# Shot Noise in Quantum Conductors

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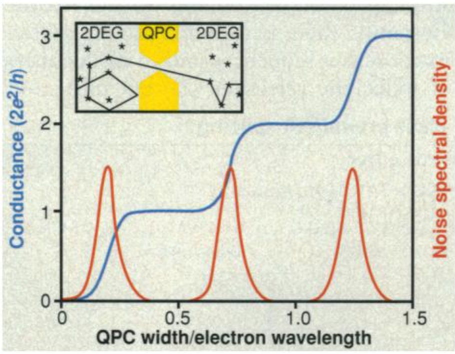
Fluctuations of an electronic current around some average value are often regarded as unwanted and are disparaged as noise. In most practical cases, noise indeed arises from annoying causes such as bad wire connections or stray electromagnetic fields. When these sources are expelled from a well-designed electronic circuit, one can encounter a more fundamental type of noise. At finite temperatures, electrons have some random motion that causes a voltage noise across a resistor. This thermal noise, or Johnson-Nyquist noise, is usually the theoretical limit in electronic circuits. However, if devices are made very small and measurements are taken at low temperatures, the particle character of the current carriers leads to another type of noise: "shot noise." Recent experiments (*1–6*) have studied shot noise in quantum conductors. Here we encounter an interesting conflict between the particle nature of shot noise and the wave nature of quantum devices.

To get a feeling for shot noise, one can think of the granular sound one hears during heavy rain, or even better, during a hailstorm. If we think of electrons as particles, one can imagine a similar sound when a beam of electrons arrives at some sort of detector. Vacuum diodes are a particularly simple model system for describing shot noise. The process of electron emission from a cathode can be considered to be purely stochastic and is thus described by a Poisson distribution. The scattering in the vacuum between cathode and anode is simply absent. Schottky (*7*) showed in 1918 that this leads to a noise spectral density $S = 2Ie$, where $I$ is the absolute value of the average current and $e$ is the electronic charge. This spectral density is a "white" noise, meaning that all frequencies contribute equally to the noise power.

Do we have shot noise in everyday conductors? Imagine somebody emptying a bucket of water over your head. In this case, the granularity is lost and you will hear an averaged, single sound. The same holds for a macroscopic conductor. Going through a large conductor, electrons experience many scattering events in which they exchange some energy with the material. This exchange suppresses the shot noise spectral density by a factor $L_{in}/L$, where $L_{in}$ is the length scale between inelastic scattering events and $L$ is the size of the conductor. Now consider a conductor that is free from impurities such that electrons can traverse the conductor without being scattered. This ballistic transport regime is the solid-state analog of the vacuum tube.

The ballistic device that has been studied in recent experiments is the quantum point contact (QPC) (see figure). A QPC is a short, narrow constriction that forms the connection between two segments of a two-dimensional electron gas. The properties of the QPC can be measured as a function of width by varying the gate voltage. The figure shows schematically that the conductance of a QPC changes in quantized steps of $2e^2/h$, where $h$ is Planck's constant. These quantized steps are a manifestation of the wave nature of electrons. At the lowest step, half of an electron wavelength fits in the QPC; at the second step, one full wavelength fits in; at the third step one- and a-half; and so on. So, basically, a QPC is a wave guide for electrons. Now the interesting question arises: Does the current through a quantum conductor acting as a QPC show shot noise originating from the particle granularity of electrons?




**Noisy currents. (Inset)** Electrons flowing from the two-dimensional electron gas (2DEG) on the left to the 2DEG on the right have to go through the small opening defined by the QPC. The width of the contact is of order 0.1 μm but can be reduced to zero by applying negative voltages to the gates (yellow). A schematic electron trajectory illustrates that scattering only occurs at impurities (marked with asterisks) in the 2DEGs. The blue curve shows that the average conductance is quantized at multiple values of $2e^2/h$. The red curve shows that shot noise is nonzero during transitions between conductance plateaus. The maximum shot noise value is one-fourth of the Poisson value. The typical temperature for such measurements is 1 K.

