Tunable quantum interference between noisy electron sources

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We report shot noise cross correlation measurements in a four terminal beam splitter configuration. By using two tunnel barriers as independent electron sources with tunable statistics and energy, we can adjust the degree of quantum interference that results when the electrons scatter at a beam splitter. Even though quantum interference is only weakly affected by noise, it can be strongly suppressed by detuning the energies of the interfering electrons. Our results illustrate the importance of indistinguishability for quantum interference, and its resilience to unsynchronized electron sources and noise.

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Shot noise measurements in multi-terminal mesoscopic devices have been used to probe quantum statistics and interference [2, 3, 4, 5, 6], to understand the dynamics of electrons and their interaction [7, 8, 9, 10, 11, 12], and have even been proposed as probes for electron quantum entanglement [13, 14, 15, 16, 17, 18, 19], which has not yet been observed. To date, most experimental reports on electron quantum statistics and interference use three terminal configurations with a single electron source [4, 5, 11, 12], even though configurations which use two electron sources are essential for measuring electron quantum entanglement. In the only two-electron source measurement reported to date, Liu et al. [3] used shot noise cross correlation measurements to observe destructive quantum interference between two noiseless electron sources. However, it was pointed out that in order to proceed towards the observation of electron entanglement, the effects of noise and lack of synchronization on quantum interference had to be understood [20]. In this Letter we use shot noise cross correlation measurements to observe quantum interference between two noisy electron sources. These tunnel barrier electron sources are unique since (i) the statistics of the tunneling currents can be tuned over a wide range and (ii) the energy of the tunneling electrons can be precisely controlled. Our data indicates that quantum interference between electrons from the two uncorrelated and unsynchronized sources can occur even in the presence of noise. Even though quantum interference is only weakly dependent on the amount of noise present in the sources, it can be strongly suppressed by decreasing the energy overlap between electrons from both sources. Our experiments thus provide a direct observation of the fundamental relation between indistinguishability and quantum interference.

The samples used in this experiment were defined on a GaAs/AlGaAs heterostructure using electrostatic gates [21]. At low temperatures a two dimensional electron gas (2DEG) with electron mobility \( \mu_e = 6.1 \times 10^5 \) cm\(^2\)/Vs and carrier density \( n = 1.8 \times 10^{15} \) m\(^{-2}\) forms 50 nm below the wafer surface. A schematic of the gates is shown in Fig. 1(a). Negative voltages are applied to gates 1, 2 and 3 to form two tunnel barriers, and to gates 6, 7, and 8, to form a beam splitter at the thin section of gate 7. The transmission coefficient \( t \) of the beam splitter can be adjusted by changing the voltage on gate 7. Electrons injected from reservoirs \( A \) and \( B \) tunnel through the barriers and are guided by additional gates 4 and 5 towards the beam splitter, where they scatter into channels \( C \) and \( D \). Mean free paths in our devices are \( \sim 1 \) \( \mu \)m and thus electrons travel ballistically from the tunnel barrier to the beam splitter. The current fluctuations in both channels are measured by two cryogenic preamplifiers, further amplified at room temperature, and eventually fed into a spectrum analyzer, which calculates their cross correlation 5 [1]. All measurements are done in a 20 kHz window around 220 kHz and at a temperature of 70 mK. Details of the measurement setup and of the thermal noise background subtraction procedure used to obtain the current shot noise are described in detail elsewhere [21]. We studied a total of 4 devices, repeating the measurements on each device after multiple room temperature thermal cycles. The same general behavior was observed every time. Except when explicitly noted, the data reported here is for a single device on a single cooldown.

FIG. 1: (a) Device schematic. \( A, B, C, \) and \( D \) are electron reservoirs, while gates 1, 2, and 3 define the two tunnel barriers. Large negative voltages are applied to gates 6 and 8 so that the partition of electrons occurs only at the narrow section of gate 7 between the bottom of gate 1 and the top of gates 6 and 8. (b) & (c) Conductance and Fano factor of the (b) left and (c) right tunnel barriers.
Tunnel barriers fabricated in semiconductor heterostructures usually contain localized electronic states [22, 23, 24] which can be probed with conductivity and shot noise measurements. It has been previously reported that by tuning the gate voltages used to form such tunnel barriers, the energy of the localized states and the coupling between them and the electron reservoirs can be adjusted. This modifies not only average transport quantities such as the tunneling current $I$, but also fluctuations dependent on the electron transport statistics, such as the shot noise. Therefore a tunnel barrier is an electron source with tunable statistics characterized by the Fano factor $F$, defined as the ratio of the total shot noise current power and $2eI$.

