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13. ABSTRACT (Maximum 200 words)

Research in quantum electron optics is a new direction in semiconductor nanostructures which seeks to probe the fundamentals of quantum mechanics by merging concepts from quantum optics with the physics of mesoscopic devices. Our work in this area has included both theoretical and experimental efforts to model and demonstrate quantum optical phenomena for electrons. Our main effort has been to analyze and measure the noise properties of mesoscopic devices that might exhibit such effects. This is motivated not only by basic physics, but also by a desire to understand the limits placed on device noise performance by the quantum mechanics of electrons.

Our main results include (1) a theoretical analysis of the transition from quantum partition noise to thermal noise in mesoscopic branching circuits as the degree of dissipation is increased, (2) the recovery of the full frequency-dependent Johnson-Nyquist equilibrium noise in this transition, (3) an experimental measurement of the partition noise of a quantum point contact, and (4) the first demonstration of a quantum statistical effect in the collision of electrons.

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QUANTUM NOISE IN MESOSCOPIC ELECTRON TRANSPORT

FINAL REPORT

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STATEMENT OF PROBLEM

One hundred years after the discovery of the electron, and fifty years after the invention of the transistor, we are now at a point where physical limits may hinder the pace of electronic technology development. There is a continual trend to minimize the size of electronic devices with the desire of making ever faster processors and higher density memories. However, this trend is endangered by the physics of lithographic fabrication, power dissipation, and other practical design issues. From the basic physics viewpoint though, a more fundamental limit is the breakdown of the traditional paradigms used to understand device transport. When device dimensions become on the order of the deBroglie wavelength of the electron, the classical, macroscopic transport picture fails, and the inherent quantum mechanical nature of the electrons must be taken into account.

In this work, we focused on one area where such effects can be profound: noise. For instance, circuits which divide currents are inescapable in modern electronics. The dissipative resistors making up the branches have intrinsic noise sources associated with them; their power is described by the Johnson-Nyquist noise spectral density. Generally, the usual macroscopic paradigm is to employ Kirchoff's rules to analyze how these noise sources contribute to the noise in each branch. However, in small devices where dissipation does not occur in the branching, and the wavepacket of the electron is coherently transmitted, partition noise arises that cannot be explained by the application of Kirchoff's rules. It arises from the random division of discrete electrons into one branch or another; in the limit of small transmissions, it approaches the poissonian limit of shot noise.

The study of the physics of such effects falls within the realm of mesoscopic physics, which, in its broadest characterization, is the study of phenomena on a length scale between the microscopic, atomic regime, and the classical, macroscopic regime. By definition, it investigates the transition between the classical and quantum worlds. In this particular case, the noise appears only in the regime of mesoscopic transport where the wave nature of the electron usually dominates the transport phenomena. Why is it absent in macroscopic circuits? How is this noise suppressed in the transition from quantum to classical branching?

To answer these questions, it is useful to expand beyond mesoscopic electrons and draw analogies to other mesoscopic systems such as photons. In fact, it is significant to note that whereas partition noise is suppressed in macroscopic electrical circuits with lots of scattering, it is not in the case of a large amount of photon scattering. What is different about electrons in contrast to photons?

This question of comparison is actually interesting for its own sake, beyond the issue of noise suppression, because of the potential to stimulate new ideas and experiments in basic physics. The history of the electron is full of examples of this cross-fertilization. For instance, although electrons were first visualized as particles and light was understood as a wave phenomenon, quantum mechanics changed this perspective. The formal equivalence of Schroedinger's equation for an electron wavefunction and Helmholtz's equation for a scalar electromagnetic wave made it clear that electrons should exhibit classical wave optical behavior. This led to an extensive exploration of classical electron optics, resulting in demonstrations of focusing, diffraction and interference with electrons in free-space and mesoscopic devices, and resulting in technologies such as the Scanning Electron Microscope (SEM).