Before the early experiment by Li *et al.* (*1*), this question was addressed in several theoretical works (*8*). Besides the quantum-wave aspect of a QPC, there is a second way in which it differs from a vacuum tube. The emission from the two-dimensional electron gasses into the QPC is described by a Fermi-Dirac distribution. This distribution includes the quantum statistics of electrons arising from Pauli's exclusion principle: Two electrons with the same spin cannot occupy the same quantum state. Compared to the purely stochastic Poisson distribution, the Fermi-Dirac distribution includes this quantum correlation in the emission process. Note that correlations reduce noise. The theoretical predictions for shot noise in a QPC are also sketched in the figure. When the conductance is on a quantized plateau, the wave nature wins and the shot noise is suppressed. A quantum device can thus be completely noiseless. Between plateaus, the wave nature is less well defined, and shot noise arises. So, we conclude that the particle and wave natures of electrons exclude each other in average conductance and noise measurements.

How are we to measure quantum mechanically suppressed noise levels with a classical apparatus that itself has a much larger noise level? Indeed, to test these theoretical predictions, existing measurement techniques had to be rigorously improved. Reznikov *et al.* (*3*) at the Weizmann Institute of Science in Israel have developed a high-frequency measuring method. Kumar *et al.* (*4*) from Saclay in France have used two independent measuring apparatus in a configuration such that the instrument noise is averaged out and only the noise from the QPC remains. The experimental data of these and other groups (*5, 6*) confirm the predictions in detail.

What about the coulomb interaction between electrons? Such an interaction correlates the flowing electrons and would thus reduce the shot noise further. This effect has recently been measured in so-called coulomb blockade structures by Birk *et al.* (*2*). The Weizmann group (*3*) has suggested such coulomb correlations to explain their QPC data. Although this result is preliminary, it does indicate that shot noise experiments could become a very important tool in measuring how electrons affect each other while traversing a conductor. Such information is hard or impossible to obtain from averaged current measurements. With these experimental successes, it now becomes possible to perform experiments on quantum conductors that are analogous to intensity-intensity correlation measurements in optics. In contrast to photons, electrons carry a charge that makes their quantum mechanical phase sensitive to an Aharonov-Bohm magnetic flux. Büttiker (*9*) has used this fact in his calculations of correlations

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between different currents that leave the same quantum conductor. One result is that current-current correlations can show two-electron interference effects that are periodic in magnetic flux. The first researcher to perform such an experiment will definitely not be annoyed when his apparatus picks up noise that is periodic with a magnetic flux quantum.


### References

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# AT-AC Introns: An ATtACk on Dogma


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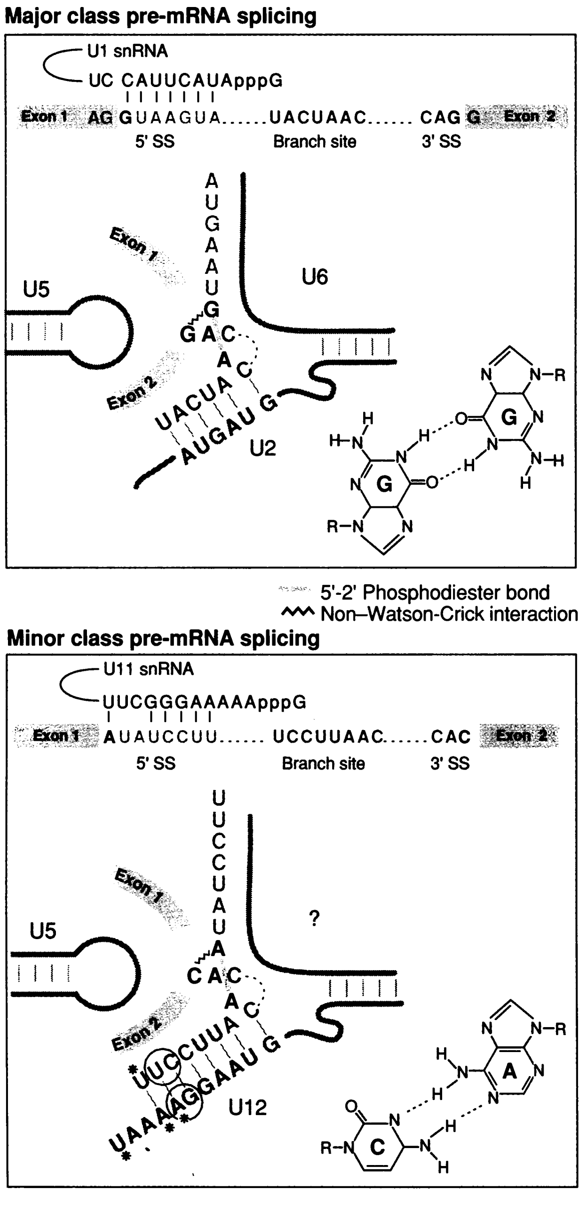
In the years immediately after the discovery that messenger RNAs (mRNAs) were spliced together from larger precursors, a common sequence feature was described in these precursors—invariant GT and AG dinucleotides at the ends of the intron (corresponding to GU and AG in the RNA). These short, conserved sequences (see figure) reflect the mechanism by which introns are removed from the precursor, and are not found in self-splicing, organelle, or transfer RNA introns (which are removed by other mechanisms). Among pre-mRNA introns, exceptions to this consensus are rare, and greater than 99% of pre-mRNA splice sites conform to the consensus sequences in the figure (*1*). The extent of agreement varies, but the "GT-AG" rule is followed particularly well. Apparent exceptions that prove the rule include 5′ splice sites with C at the second position and an otherwise excellent match to consensus. Most exceptions in the databases can be attributed to sequencing errors, genetic polymorphisms, somatic mutation, or errors in database annotation (*1*).

