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Collinear electron-electron scattering and cat's-eye retroreflection effect probed by electron transport through point contacts

Long distance electron-electron scattering detected with point contacts
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Recommended with a Commentary by Leonid Levitov, Physics Department, Masshachusetts Institute of Technology

This article reports on measurements of electron transport through a narrow constriction—known as a point contact—and provides evidence for electron-electron (ee) collisions near a 2D Fermi surface having a strongly collinear character, despite the electron-electron interaction itself not having a strong angular dependence. This surprising behavior can be understood by comparing electron collisions in 3D and 2D Fermi gases. In both cases, as is well known, the phase space for low-energy quasiparticles, as well as their lifetimes, are subject to constraints due to fermion exclusion. In 3D, fermion exclusion constrains quasiparticle energies to a narrow band of width $\sim T$ near the Fermi level. In this case, the kinematic constraints due to momentum conservation generally allow for quasiparticle scattering at large angles. A very different situation occurs in 2D electron gases[1–3]. Here, scattering processes allowed in quasiparticle collisions are more constrained than for 3D fermions, with a dominant role played by head-on collisions and retroreflection processes.

This behavior is a consequence of basic kinematics, as can be made clear by inspecting the scattering of a pair of low-energy quasiparticles. For simplicity, we assume a 2D system with parabolic band dispersion and a circular Fermi surface. At $T \ll E_F$, the phase space allowed by fermion exclusion is a narrow band of states at the Fermi surface, shown in pink in Fig.1. If particles 1 and 2 collide in a perfect head-on arrangement, as in panel a), the outgoing states are also head-on, and the scattering angles $\Delta\theta$ are unconstrained. However, for non-head-on processes, pictured in panel b), the phase space for outgoing states allowed by kinematics becomes constrained, suppressing scattering and rendering such

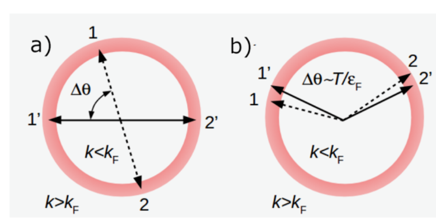

Figure 1: Different scattering processes, head-on (a) and non-head-on (b), occurring at a 2D Fermi surface.

collisions inefficient for angular relaxation. At low temperatures, only processes in which the angles between momenta $\vec{p}_1$ and $\vec{p}_2$ are within $\Delta\theta_T \lesssim T/E_F$ of π remain effective, whereas larger-angle scattering processes are blocked by kinematics and fermion exclusion. An experimental demonstration of these phase space effects, which have many interesting implications for electron transport in 2D fermion systems, has so far been lacking.

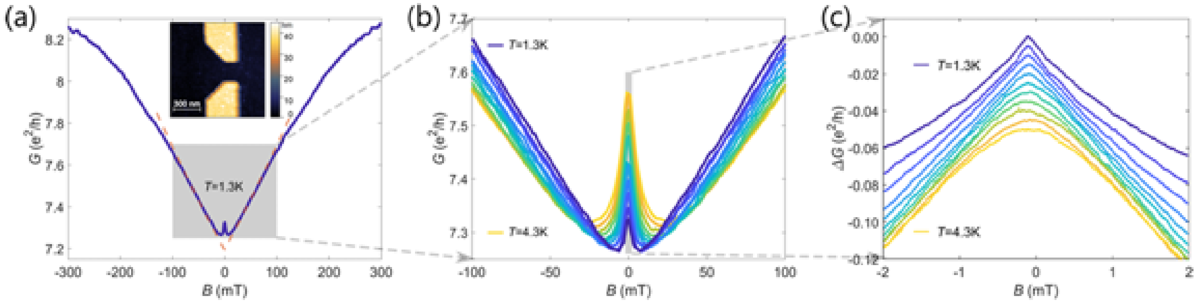

Figure 2: Transport through GaAs point contact. a) Device geometry and an overview of conductance vs. B dependence. b) Magnetoconductance peak at $B = 0$ zoom-in. Conductance traces at different temperatures are shown in different colors. c) The tip of the peak zoom-in, with different curves scaled to facilitate comparison [adapted from Ginzburg et al., PRX 5, 043088 (2023)].

