Enhanced shot noise in resonant tunnelling via interacting localised states

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In a variety of mesoscopic systems shot noise is seen to be suppressed in comparison with its Poisson value. In this work we observe a considerable enhancement of shot noise in the case of resonant tunnelling via localised states. We present a model of correlated transport through two localised states which provides both a qualitative and quantitative description of this effect.

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Understanding the role of electron coherence and Coulomb interaction in electron transport is one of the main directions of contemporary research in mesoscopic physics. Recently, shot noise measurements have proved to be a useful tool for these studies, since they provide information which is not available from standard conductance measurements. Shot noise, i.e. fluctuations of the current in time due to the discrete nature of electrons, is a measure of temporal correlations between individual electron transfers through a mesoscopic system. Uncorrelated transfers result in the Poisson shot noise with the noise power $P = e^2 I$, where $I$ is the current and $e$ is the electron charge, and is the average current). The effects on noise of the Pauli exclusion principle and the Coulomb repulsion turn out to be similar in most mesoscopic systems. Both were predicted to impose a time delay between two consecutive electron transfers, which results in negative correlations between them and, therefore, suppression of shot noise. This idea has been intensively explored in studies of the shot noise properties in ballistic and diffusive systems.

Electron transport via localised states in a potential barrier between two contacts has been a subject of intensive investigations. If the size of a mesoscopic barrier is small, resonant tunnelling (RT) through a single localised state (impurity) becomes responsible for conduction across the barrier. When the resonant level coincides with either of the Fermi levels in the contacts, $\mu_{L,R}$, a peak in the conductance appears. The amplitude of the peak is determined by the ratio of the leak rates $\Gamma_{L,R} \propto \exp(-2\pi r_{L,R}/a)$ from the resonant impurity to the contacts, where $r_{L,R}$ are the distances between the impurity and the left or right contacts, and $a$ is the localisation radius of the state, Fig. 1a. The current is given by the relation $I_0 = e\Gamma_L\Gamma_R/\left(\Gamma_L + \Gamma_R\right)$. It has been predicted in that for RT via a localised state shot noise is suppressed by the Fano factor $F \equiv S_1/2eI_0 = \left(\Gamma_L^2 + \Gamma_R^2\right)/\left(\Gamma_L + \Gamma_R\right)^2$. The Fano factor then ranges from 0.5 (for equal rates) to 1 (for significantly different rates) dependent on the position of the resonant impurity inside the barrier. Suppression of shot noise in accordance with this relation has been first observed in a resonant tunnelling structure. Similar suppression of shot noise in the Coulomb blockade regime has been seen in a quantum dot. In electron hopping (sequential tunnelling) through $N$ equivalent barriers the Fano factor is also expected to be suppressed, $F = 1/N$, if one assumes that the Poisson noise is generated across a single barrier.

In this work we present a study of time-dependent fluctuations of the RT current through a short ($0.2 \mu m$) tunnel barrier. Surprisingly, we observe a significant enhancement of shot noise with respect to the Poisson value. We explain this effect by correlated resonant tunnelling involving two interacting localised states.

The experiment has been carried out on a $n$-GaAs MESFET consisting of a GaAs layer of $0.15 \mu m$ (donor concentration $10^{17} cm^{-3}$) grown on an undoped GaAs substrate. On the top of the structure an Au gate is deposited with dimensions $L = 0.2 \mu m$ in the direction of the current and $W = 20 \mu m$ across it, Fig 1b. By applying a negative gate voltage, $V_g$, a lateral potential barrier is formed between the ohmic contacts (source and drain).

FIG. 1: (a) Resonant tunnelling through a localised state in a barrier. (b) Cross-section of the transistor structure with two ohmic contacts and the gate between them. (c) Typical RT peaks in the ohmic conductance at different temperatures.
Its height is varied by changing $V_g$. When a source-drain voltage $V_{sd}$ is applied, fluctuations of the current between the ohmic contacts are measured by two low-noise amplifiers. The cross-correlation spectrum in the frequency range $50 \sim 100$ kHz is detected by a spectrum analyzer. This technique removes noise generated by the amplifiers and leads.