Although there have been successes with the wave analogy between photons and electrons, much less has been done to explore the particle analogy. This is in part because photons and electrons are in fact very different kinds of particles. This fact is demonstrated most clearly when considering the behavior of many identical quantum particles. The probabilistic nature of the wavefunction in quantum mechanics leads to an inherent

indistinguishability between overlapping, identical particles. This is in contrast to classical mechanics where two identical particles can always be distinguished by their unique, deterministic trajectories. To avoid mathematical ambiguities and problems with physical predictions related to this indistinguishability, it is necessary to introduce a symmetrization postulate allowing only two kinds of quantum particles -- fermions and bosons.¹ As is well known, fermions have an antisymmetric wavefunction upon interchange of two particles, while bosons have a symmetric wavefunction. This difference in how the fields are quantized into particles has significant implications for the behavior of fermions and bosons, especially when compared to classical particles. For example, one of the profound consequences of the antisymmetry of fermions is the Pauli exclusion principle which states that two fermions cannot have the same set of quantum numbers.

A large body of experiments exists for both fermion and boson systems whose explanations are ultimately traced back to the statistics of identical antisymmetric or symmetric particles. But in most cases, because of their drastically different equilibrium distribution functions, it is difficult to draw direct analogies between phenomena observed for the different particles. One area where this is changing though is in the study of particle coherences through higher order amplitude correlation functions.

This is the realm of quantum photon optics, which has a long history of investigating how bosonic quantum statistics can affect these coherences. Indeed, perhaps the earliest experiment in quantum photon optics is the intensity-intensity correlation measurement performed in 1957 by R. Hanbury Brown, and R. Q. Twiss on a chaotic, thermal light source.² E. M. Purcell made the important comment that the observed correlation between the photodetected light at two outputs of a beam splitter can be explained by a statistical tendency for thermal photons to bunch together due to the symmetry of their wavefunction.³

Purcell also noted that if fermions are used instead, an antibunching effect should be observable. However, very little thus far has been accomplished in probing this or any higher order fermion coherences. One of the main problems has been the availability of appropriate sources that have a high degeneracy, or average number of particles per quantum state. Only in this limit can multiple-particle quantum statistical effects hope to become dominant over single-particle, classical phenomena. Fermions have a maximum degeneracy of only unity, but most modern fermion sources are very far from this limit. This degeneracy problem can in principle be overcome, however, in a mesoscopic device. Experiments in mesoscopic electron transport are now routinely performed in nanostructures fabricated on GaAs two-dimensional electron gas substrates and cooled to low temperatures. Such a system naturally exhibits a high degree of degeneracy due to the near-zero temperature Fermi-Dirac distribution, and device dimensions on the order of the deBroglie wavelength. This innovation provides new possibilities for performing experiments in "quantum electron optics." For instance, one analogy of the intensity-intensity correlation measurement is simply a measurement of the current noise, which has the same dependence on the wavefunction amplitude. An example of this is just the partition noise observed in mesoscopic devices. However, partition noise is simply a classical phenomenon arising from the stochastic division of individual particles; it is a single-particle effect. But if two electrons are simultaneously sent into a mesoscopic branching circuit, two-particle quantum interferences can change the output statistics from the classically expected behavior. A measurement of the output noise can then reveal a quantum statistical effect.

Thus, an investigation of the noise properties of mesoscopic devices represents a relatively new and important direction in the study of electron transport. It can contribute not only to (1) studying practical technology issues, but also to (2) revealing interesting quantum statistical phenomena never previously observed with fermions. The work supported by this grant attempts to address both motivations. The principal results show (1) a theoretical

justification of the generalized Johnson-Nyquist noise in the presence of nonequilibrium, dissipative transport, and (2) an experimental confirmation of a fermionic quantum statistical interference arising from the collision of electrons.

SUMMARY OF RESULTS

As discussed above, the two main accomplishments of our study of mesoscopic electron noise are (1) the understanding of the suppression of partition noise in the transition from mesoscopic to macroscopic electron branching, and (2) the observation of a fermionic quantum statistical effect with electrons in a mesoscopic device.

To reach the first result, we studied partition noise within the context of the coherent scattering theory which allows us to treat the dual particle-wave nature of the electrons. We found that besides the noise associated with particle division, splitting also introduces a noise in the wave phase of the particle. A complementarity arising from the Heisenberg uncertainty relation exists between the number and phase difference noise induced by partition. Although this picture applies equally well to electrons and photons since the origin of partition noise is the same in both cases (namely, vacuum fluctuations), similarities and differences in the noise for the two kinds of particles do exist.