We first characterize each of the tunnel barriers by measuring their conductivity and Fano factor as a function of gate voltage [Figs. 1(b) and 1(c)]. Shot noise suppression below the ideal tunnel barrier value of $F = 1$ occurs when transport is dominated by conduction through localized states, as also evidenced by the strong conductance modulation with gate voltage. Therefore by adjusting $V_2$ ($V_3$) we can control the statistics of electrons coming from the left (right) tunnel barrier. Furthermore, we observe that the two electron sources can be tuned independently. Figure 2(a) shows that as $V_2$ changes, the Fano factor of the left barrier is strongly modulated, while the Fano factor of the right barrier remains constant. Similarly (data not shown), the properties of the left barrier are unmodified when $V_3$ is changed. In order to show that the two tunnel barriers inject uncorrelated electrons, we measured the cross correlation $S$ of the signals at electron reservoirs $C$ and $D$ for both $t=0$ (beam splitter completely closed) and $t = 0.5$. Figure 2(b) shows that there is zero cross correlation when the beam splitter is completely closed, but a clear gate voltage dependent cross correlation when $t = 0.5$, demonstrating that the only significant source of correlations occurs when the electrons scatter at the beam splitter. Therefore, we conclude that the tunnel barriers act as uncorrelated sources of electrons with independently adjustable statistics.

Our goal is to quantify the quantum interference between these two electron sources by measuring the cross correlation at reservoirs $C$ and $D$. However, even single source injection produces a nonzero cross correlation [4, 5, 11, 12, 25]. Therefore, we first perform single source cross correlation measurements. Electrons are injected from reservoir $A(B)$ through a single tunnel barrier while the shot noise cross correlation $S_A(S_B)$ between reservoirs $C$ and $D$ is measured. The subindexes $A$ and $B$ indicate which tunnel barrier was used as an electron source. It was previously found [23] that $S_A(S_B)$ is related to $F_A(F_B)$, the Fano factor of the source barrier, by

$$S_i = 2eI_i(F_i - 1)t(1 - t),$$

where $i = A, B$. The solid symbols in Fig. 3(a) show typical single source cross correlation measurements as a function of the beam splitter transmission coefficient. For the data shown here $F_A = 0.45$ and $F_B = 0.37$, but good agreement of the single source cross correlation with Eq. 1 (solid curves) was found for all other measured values of the Fano factors.

For the dual source experiments, electrons are injected from both reservoirs while the shot noise cross correlation $S$ between reservoirs $C$ and $D$ is measured. The dual source cross correlation data [open circles in Fig. 3(a)] show a similar dependence on $t$, but with larger negative values. For uncorrelated sources which inject distinguishable particles, electrons from different sources scatter at the beam splitter independently, so the total cross correlation is simply $S_{\text{indep}} = S_A + S_B$ [lower dashed line in Fig. 3(a)]. On the other hand, for uncorrelated sources of identical particles, quantum interference due to electron wavefunction overlap at the beam splitter needs to be taken into account. Theory predicts that for two uncorrelated, noiseless electron sources ($F_A = F_B = 0$), $S_{\text{ideal}} = -2eI(1 - t)$ [26], where $I$ is the average current.
in each channel, and thus $S_{\text{ideal}}$ is only one half of $S_{\text{indep.}}$ [upper dashed line in Fig. (a)]. Since for every $t$ the measured dual source cross correlation is less than that for the case of uncorrelated and distinguishable particles ($|S| < |S_{\text{indep.}}|$), we can conclude that there is quantum interference between electrons arriving from the two different sources as they scatter at the beam splitter. It was pointed out that quantum interference can only occur when there is simultaneous arrival of electrons from both sources at the beam splitter, or equivalently, that there should be enough wavefunction overlap between pairs of electrons at the beam splitter to make the particles indistinguishable [20]. However, this is not guaranteed if noisy sources are used, since in that case the time interval between successive electron arrivals at the beam splitter is a random variable, and thus interfering electrons are unsynchronized. As such, electrons from two uncorrelated and noisy sources could have little or no spatial overlap and quantum interference might not occur. Nevertheless, the data of Fig. (a) clearly show that such quantum interference does exist for noisy sources.

To better characterize the effect of quantum interference, we now define a dimensionless quantity $S_N = S/(S_A + S_B)$. Explicitly,

$$S_N = S/((2eI_A(F_A - 1) + 2eI_B(F_B - 1))(1 - t)). \quad (2)$$

With this definition, uncorrelated and distinguishable particles, which present no quantum interference, have $S_N = 1$. On the other hand, for uncorrelated and noiseless sources emitting indistinguishable particles, quantum interference is maximum and $S_N = 0.5$. The results of measurements of $S_N$ as a function of $F_A + F_B$ for $t = 0.5$ for three different samples are shown in Fig. (b). For each of the samples and each of the $F_A$, $F_B$ combinations we first obtained data similar to that shown in Fig. (a). Good agreement of $S_A$ and $S_B$ with Eq. (1) was always observed. Figure (b) shows that for all $F_A$, $F_B$ combinations, there is always some degree of quantum interference ($S_N < 1$), but ideal quantum interference is never obtained ($S_N > 0.5$ even for the sources with the smallest Fano factors). In addition, we do not observe any clear relation between $S_N$ and $F_A$, $F_B$. This is in contrast with the results of single source cross correlation measurements where $S_i$ is determined by $F_i$ as shown by Eq. (1). As we will now show, the degree of quantum interference measured by the dimensionless cross correlation $S_N$ is determined mainly by the energy overlap of the electrons coming from the two sources, and not by the tunnel barrier Fano factors.