Fig.1 shows an example of conductance peaks as a function of $V_g$ in the studied sample at $V_{sd} = 0$ and different temperatures down to $T = 0.07$ K. One can see that with lowering temperature the background conductance (due to electron hopping) decreases and the amplitude of the conductance peaks increases. This increase is a typical feature of resonant tunnelling through an impurity.

The box in Fig.2 indicates the range of $V_g$ where shot noise has been studied at $1.85 \text{ K} < T < 4.2$ K. In Fig.2 (inset) an example of the excess noise spectrum is shown at a gate voltage near the RT peak in Fig.2a. In this spectrum thermal noise has been subtracted and the effect of the stray capacitance has been taken into account according to [12]. Shot noise is determined from the spectrum thermal noise has been subtracted and the effect of the stray capacitance has been taken into account according to [12].

Fig.2b shows the dependence of the shot noise power on $V_{sd}$ at two temperatures. At small biases ($V_{sd} < 3 \text{ mV}$) a pronounced peak in noise is observed with an unexpectedly large Fano factor $F \sim 1$. This is seen by plotting the dependences $S_I (V_{sd})$ with different $F$ using the phenomenological expression for excess noise in the case of RT through a single impurity (cf. Eq.(62) in [1]) and Eq.(11) in [8]):

$$S_I = F 2 e I_{sd} \coth \left( \frac{e V_{sd}}{2 k_B T} \right) - F 4 k_B T G_S.$$  \hspace{1cm} (1)

(The expression describes the evolution of excess noise into shot noise $S_I = F 2 e I_{sd} at e V_{sd} > k_B T$; $G_S$ is the ohmic conductance of the sample) At large biases ($V_{sd} > 3 \text{ mV}$), however, shot noise decreases to a conventional sub-Poisson value, $F \sim 0.6$.

We have established that the increase of shot noise exists only in a specific range of $V_g$. It is worth noting that there is no negative differential conductance in the region of $V_{sd} - V_g$ where the peak in the noise appears, and, therefore, we cannot link this enhancement to some sort of instability. Instead, we will show that in this region of $V_{sd} - V_g$ the resonant current is carried by two interacting impurities and this leads to the increase of shot noise.

We will first show that interaction between two states can considerably increase shot noise. Let us start with a simple illustrative model and consider two spatially close impurity levels, $R$ and $M$, separated in the energy scale by $\Delta \epsilon$. If impurity $M$ is charged, the energy level of $R$ is shifted upwards by the Coulomb energy $U \sim e^2 / \kappa r$, where $r$ is the separation between the impurities and $\kappa$ is the dielectric constant. Fig.3 (diagram 1). Thus, dependent on the occupancy of $M$, impurity $R$ can be in two states: $R1$ or $R2$. Further we assume that $V_{sd}$ is small enough so that state $R2$ is above the Fermi level in the left contact, Fig.3 (diagram 2). Then electrons are transferred via $R$ with the rates $\Gamma_{L,R}$ if $M$ is empty, and cannot be transferred if $M$ is charged. It is assumed that impurity $M$ changes its states independently of the state of impurity $R$: from empty to charged state with the rate $X_e$ and from charged to empty state with the rate $X_c$. If $M$ changes its occupancy at a slow rate, i.e. $X_{e,c} \ll \Gamma_{L,R}$, its contribution to the current is negligible and we will call $M$ a modulator since it modulates the current through impurity $R$. This current jumps randomly between two values: zero, when $M$ is occupied, and $I_0$ when $M$ is empty, Fig.3 (inset). If the bias is increased, the upper state $R2$ is shifted down into the conducting energy strip and the modulation of the current via impurity $R$ vanishes, Fig.3 (diagram 3).

