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# Two Indistinguishable Electrons Interfere in an Electronic Device

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ing of methyl groups, and confirmed interatomic distances by paramagnetic resonance enhancement. The coiled-coil hot spot of ClpB lodges in the jaws of the DnaK ATPase domain, inhibiting DnaK nucleotide exchange and activating the ClpB toggle. As part of its chaperone function, activation of DnaK by the nucleotide exchange factor GrpE triggers release of bound substrate into solution. By contrast, during disaggregation, ClpB binding to DnaK reprograms DnaK to hand over its polypeptide substrate for translocation through the ClpB channel (see the figure). Indeed, ClpB and GrpE compete for the same binding site on the DnaK ATPase domain. After translocation through ClpB, the polypeptide is refolded by the DnaK system or by other chaperones such as GroEL. A critical step in the pathway is that the polypeptide must find its way from DnaK to the entrance of the ClpB channel. A model for the DnaK-ClpB complex with DnaK in the domain-docked state suggests that the substrate-binding site faces away from the ClpB ring. Moreover, ClpB binding to DnaK is not compatible with the docked position of the DnaK helical lid, suggesting that the ClpB interaction may involve a different, as yet undescribed, DnaK domain assembly.

Although the mechanism of polypeptide handover from DnaK to ClpB is still unclear, the mapping of DnaK-ClpB binding interactions and the competition between different binding partners for the DnaK ATPase domain reveal key steps of protein disaggregation in bacteria, plants, and fungi. Mammalian cells appear to have a similar disaggregation activity, but so far no direct homologs of ClpB have been found in animals. Although there is no immediate prospect of combating conditions such as Alzheimer's disease with a "disaggregase," these recent studies provide an important advance in understanding the remarkable ability of cells to reverse protein aggregation.

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PHYSICS

# Two Indistinguishable Electrons Interfere in an Electronic Device

An electronic device that entangles indistinguishable electrons from two independent sources has applications in quantum information processing.

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In quantum mechanics, particles can be prepared in entangled states, so that measurement of a property on one particle determines the outcome for the other, no matter how far apart the particles may be. This "spooky action at distance" was demonstrated first with photons (*1*). One goal of condensed–matter physics has been to replicate quantum optics experiments with electrons (*2*). For example, the Hong-Ou-Mandel (HOM) experiment (*3*) can determine if two photons are indistinguishable—meaning that they have the same wavelength and polarization, and that they can become entangled if they overlap during propagation, as can happen at a beam splitter (a semitransparent mirror; see the figure, panels A and B). An electronic device that could demonstrate indistinguishability of electrons would be useful for quantum computing applications. On page 1054 of this issue, Bocquillon *et al*. (*4*) demonstrate such an analog of the HOM experiment with two electrons, generated from two different single-electron sources, colliding in the equivalent of a beam splitter in a single device.

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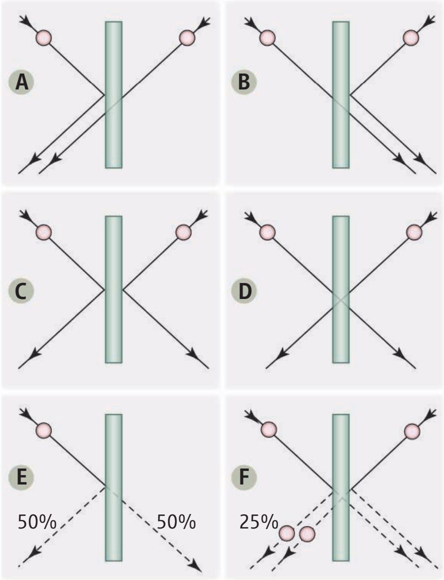
The authors assembled all of the electronics analogs of the necessary optical components in a gate-tunable electronic device. First, an electron beam source requires that electrons move as nearly free particles. The edges of two-dimensional electron gas systems formed in layered heterostructures of semiconductors are ideal channels for electrons; like light beams, they can be made directional with an applied magnetic field (*5*). Tunable electron beam splitters are realized with so-called quantum point contacts that can adjust the fraction of electrons transmitted and reflected (*6*).

The statistical properties of this process can be analyzed by measuring electronic noise (*7*). The partitioning of incoming electrons at the beam splitter results in a random occupation of the outgoing channels with a fixed average occupation defined by the predetermined transmission and reflection probabilities. The noise is maximized at 50% transmission probability and otherwise suppressed.

Instead of measuring the noise, which is the autocorrelation of the time-dependent electrical current, cross-correlations between two different channels are a useful alternative. In the HOM experiment, the coincidence rate of photons in two partial beams was measured. The coherence of a source is now commonly characterized by measuring intensity correlations, a method that goes back to Hanbury-Brown and Twiss (HBT), who realized that both temporal and spatial coherence can be obtained from intensities alone [see, for example, (*8*)].