In the experiment by Ginzburg et al., a regime is identified where collinear scattering processes can be directly observed and probed using transport techniques. This study examines electron transport through point contacts in an electron gas within high-mobility AlGaAs/GaAs heterostructures and graphene across various temperatures, magnetic fields, and electron densities. The key findings are summarized in Fig.2.

A magnetoconductance peak is observed around $B = 0$. As the temperature increases, the width of this peak increases monotonically, while its amplitude initially increases and then decreases. The analysis suggests that the growth of the conductance peak at low temperatures is due to electron-electron (ee) collisions, whereas the suppression of conductance at higher T can be attributed to electron-phonon scattering. Indeed, electron-electron collisions are expected to facilitate transport, leading to resistance decreasing with temperature[4], whereas electron-phonon collisions have the opposite effect.

The study focuses on the low-temperature regime, where an unconventional behavior of magnetoconductance is found. For GaAs point contacts, the peak is extremely sharp at relatively low temperatures ($T \approx 1.5K$). The curve rounds off on a scale of a few tens of microteslas, small values which appear to indicate mean free paths for the corresponding scattering processes as large as several millimeters.

The mechanism by which collinear scattering leads to a sharp peak in magnetoconductance can be understood as hole retroreflection. When an electron with momentum $\vec{p}$ is transmitted through the point contact collides head-on with the equilibrium electron distribution in 2DEG surrounding the point contact, an electron with momentum near $-\vec{p}$ is scattered sideways. This process generates backscattered hole that propagates back into the point contact (Fig. 3a). This counterpropagating hole contributes to the current with the same sign as the electron, effectively doubling the current at $B = 0$.

However, applying a magnetic field produces a Lorentz force, which acts in opposite directions on electrons and holes and splits their trajectories (Fig. 3b). This separation reduces the hole's contribution, decreasing the current through the point contact as B increases. The low electron-electron collision rates mean that these collisions typically occur far from the point contact. The collinear arrangement of electron and hole velocities makes this process highly sensitive to B, explaining the extreme narrowness of the peak.

Hole retroreflection, enabled by collinear head-on electron-electron scattering, represents an electronic analog of cat's-eye retroreflection. Because of the Lorentz force steering electrons and holes in opposite directions, this retroreflection effect is expected to be highly susceptible to magnetic field. While this explanation of an abnormally narrow magnetoconductance peak in transport through point contacts appears well-founded and qualitatively correct, a complete theoretical understanding of hole retroreflection processes and their implications is currently lacking. These findings also pose other intriguing questions for theory, in particular regarding the relation to other unusual phenomena anticipated in this regime, such as the existence of long-lived excitations with lifetimes greatly exceeding those predicted by Landau's Fermi-liquid theory [5, 6], as well as the linear-in-T non-Fermi-liquid temperature dependence of conductance extending down to lowest temperatures[6, 7].

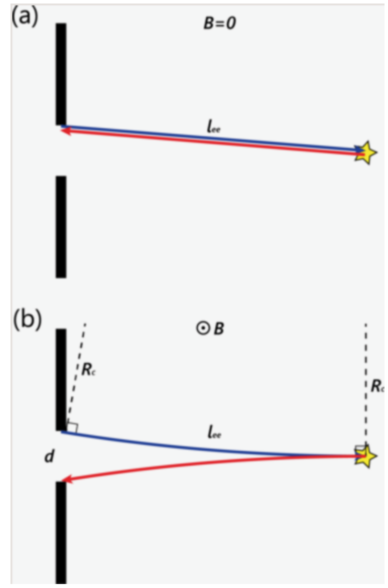

Figure 3: Electron retroreflected as a hole, a process relevant at low temperatures: (a) at $B = 0$ and (b) at $B \neq 0$. Black areas represent depleted parts of the 2DEG forming the point contact. The electron moving through the point contact is shown with blue arrows, and the retroreflected hole is shown with red arrows. The electron-electron scattering event occurs at the position marked with a star [adapted from Ginzburg et al., PRX 5, 043088 (2023)].

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