In the modulation regime, the average current through impurity $R$ and the corresponding zero-frequency Fano factor can be written, respectively, as

$$I = \frac{e \Gamma_L \Gamma_R}{\Gamma_L + \Gamma_R} \frac{X_e}{X_e + X_c}$$ \hspace{1cm} (2)

and

$$F = \frac{\Gamma_L^2 + \Gamma_R^2}{(\Gamma_L + \Gamma_R)^2} + 2 \frac{\Gamma_L \Gamma_R}{\Gamma_L + \Gamma_R} \frac{X_e}{(X_e + X_c)^2}.$$ \hspace{1cm} (3)

The first term in Eq.(3) describes the suppression of the Fano factor below unity, whereas the second term...
gives a positive contribution. To illustrate the origin of the second term, one can think of the modulated current as random telegraph noise (RTN), i.e. spontaneous jumps between zero and $I_0$. The second term can then be obtained from the spectrum of RTN \([4]\) with characteristic times of the upper and lower states - $1/X_e$ and $1/X_c$, respectively. If $X_{e,c} \ll \Gamma_{L,R}$, a substantial enhancement of shot noise, $F \gg 1$, is expected from Eq. 3. Another way to illustrate the origin of this effect is to assume that $M$ is close to the left contact. As a result, impurity $M$ spends more time in its charged state, i.e. $X_e \ll X_c$ and the current through $R$ is transferred in bunches, with the average duration of a bunch $\tau_e = 1/X_c$. The noise due to the ‘chopping’ of the current can then be estimated as $S_I = 2QI$, where $Q$ is the average charge transferred in one bunch. This charge is equal to $I_0\tau_e$, and this again gives the second term in Eq. 3.

This model of a slow modulator which changes its state independently of impurity $R$ may look too simplistic. However, its generalisation (for any relation between $X$ and $\Gamma$) is straightforward and provides a consistent quantitative description of the observed effect. Our theoretical model is based on the master equation formalism \([8, 16]\). It is applicable when $\Gamma_{L,R} < k_BT$ - the condition satisfied in our experiment. Then the system of two interacting impurities $R$ and $M$ can be in four possible states. The transition rates between these states are determined by tunnelling between the contacts and impurities and depend on temperature and the level positions with respect to the Fermi levels $\mu_{L,R}$. The resulting transport problem is reduced to numerical diagonalisation of a $4 \times 4$ matrix. As a result, the current and the Fano factor are obtained as a function of the energy positions of the two impurities, which are linearly dependent on $V_{sd}$ and $V_g$. It is important that in our calculations the effect of temperature, which suppresses the enhanced Fano factor in Eq. 3, is taken into account. (In a similar master equation approach an increase of shot noise for two interacting quantum dots was also obtained in \([17]\), however at $T = 0$.)

By measuring the differential conductance as a function of $V_g$ and $V_{sd}$ we have been able to show directly that the increase of shot noise occurs in the region of $V_g - V_{sd}$ where two interacting impurities carry the current in a correlated way. Fig.3 presents the grey scale of the differential conductance plotted versus $V_g$ and $V_{sd}$. When a source-drain bias is applied, a single resonant impurity would give rise to two peaks in $dI/dV(V_g)$, which occur when the resonant level aligns with the Fermi levels $\mu_{L,R}$. On the grey scale these peaks lie on two lines crossing at $V_{sd} = 0$. Consider, for example, point $M$ in Fig.3. The central area between the lines corresponds to the impurity level between $\mu_L$ and $\mu_R$, that is when the impurity is in its conducting state. Outside this region the impurity does not conduct, as it is either empty (on the left of the central region) or filled (on the right of it).

