PERSPECTIVES: ELECTRON STATISTICAL EFFECTS

Bunches of Photons—Antibunches of Electrons

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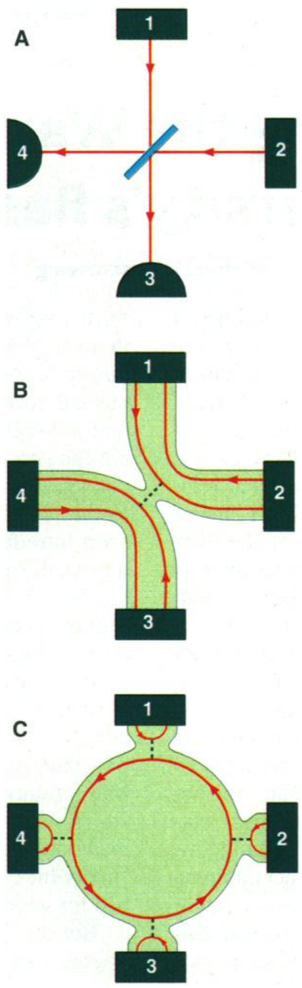
In the 1950s, Hanbury Brown and Twiss (HBT) showed in pioneering experiments that the spatial coherence properties of light emitted by a star can be used to determine its diameter. A laboratory, or table-top version (*1*), of the HBT experiment (see the figure, panel A) invokes one or two sources of light and at least two detectors that can be used to measure the intensity correlation between light beams generated by transmission through and reflection at a half-silvered mirror. Since the early HBT experiments, the interest has shifted from the spatial coherence of the light to the temporal coherence of the light beam, with the same arrangement as in panel A of the figure. At the core of these observations lies a fundamental property of the photons that make up the light: They are bosons, that is, particles that can occupy the same energy state. Bosons have a tendency to bunch in clusters, a phenomenon describing the multiple occupations of the same state by a number of identical particles. Such "bunching" can be observed in HBT experiments, where a positive correlation is observed when the intensities at the two detectors are compared as a function of time.

The intensity correlation of the light measured with the help of two detectors depends in a sensitive way on the bunching of the photons. The type of particles and the statistics they obey thus play a crucial role in these experiments. What would happen if the bosons were replaced by fermionic particles such as electrons? Fermions cannot occupy the same energy state, and "antibunching"—an anticorrelation between the particle intensities measured at two detectors—would be expected in equivalent experiments. Two reports in this issue, one by Henny *et al.* [(*2*), page 296] from the University of Basel and one by Oliver *et al.* [(*3*), page 299] from Stanford University, now report successful realizations of fermionic HBT experiments in mesoscopic electric conductors. Both studies show that the expected antibunching is indeed observed.



How to antibunch electrons. **(A)** The classical optical HBT table-top experiment. A beam from source 1 (source 2) is transmitted through the half-silvered mirror to detector 3 (detector 4) and reflected at the mirror to detector 4 (detector 3). **(B)** Equivalent experimental setup with a mesoscopic conductor. **(C)** Sketch of an experiment that would permit demonstration of phase coherence in a conductor. Arrows in (B) and (C) denote motion along unidirectional edge states created by a high magnetic field.

The realization of a fermionic HBT experiment was complicated by the fact that statistical effects measured in a correlation depend quadratically on the occupation of the available states. Sources that emit electrons into the vacuum simply cannot populate the many states available to electrons to a sufficiently high degree for correlation effects to be observed. This problem can be circumvented if the experiment is performed not in a vacuum but in electrical conductors at very low temperatures. In electrical conductors, the Pauli principle guarantees a compact filling of the available states (*4*, *5*). Mesoscopic conductors can now be fabricated in sufficiently small dimensions so that at low temperatures the wave function nature of the electrons becomes apparent and transport is phase coherent (*6*). It is in such mesoscopic conductors that the successful HBT experiments mentioned above have been carried out.

Panel B of the figure shows a possible electrical analog of the HBT experiment in a mesoscopic conductor (*4*). The structure is patterned into a material such as GaAs that forms a two-dimensional electron gas. A narrow opening (a quantum point contact) separates two halves of the conductor. The opening is so narrow that some carriers are reflected and others are transmitted. If the conductor is placed in a high magnetic field, this leads to a cyclotron motion of the electrons. Only states near the boundary of the conductor, where carriers skip along the surface, provide transport channels. The quantum mechanical equivalent of such a skipping orbit is called an edge state (*7*). Motion along such edge states is unidirectional (see arrow in panel B), and—very importantly—this motion is immune to disorder. The magnetic field reduces the number of states at the Fermi level available for carrier propagation substantially. Edge states are thus a perfect way of guiding electrons toward a scatterer, the narrow orifice in panel B.

An electrical analog of the optical intensity-intensity correlation measurement at the two detectors can, for example, be created by measuring the correlation of the reflected current at contact 4 and the transmitted current at contact 2 for carriers that are incident from contact 1. Whereas for bosons, such a correlation would be positive as a result of bunching of carriers, for fermions, this correlation is negative because of the Pauli principle, resulting in antibunching (*2*, *3*).

