PHY 123/253
Shot Noise

Complete Pre-Lab before starting this experiment

HISTORY

In 1918, experimental physicist Walter Scottky working in the research lab at Siemens was investigating the origins of noise in vacuum tube circuits. He discovered that there was a wideband current noise in vacuum diodes proportional to the square root of the DC current. From its wideband nature he dubbed it "Schrot" noise [Schrot is German for buck shot: factories that make buck shot by dropping cooling molten metal pellets a large vertical distance generate a wideband audio noise which may be heard from afar.]

THEORY OF SHOT NOISE

Shot noise is a result of any random process involving uncorrelated arrival of discrete objects. This is true whatever the nature of the discrete objects, from marbles to charged particles to quanta of light. In the case of electrons, this Poisson process results in current noise. In the case of photons there is a corresponding fluctuation in arrival rate. These statistical fluctuations occur over a broad range of timescales. The frequency spectrum of shot noise is covered in more depth in Week 3 (see notes.pdf). Other useful references are the pdf files "Shot Noise History" and "MIT Experiment."

The uncorrelated and random nature of the discrete objects is important. For example, in a metal conductor the electrons become correlated because of their mutual electric fields and the shot noise disappears. In a diode the individual electrons are forced to pass a barrier, so that their individual discrete nature is preserved. In that limit they represent random Poisson events.

For such a Poisson process, consider n events (electrons) in time τ. Then the variance in n (the mean square fluctuation of n) is equal to the average n during that time interval,

$$\left\langle (\Delta n)^2 \right\rangle_{time} = \bar{n}$$

For electrons, the current I is given by

$$I = \bar{n} e / \tau$$

Thus, the shot noise current variance is given by

$$\overline{(\Delta I)^2} = \overline{(\Delta n)^2} e^2/\tau^2 = \bar{n} e^2/\tau^2 = eI/\tau$$

In principle, with the right equipment, you could measure these fluctuations on arbitrary timescales τ. However real experiments measure voltages over a range of timescales (or equivalently a range of frequencies) limited by the measurement apparatus. Indeed, it is convenient to define a measurement bandwidth by introducing a bandpass filter which passes voltage fluctuations only over a defined range of frequencies Δf. Integrating for a fixed timescale of τ, in the frequency domain corresponds to a filter with "square" bandpass Δf = 1/ 2τ. Thus, the root mean square (RMS) current shot noise in such a passband Δf is given by

$$I_{noise,RMS} = [\overline{(\Delta I)^2}]^{1/2} = (2eI_{DC}\Delta f)^{1/2}$$

If a DC current of I_{DC} is sent through a barrier such as a diode so that individual electrons randomly cross the barrier then the resulting current noise is given by the above relation. For example, a DC current of 1 mA in such a circuit results in a RMS current noise of 1.8 nA measured in a 10 KHz passband. If this current is passed through a 100 Ω resistor, the resulting RMS voltage fluctuation across the resistor is 180 nV RMS. You could measure this with a low noise preamplifier, RMS voltmeter, and spectrum analyzer.

EXPERIMENT GUIDE

This experiment consists of three parts. In the first part you will gain familiarity with your equipment, including a noise generator, oscilloscope, and spectrum analyzer. In the second part you will measure the charge on the electron by measuring the shot noise of a DC current passing through a forward biased diode as a function of the DC current. In the third experiment you will measure photon shot noise using a photomultiplier tube (PMT) to count individual photons. Be sure to write down and discuss all your results in your lab book.

EXPERIMENT 1.

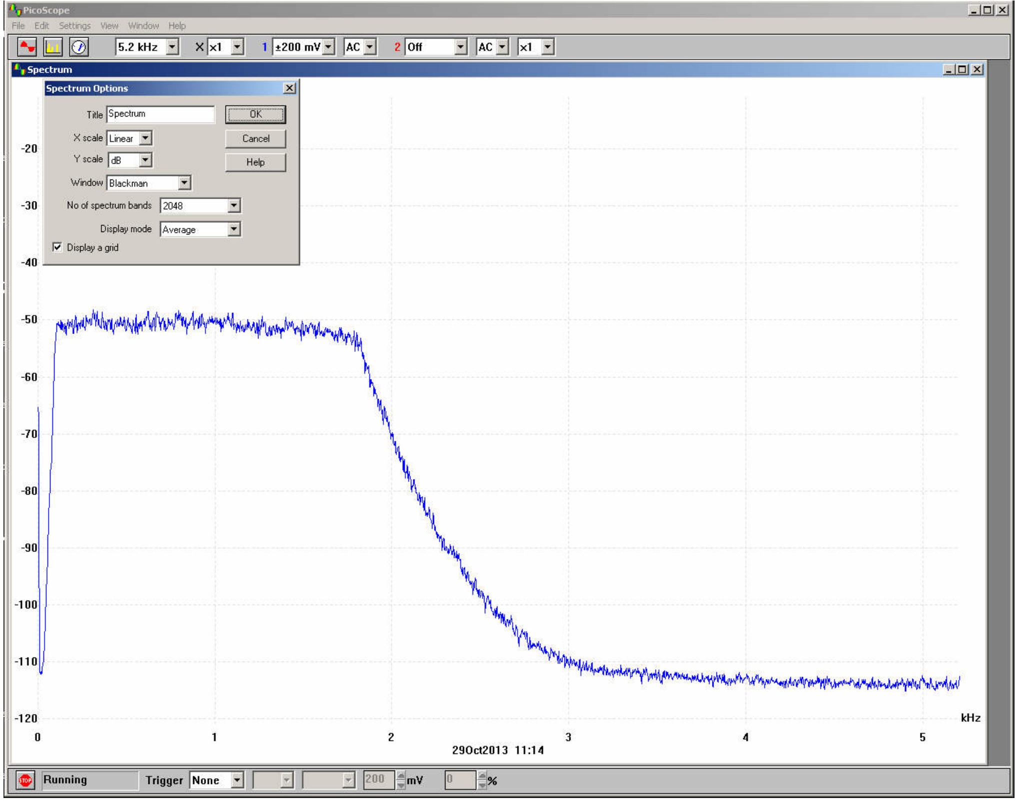
This is designed to familiarize you with your measuring equipment. Using the General Radio 1390B noise generator on the 20KHz setting, observe the noise output on your oscilloscope. You will not need a preamplifier since the noise output of the GR1390B is on the order of a volt. Adjust the output to about 0.1 volt AC RMS on the scope and look at the noise using a wide range of timescales by changing the time base. Observe the self similarity of this noise on most all time base displays. What does this imply regarding the shape of the noise power spectrum vs frequency? Is there a short timescale on which the noise amplitude decreases? What is its origin?