Experimentally, at small $V_{sd}$ we see such a cross-like feature near point $R2$, with the left line being more pronounced. The exact positions of the maxima of the conductance peaks of this line are indicated by circles. It is seen that with increasing $V_{sd}$, a new parallel line $R1$ appears at $V_g \approx -1.694$ V and $V_{sd} \approx 1$ mV, shifted to the left by $\Delta V_g \approx 4$ mV. The maxima of the conductance peaks of this line are shown by triangles. In Fig.3 the modulator cross is plotted according to the analysis below - experimentally we cannot observe these lines because the modulator conductance peaks are too small, due to low leak rates $X_e$ and $X_c$. The $R1$-line occurs in the inner region of the modulator cross, i.e. where the modulator occupancy changes in time. Therefore, lines $R1$ and $R2$ reflect the Coulomb shift of level $R$: the former corresponds to the empty modulator and the latter - to the occupied one. The modulation of the current should then occur in region (2), Fig.3 the central part of cross $M$ between lines $R1$ and $R2$, corresponding to diagram (2). As discussed before, in region (3) there is no modulation as both states $R1$ and $R2$ can conduct, and in region (1) there is no current as the low state $R1$ is still above $\mu_L$.

In Fig.4 current noise and the Fano factor are presented as functions of $V_{sd}$ for different $V_g$. It shows that indeed the increase of noise occurs only in region (2) in Fig.4. Namely, the increase of noise appears only between $V_g = -1.699$ V and $V_g = -1.693$ V, that is, in the central region of cross $M$. In addition, when $V_{sd}$ is swept at
fixed $V_g$, one can see that the hump in the Fano factor appears only between lines R1 and R2.

In order to quantitatively compare the model with the experiment we have to take into account that in our experiment resonant tunnelling via state $R$ exists in parallel with the background hopping. Then the total Fano factor has to be expressed as $F = (F_{RT}I_{RT} + F_BI_B)/(I_{RT} + I_B)$, where $F_{RT}$, $F_B$ and $I_{RT}$, $I_B$ are the Fano factors and currents for RT and hopping, respectively. In order to get information about the background hopping we have measured noise at $V_g > -1.681 \text{ V}$, i.e. away from the RT peak under study in Fig.3. It has been estimated as $F_B \sim 0.4$. This value of the Fano factor is expected for shot noise in hopping through $N \sim 2-3$ potential barriers (1-2 impurities in series). The bias dependence of the background current at this $V_g$ is also consistent with hopping current via two impurities: $dI/dV \propto V_{sd}^{2/3}$.

Assuming that the background current is approximately the same for all studied gate voltages, we have added up the contributions to the Fano factor from RT via two interacting impurities, $R$ and $M$, and the background hopping. The numerical results have been fitted to the experimental $dI/dV (V_{sd}, V_g)$ and $S_f (V_{sd}, V_g)$, Fig.4. The fitting parameters are the leak rates of $R$ and $M$ ($\Gamma_L \approx 394 \mu \text{eV}$, $\Gamma_R \approx 9.8 \mu \text{eV}$, and $hX_c \approx 0.08 \mu \text{eV}$, $hX_c \approx 0.16 \mu \text{eV}$), the energy difference between $R$ and $M$ ($\Delta E = 1 \text{ meV}$), and the Fano factor for the background hopping ($F_B = 0.45$). The coefficients in the linear relation between the energy levels $M$, $R$ and $V_{sd}$, $V_g$ have also been found to match both the experimental data in Fig.4 and the position of lines R1 and R2 in Fig.3. One can see that the model gives good agreement with the experiment. The Coulomb shift ($U \sim 0.55 \text{ meV}$) found from Fig.4 agrees with the estimation for the Coulomb interaction between two impurities not screened by the metallic gate: $U \sim e^2/k\ell \sim 1 \text{ meV}$, where $d \sim 1000 \text{ Å}$ is the distance between the gate and the conducting channel.

It is interesting to note that the hopping background effect hampers the manifestation of the enhanced Fano factor $F_{RT}$, i.e. without the background the Fano factor enhancement would be much stronger. The largest experimental value of $F$ in Fig.4 (at $V_g = -1.6975 \text{ V}$) is approximately 1.5, while a numerical value for RT at this $V_g$ is $F_{RT} \approx 8$.

In conclusion, we have observed enhanced shot noise in resonant tunnelling via localised states in a short-barrier structure. We have demonstrated that this effect originates from Coulomb interaction between two localised states which imposes correlations between electron transfers. A simple model is shown to provide a quantitative description of the observed enhancement.

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