Figure (a) shows $S_N$ as a function of gate voltage $V_3$ at seven different values of gate voltage $V_2$. By varying $V_2$ and $V_3$ the energy of the localized states through which electrons tunnel in the two source barriers are changed. In this set of measurements, $S$ is measured at each $V_2$, $V_3$ combination and $S_N$ is calculated using Eq. (2). Again, in all measurements $S_N$ is always between 0.5 and 1, suggesting partial quantum interference of electrons. Furthermore, there is a strong dependence of $S_N$ on $V_2$ and $V_3$. For every value of $V_2$, $S_N$ always has a minimum at a certain value $V_3 = V_{3,\text{min}}$ and approaches 1 as $V_3$ is tuned away from $V_{3,\text{min}}$. As $V_2$ changes from -0.25V to -0.266V, the position of the minima shifts linearly from -0.242V to -0.266V, giving a ratio of $\Delta V_2/\Delta V_3 = 1.5$. The sensitivity of the localized state energy to changes in gate voltages can be independently measured by calculating the full width at half maximum of the conductance curves in Figs. (b), (c), which are 52 mV and 34 mV respectively. The ratio $\Delta V_2/\Delta V_3$ obtained in this way is 1.53, in agreement with the ratio obtained from the cross correlation measurements, suggesting that the gate voltage dependence of $S_N$ in Fig. (a) is a measure of the degree of alignment of the energies of the localized states in the two tunnel barriers.

The importance of the energy overlap between electrons from the two sources for quantum interference is now explained. In most theoretical studies of quantum interference in a beam splitter configuration, electrons are assumed to be in plane wave states with well defined wave vectors and energy. However, a more realistic picture is to view electrons as energy wave packets with a finite energy broadening defined by the coupling between the localized states and the reservoirs [21]. If electrons from the two sources have similar energies, that is, the
two wave packets have a significant overlap on the energy scale, then these electrons become indistinguishable when their wavefunctions overlap at the beam splitter. In such a case, quantum interference occurs and the shot noise cross correlation is suppressed \([\text{minima in Fig.} \, \text{4} \, \text{a}]\). On the other hand if electrons from the two sources have very different energies, then we could in principle identify each electron by measuring its energy (since the distance from the source to the beam splitter is smaller than the mean free path, electron motion is ballistic and thus electron scattering can be ignored). In such a case, these electrons become effectively distinguishable even when their spatial wavefunctions overlap. As a result, no quantum interference occurs, and thus there is no shot noise cross correlation suppression \([\text{saturation towards} \, S_N = 1 \, \text{in Fig.} \, \text{4} \, \text{a}]\).

Figure 4(b) shows the minimum values (maximum quantum interference) of the seven curves shown in Fig. 4(a) as a function of \(F_A + F_B\). We want to point out that the seemingly random point to point fluctuations are actually reproducible in repetitive measurements. The size of the error bars (\(\sim 0.01\)) is only one third of the typical point to point fluctuation. Once the gate and bias voltages are fixed, the same \(S_{N, \text{min}}\) values will be obtained. Our data indicates that the changes in \(S_{N, \text{min}}\) with \(F_A + F_B\) are much smaller than the changes in \(S_N\) obtained when the energies of electrons from both sources change from aligned to not aligned \([\text{Fig.} \, \text{4} \, \text{a}]\). This shows that even as the Fano factor, and therefore the noise, of the sources varies by over a factor of two, there is very small change in the degree of quantum interference. This evidences that quantum interference is extremely resilient to noise and lack of synchronization.

We also observed that varying the bias voltage by almost a factor of two (for the sample studied here between 0.15 mV and 0.25 mV), has no effect on quantum interference. Figure 4(c) shows that as a function of the bias voltage (equal for both barriers), and for fixed gate voltages \(V_2\) and \(V_3\), \(S_N\) varies by less than 1\%, a few times smaller than the variation of \(S_N\) with \(F\) shown in Fig. 4(b). As long as the bias voltage is varied over this range, tunneling should occur through the same set of localized states in each barrier. Since \(V_2\) and \(V_3\) are fixed, the energy of these states remains unchanged, so varying the bias voltage should have negligible effect on tunneling, and thus no effect on the quantum interference occurring at the beam splitter. Therefore quantum interference is very insensitive to the bias voltage, weakly dependent on the source noise, but strongly affected by the energy overlap of the electrons from each source.

In summary, we performed shot noise cross correlation measurements in a four terminal beam splitter configuration using two uncorrelated tunnel barriers to inject electrons. The observed shot noise suppression of electrons leaving the beam splitter is a direct manifestation of quantum interference. We observe that quantum interference occurs even for noisy sources and that the degree of quantum interference is only weakly sensitive to the amount of noise present in the electron sources. Therefore, our observations show that the synchronization of electrons is not critical for observing quantum interference. However, quantum interference can be greatly suppressed by detuning the energy of the two localized states, since in such a case electrons from the two sources have different energy and become distinguishable. Therefore, in order to observe maximum electron quantum entanglement, it is not the statistical properties of the electron sources that matters most, but rather the indistinguishability of the electrons brought about by carefully aligning their energies.

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