The high magnetic field used in the experiment of Henny *et al.* (*2*) is not necessary for the experiments. Oliver *et al.* (*3*) carried out their experiment in a mesoscopic conductor at zero magnetic field. However, the magnetic field provides an advantage: Henny *et al.* achieved complete anticorrelation within experimental accuracy. This is a consequence of the very limited number of states available in a high magnetic field and the fact that impurities introduce no additional fluctuations. As pointed out in their report, complete anticorrelation demonstrates that the incident carrier stream is in fact noiseless, a property that is of fundamental importance in our understanding of the occurrence of quantized conductance phenomena, the quantum Hall effect, and the behavior of quantum point contacts in zero magnetic field.

In the experiments of Henny *et al.* (*2*) and Oliver *et al.* (*3*), only one incident carrier stream is used. However, as in the original HBT experiment, noise measure-

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ments that deal with multiple incident carrier streams are also of interest. Such experiments would permit the investigation of exchange effects on the noise, which represent an explicit demonstration that we deal with indistinguishable particles. If carriers were incident from both contacts 1 and 3, the conductor in panel B of the figure would be noiseless in the zero-temperature limit. All current correlations would then vanish. A first experiment in this direction has recently been performed by Liu *et al.* (*8*), who demonstrated that in the presence of currents incident from two contacts the noise is reduced below the value that is measured if current is incident from one contact only.

In contrast to conductance, which can be specified in terms of transmission probabilities for one carrier to traverse the conductor from one contact to another, exchange effects in noise correlations are specified by scattering amplitudes with an amplitude and a phase (*4*). The conductor in panel C of the figure is one possible experimental setup that would permit demonstration of the phase sensitivity of exchange effects. This conductor is an electrical equivalent of an optical interferometer. The contacts connect to a central orbit that circles the outer wall of the conductor. In the presence of two incident currents, the exchange effect in one of the current-current correlations is a function of the phase of the periodic orbit; depending on this phase, the exchange effect either vanishes or is as large as the noise of the two currents added classically.

Current-current correlations are a sensitive probe of the statistical properties of a system. In systems that are composed of superconductors and normal conductors (such as metals or semiconductors), it has been predicted that the correlation functions can change sign because of strong electron-hole correlations resulting from reflections at the interface between the superconductor and the other material (*9*). Measurements of current-current correlations in the fractional quantum Hall regime should be even more interesting. Current theoretical understanding attributes such states to quasi-particles that are very unconventional in that they are neither fermions nor bosons. In contrast to the integer quantum Hall effect, which can be explained by using the edge states described above, our understanding of the fractional quantum Hall effect is rather limited. Presently, it is not even clear whether noise should be generated at the interface of a normal contact and a two-dimensional electron gas (*10*) in a fractional quantized state.

Optical experiments have reached a particularly high level of sophistication since sources producing twin pairs of photons have become available. Sources that produce such entangled states (coherent superpositions of multiparticle states) of electrons are not yet available but are clearly desirable for noise experiments and also in the emerging field of quantum computing. The Pauli principle works to suppress noise. But its effectiveness can be overcome in systems far from equilibrium if collective electron motion becomes important. This was demonstrated in recent experiments on resonant tunneling structures (*11*) and has been investigated theoretically (*12*). Yet another interesting avenue is the connection of shot noise and the dephasing of quantum coherent electron transport (*13*). These considerations promise interesting future experiments on electron coherence and statistical effects in a wide variety of systems.

References and Notes

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PERSPECTIVES: ECOLOGY

Heeding the Warning in Biodiversity's Basic Law

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The great 19th-century scientist Alexander von Humboldt gave ecology its oldest law: Larger areas harbor more species than smaller ones (*1*). Even back then, naturalists were quick to perceive the mathematical regularity of this species-area relationship (*2*). For most of the 20th century ecologists have keenly studied this relationship convinced that, in finding the explanation for it, they would uncover the key to understanding and predicting Earth's biodiversity (*3*). The report by Harte *et al.* on page 334 of this issue (*4*) is an elegant contribution to the onslaught of recent advances leading toward an explanation. The puzzle of the species-area relationship is now in full retreat. Admittedly, we have not yet achieved its unconditional surrender. But, given the mass extinction of plant and animal species that human culture and population growth have set in motion, our progress toward that surrender comes just in the nick of time.

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Debate about the mathematical form taken by the species-area relationship began about 1920 and still continues (*5*). The form $S = CA^z$ (the number of species found in a sampled patch of area A is a constant power of A) proved a convenient mathematical equation for reporting, organizing, and analyzing this relationship. No one claimed to understand why. Then Fisher connected the problem of species diversity to that of species abundance (*6*). Preston soon introduced and championed the log-normal form of species-abundance distribution (*7*). He also supplied a flawed, although enchanting, proof that a certain type of log-normal distribution implied a species-area relationship that came quite close to $S = CA^z$ with z about 0.26 (a number close to values derived from data sets of island plant and animal diversity) (*8*). May's flourishes and extensions (*9*) to Preston's work were so impressive that they made us believe, for a while, that we could finally tuck this chapter of ecology into its bed for good.

But the data would not cooperate (*10*). Species-area relationships with z-values strikingly different from 0.26 kept popping up (*11*). Worse still, these z-values had a definite pattern: Larger scales of space and time generated species-area relationships with larger z-values.

The theoretical bubble burst too (*12*). It had relied on a tacit assumption of self-similarity among species (the abundance distribution of complete sets of species is the same regardless of the spatial scale at which

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