The quantum mechanical picture implies that the suppression of the number difference noise should be accompanied by the enhancement of the phase difference noise. This suppression apparently occurs in the transition from the mesoscopic to macroscopic circuit -- a transition which usually sees an increasing amount of both elastic and inelastic scattering. However, both processes can happen for photons as well, without a noise suppression effect. By building models that include inelastic scattering and the Pauli exclusion principle, we showed that the reduction of electronic noise in the macroscopic limit can be explained. The transition was first treated within the coherent scattering formalism using a macroscopic, deterministic inelastic scattering model. This so-called reservoir model introduces regions along the conduction path where all electrons undergo thermalization, forcing equal amounts of scattering into both the forward and reverse directions. The reduction of the zero temperature and frequency partition noise in an output port of the beam splitter or Y-branch circuit in the presence of this scattering was shown. Moreover, the production of a spin-squeezed state via the simultaneous suppression of the number difference noise and enhancement of the phase difference noise was also demonstrated. The main conclusion from this model is that the impedance associated with energy dissipation is an important parameter for suppression of the noise through a mechanism involving the Pauli exclusion principle.

To account for the stochastic nature of inelastic scattering, and to further highlight the dynamic role of the Pauli exclusion principle, a second model based on a Monte Carlo simulation was studied. The stochastic inelastic scattering can, in the limit of little scattering, actually cause an increase in the noise. However, this is always less than the noise due purely to ballistic partitioning. Moreover, distributed elastic scattering alone can also suppress the noise. This result emphasizes the point that the essential origin of the suppression is a Pauli exclusion blockade feedback mechanism which correlates the current, and not just dissipation. It is these multiple-particle correlations and the associated reduction in the randomness of the electron distribution which are at the heart of the noise suppression mechanism at zero frequency.

The main goal of this investigation, however, was to provide an explanation for how the finite temperature and frequency generalized Johnson-Nyquist noise can be recovered despite the excess partition noise which exists for mesoscopic circuits. Returning to the reservoir model and extending it to finite temperature and frequency, we derived the generalized Johnson-Nyquist noise in the limit of fully dissipative transport, providing the first justification of this common practice.

Although there have been many theoretical treatments of noise in mesoscopic devices, only a few experiments have been carried out. Thus, a great deal of effort in the project was

devoted to measuring noise in mesoscopic devices. One of the most basic experiments is the direct observation of partition noise. This was achieved for a quantum point contact, the electronic analog of an optical waveguide. New experimental techniques enabled very sensitive measurements of the partition noise on only a few hundred nanoamperes.

The second main goal of this research, though, was to observe a multiple-particle effect rather than a single-particle effect in the noise. This was accomplished when we achieved the first experimental realization of a quantum statistical interference between two electrons colliding at a mesoscopic beam splitter. In contrast to bosons, the collision should result in a suppression of current fluctuations in the output, and would provide a very simple and direct demonstration of the Pauli exclusion principle. Further advances in noise measurement techniques enabled the confirmation of this effect.

Finally, such experiments should help to extend the study of the fundamental nature of quantum mechanics to fermionic particles. Noise measurements open new opportunities in "quantum electron optics," and may provide tools for studying entangled electrons, as well as the quantum statistics of composite particles.

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LIST OF SCIENTIFIC PERSONNEL

Robert C. Liu earned his Ph.D. at Stanford while employed on this project. Brian Odom was an undergraduate research assistant at Stanford who contributed technical aid to the project. Jungsang Kim was a graduate research assistant at Stanford who contributed technical aid to the project. Peter Eastman was a graduate research assistant at Stanford who contributed to the computer simulations conducted as part of the project. Dr. Seigo Tarucha was a senior researcher at NTT Basic Research Labs who contributed to the fabrication of devices used in the project. Dr. Yoshihisa Yamamoto is the principal investigator who guided the research.

REPORT OF INVENTIONS

Not applicable.

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