite effect. In contrast to the bunching of photons[3], this experiment confirms the theoretical prediction[4] that a stream of coherent electrons will 'anti-bunch', tending to become more equally spaced than the classical Poisson prediction (Fig. 1). In the quantum regime, electrons have an innate tendency to avoid each other, thereby demonstrating a fundamental difference in the way light and electrons interfere with themselves.

In the 1950s, the astronomers Robert Hanbury Brown and Richard Twiss devised the famous experimental arrangement, known as intensity interferometry, to study these effects for photons in the form of light from distant stars[5]. They split the light into two beams using a half-silvered mirror, then compared the arrival times of photons at two separate detectors. Due to bunching, they saw that coincident photon arrivals were more likely than expected by chance. Hanbury Brown and Twiss realized they could use this bunching to infer the angular size of distant stars.

The similar experiment performed by Kiesel *et al.*[2] with electrons finds coincident arrivals less probable, which indicates anti-bunching. In fact, although an anti-bunching effect was reported three years ago[6,7] for electrons in solids, Kiesel and colleagues' experiment is the first to mimic the original of Hanbury Brown and Twiss for a beam of free particles. It is because the effect is so much weaker with electrons that it has taken nearly fifty years to detect it.

Kiesel *et al.* used a field-emission point source of electrons to illuminate two detectors, recording the time between the arrival of electrons at each detector. To observe anti-bunching, the researchers needed to prepare a laser-like group of 'coherent states' for the electrons and attempt to crowd as many electrons into them. By 'coherent', we mean that the waves originate from a common point source, and all vibrate in unison for a period of time, called the coherence time (wave–particle duality tells us that particles can be described as waves). As the product of the coherence time and the energy spread of electrons has a fixed value (equal to Plank's constant, by Heisenberg's uncertainty principle), the authors required an extremely small, bright source of electrons with very small energy spread to maximize the coherence time, and, ideally, a detector capable of responding within this time. Uncertainty results from coherence.

The crowding of particles into a state is measured by degeneracy (or maximum number of particles), δ, which is thus a measure of the strength of anti-bunching and many-particle effects. Electrons belong to a class of particles known as fermions — particles whose spin quantum number has half-integer values. Fermions have the special property that only one particle at most is allowed in a particular quantum state, according to Pauli's famous exclusion principle. In this case, $\delta = 1$. For photons, however, the maximum number of particles per state is unlimited. Photons belong to a different class of particles called bosons, with integer values of spin, and do not follow Pauli's exclusion principle.

Degeneracy is proportional to the source brightness and the cube of the particle wavelength. Although the field-emission source used by Kiesel *et al.* is brighter even than a typical photon source, the synchrotron undulator[8], [**AU: OK?**] the wavelength of electrons produced is much shorter, so δ is much smaller (about 10^{-4}, compared to 10 for the synchrotron undulator and 10^{12} for photons in a laser). This is what has made the observation of electron anti-bunching so difficult — and the achievement of Kiesel *et al.* so significant. (Incidentally, neutrons, also fermions, have even smaller degeneracies, $\delta = 10^{-10}$, making the observation of neutron anti-bunching a hopeless endeavour.)

As the source brightness is increased (approaching the emission of one electron per interval of coherence time), electrons tend to resist being crowded into the same state. The arrival of an electron at one detector indicates a filled state and so, as two electrons cannot occupy the same state, precludes the arrival of an electron at the other detector for the duration of the coherence time. So the rate of coincidences is reduced below the Poisson prediction.

A number of experimental considerations complicate this simplified picture. Earlier attempts to perform this experiment have been dogged, for example, by false coincidences caused by capacitive coupling between the closely spaced detectors. To get around this (and other problems), Kiesel *et al.* measured the rate of coincidences for different spatial-coherence conditions, effectively varying the size of the electron source. A large source destroys coherence, and then arrival times follow the classical Poisson distribution. By comparing coincidence rates for different source sizes, the signature of the anti-bunching effect can be isolated.

But the condition for a strong anti-bunching effect — that electrons are emitted from the source at time intervals shorter than the coherence time — cannot be met in Kiesel and colleagues' experiment, as the fastest detectors available are still about a thousand times slower than the longest coherence times possible with field-emission sources. Hence the effect seen is weak, but — at last — it's definitely there. ■

John C. H. Spence is in the Department of Physics and Astronomy, Arizona State University, Tempe, Arizona 85287-1504, USA.
e-mail: spence@asu.edu

1. Einstein, A. *Phys. Zeit.* **10,** 185–193 (1909).
2. Kiesel, H., Renz, A. & Hasselbach, F. *Nature* **418,** 392–394 (2002).
3. Purcell, E. M. *Nature* **178,** 1449–1450 (1956).
4. Silverman, M. *Phys. Lett. A* **120,** 442–446 (1987).
5. Hanbury-Brown, R. & Twiss, R. *Nature* **177,** 27–29 (1956).
6. Henny, M. *et al. Science* **284,** 296–298 (1999).
7. Oliver, W. D., Kim, J., Liu, R. C. & Yamamoto, Y. *Science* **284,** 299–301 (1999).
8. Spence, J. C. H. & Howells, M. *Ultramicroscopy* (in the press).

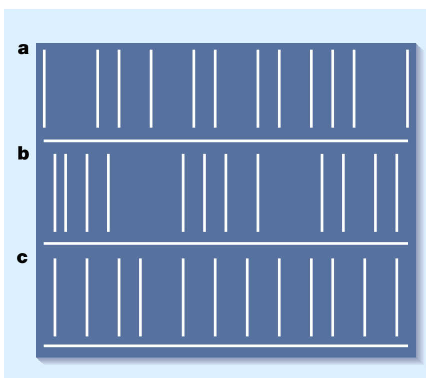

Figure 1 **Random and bunched distributions.** a, **The vertical lines represent a random distribution, such as the times at which theatregoers arrive at the box office or photons arrive at Earth from a distant star. Mathematically, this distribution was described by Poisson (1781–1840) and bears his name.** b, **But in fact the case for photons is not quite so straightforward. Quantum correlations cause the photons arrival times to bunch together — an effect exploited by Hanbury Brown and Twiss to measure the angular size of stars.** c, **For electrons, the reverse is true: quantum effects cause free electrons to 'anti-bunch', or spread out. Kiesel *et al.*[2] have now measured this 'Hanbury Brown–Twiss anticorrelation'.**