The HBT experiment was later realized with electron beams (*9*, *10*), but the devices used only a single electron source. If there are two sources with two beams incident on a beam splitter, two quantum particles may collide at the same time and entangle. The entangled state must obey a symmetry rule for interchange of two particles, changing sign for fermions (e.g., electrons) or not for bosons (e.g., photons). This rule leads to distinct differences in observables in the HOM experiment (see the figure). After the interaction at the beam splitter, the two particles may exit in one of four ways: (A) Both particles exit at the left or (B) at the right; (C) the left particle remains on the left side, while the right particle remains on the right side; or (D) the two particles exchange. If the particles do not interact, each possibil-




**To bunch or not to bunch.** Indistinguishable quantum particles incident from left and right sides of a 50% beam splitter can scatter in four ways. The symmetry of the wave function determines the outcome. For bosons, only (**A**) and (**B**) are possible (causing "bunching"), while for fermions only (**C**) and (**D**) are possible (causing "antibunching"). For comparison, (**E**) shows the random partitioning of particles incident on one input alone, and (**F**) illustrates the partitioning of two input beams of distinguishable particles. For example, for distinguishable bosons, two bosons exit with a probability of 25%, whereas indistinguishable bosons would show a twice-as-high probability of 50% for the same process.

ity should occur equally if the transmission and reflection probabilities were adjusted to 50%. However, fermions and bosons are not independent because they must obey symmetry rules. Bosons exclusively choose (A) and (B), causing them to bunch together to the same side, whereas fermions can only choose (C) and (D) and avoid each other—they antibunch.

In the optical HOM experiment, if the photons are distinguishable, they partition independently at the beam splitter (outcome F in the figure). In the electronic HOM experiment, Bocquillon *et al*. measured the noise in one of the output channels. If two indistinguishable electrons collided at the same time at the beam splitter, the noise was suppressed because both states were fully occupied without any randomness. If the two incident electrons appeared at different times at the beam splitter, they would be independent and randomly partitioned, resulting in noise. The noise suppression at zero time delay between the two electron wave packets confirmed the formation of a two-particle coherent fermionic state.

Two-particle interference in electronic devices have been studied before, exploiting two sources with a single beam splitter (*11*) and an impressive double Mach-Zehnder interferometer (*12*). The experiment by Bocquillon *et al*. comes much closer to a state-of-the-art quantum-optics experiment as it is realized in an electronic device that uses single-electron sources (*13*). In these sources, electrons can be launched on demand and with a predetermined time delay for tuning the wave-function overlap.

Unlike photons, electrons are charged particles that strongly interact. Hence, two-particle interference experiments may shed new light on the dephasing problem of electronic quantum states in quantum computing. Edge states also exist in the fractional quantum Hall state, which hosts quasiparticles with statistics distinct from those for both fermions and bosons. Recently, evidence for Majorana-like particles have been found in nanoelectronic devices (*14*), so it may be possible to probe their scattering and test their non-Abelian statistics. Less demanding, but still very exciting, is the interaction of the quasiparticle launched by the single-electron source with the "vacuum state," which for an electron system is not "empty" but a filled Fermi sea. Finally, because the electron source used by Bocquillon *et al*. provides an alternating current, it launches an electron at one instance and then a hole half a period later, which should allow the study of the interactions of electrons and holes that originate from different sources.

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ATMOSPHERE

# Leads and Lags at the End of the Last Ice Age

**Edward J. Brook**

Carbon dioxide concentrations and Antarctic temperatures were tightly coupled during the last deglaciation.

Over the course of Earth history it is generally believed that atmospheric carbon dioxide ($CO_2$) and climate are closely coupled (*1*). The most direct evidence comes from polar ice cores. Snow falling in Antarctica and Greenland gradually compacts to form solid ice and trap air. Polar ice also records past temperatures in the ratio of heavy to light isotopes in the water molecule. Ice core analyses have shown that Antarctic temperature and atmospheric $CO_2$ concentrations are highly correlated over the large-scale climate cycles of the past 800,000 years (*2*). But which came first? Does $CO_2$ drive climate cycles or is it a feedback in the system that contributes to warming? On page 1060 of this issue, Parrenin *et al*. (*3*) address this question in a study of $CO_2$ concentrations and Antarctic temperatures during the last deglaciation.

One reason that the answer to the above question is more complicated than it may seem is a peculiarity of air preservation in ice. Over the top 50 or 100 m of an ice sheet, the snowpack (firn) gradually becomes denser before it becomes solid ice containing air bubbles. Air diffuses rapidly through the firn, and the trapped air is therefore younger than the surrounding ice. In places with little snowfall, the age difference can be several thousand years. The age difference cannot be reconstructed perfectly, leading

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