Pre-mRNA introns are spliced by the spliceosome, a large complex consisting of numerous small nuclear ribonucleoprotein (snRNP) particles and other factors. During the orderly assembly of this complex, the splice site consensus sequences are recognized by small nuclear RNAs (snRNAs). The evidence that all pre-mRNA introns are removed by a single conserved mechanism had appeared to be compelling (*2*): There are few counterexamples; the splicing machinery is complex and splicing factors are strongly conserved among all eukaryotes. Certainly, there is variation among species in consensus sequences and in mechanisms of splice site selection (*2*), but until now the evidence has suggested that all pre-mRNA introns are spliced similarly—in two steps via a branched intermediate by machinery with an active site that includes the conserved snRNAs U2 and U6 (*2*) (see figure).




**The major (GT-AG) and minor (AT-AC) classes of pre-mRNA introns. (Top)** GT-AG introns base pair with snRNPs U1, U2, and U6. (**Bottom**) The corresponding interaction between AT-AC introns and U11 remains unproven. Nucleotides mediating the AT-AC intron branch point–U12 pairing established by genetic suppression (*3*) are circled. Asterisk (*), intron and U12 nucleotides shown to be in proximity. Potential non–Watson-Crick base pairs between nucleotides at the two termini of the intron are indicated at the lower right of each panel.

Results in this issue of *Science* (*3*) and in a recent issue of *Cell* (*4*) are therefore quite surprising. These papers present data showing that the splicing of a specific minor class of intron (representing something less than 0.1% of all known pre-mRNA introns) is accomplished by a mechanism involving a distinct and correspondingly rare class of snRNAs, U11 and U12. The existence of such a class of intron with bona fide nonconsensus splice sites was first proposed by Jackson (*1*). Introns in this group have AT rather than GT at the 5′ end of the intron, and AC rather than AG at the 3′ splice site. Five such AT-AC introns are known (*5–7*), and in three of these instances the intron is conserved in distinct vertebrate species. Strikingly, all of these introns, including one in the *Drosophila* homeodomain protein gene *prospero*, share not only the AT and AC dinucleotides, but a much longer consensus at both splice sites and a nearly invariant sequence (TCCTTAAC) at a consistent distance (8 to 11 nucleotides) upstream of the 3′ splice site (see figure). On the basis of potential base pairing between these consensus sequences and the minor snRNAs U11 and U12, it was proposed (*5*, *8*) that AT-AC introns are recognized by a distinct class of factors that includes U11 and U12.

This proposal has now been subjected to experimental test. Hall and Padgett (*3*) show that mutation of the putative branch point consensus (UCCUUAAC in the RNA) interferes with splicing in vivo; alteration of two nucleotides that do not occur in the branch point consensus for the major class of intron (UC to AG at the position circled in the figure) prevented splicing in transfected cells. Furthermore, splicing could be restored by providing U12 with an alteration of the complementary nucleotides (GA to CU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