Before you go too much farther you probably ought to check if there is any contamination of your signal (noise in this case!) by power line 60Hz pickup and its low harmonics. You can do this simply by triggering your scope with the power line (a trigger option). If there is such interference it will have spikes that appear stable on the time axis of your scope. Change the scale to 5ms/dev and see if you have a problem.

To make a more realistic low-level noise, use a resistive divider (front panel of GR1390B) to divide down the noise generator output to 100 microvolts or less. Note that you will not be able to measure this directly on your scope or voltmeter because this test equipment has effective input noise of several mV. Thus you will have to send this microvolt level signal to an amplifier with gain of around 1000. Then send this small noise through a 300 Hz to 10 KHz bandpass filter such as the Signal Recovery 5113 and then observe the output on the oscilloscope again over a wide range of timescales. Depending on the amplitude of your noise input you may have to use a gain of 1000 or more on the SR 5113. Do you see the low and high frequency roll-off of the bandpass filter? Is there some reason you might want to avoid 60 Hz and 120 Hz in your experiment? You can set the SR 5113 to have a more square passband by selecting 12db/octave rolloff for the high frequency limit. A single RC filter corresponds to 6db/octave rolloff.

Now send the noise output of the bandpass filter to a precision RMS voltmeter such as the Agilent 34410A. Observe this average RMS noise voltage as a function of noise generator amplitude and as a function of filter bandpass Δf. The Agilent 34410A has a statistics menu which allows RMS average and standard deviation measurements. What are the functional relations for the dependence of the RMS noise amplitude on the filter passband Δf and the input noise generator amplitude?

Finally, look at the spectrum of this noise using the PicoScope spectrum analyzer for several choices of SR5113 bandwidth and make a few plots of your spectra. The PicoScope software has some "features" if you measure wideband noise. As shown below you should use either 200mV or 500mV [not Auto] for your mode, and y scale dB.



Title: Spectrum
X scale: Linear
Y scale: dB
Window: Blackman
No of spectrum bands: 2048
Display mode: Average
☑ Display a grid

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EXPERIMENT 2.

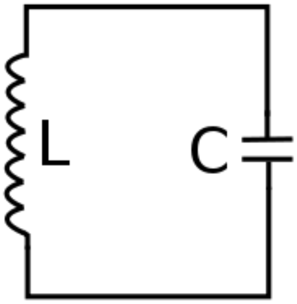
In the previous exercise you saw the effects of filtering wideband shot noise with a filter with a broad passband. In this experiment you will measure the effect of filtering wideband noise with a resonant LC circuit which passes spectral components of the noise mostly at one frequency: the resonant frequency of the LC circuit. Such circuits are used in many applications in experimental physics. The "selectivity" [called "Q"] of a resonant circuit is inversely proportional to on how much energy loss per cycle it has: i.e. the effective resistance.

In an LC circuit, the power alternates between the capacitor and the inductor at the resonant frequency given by the equation below. At this resonant frequency the AC voltage across the circuit is a maximum and the current in the inductor is maximum (allowing you to easily pick up this signal with a loosely coupled inductive loop). The resonant frequency $\omega_0 = 2\pi f_0$ of a parallel LC circuit is given by

$$\omega_0 = 1/\sqrt{LC}$$

Derive this in your lab book.

Let's make a resonant circuit that is very selective by minimizing the electrical resistance. Using the supplied 150mH ferrite core inductor and 20-400pF variable capacitor (C in figure below), construct a LC parallel circuit. What is the expected impedance across this parallel LC circuit vs frequency? Again, try to measure and estimate all sources of resistance. Next, inductively couple some oscillator power into this circuit via 1-2 turns of wire wound around the inductor. Hook this coupling coil in series with a 50 ohm resistor (so as not to load down the oscillator output amplifier) and apply a small fraction of a volt from your signal generator at a frequency near where you calculate [in Hz!] the resonance of your LC circuit will be for an intermediate setting of the variable capacitor (say 250pF). With your scope switched to high input impedance and using a X10 probe, measure the voltage across your LC circuit as you "tune" your variable capacitor. Observe the resonance. Do the reverse too: set your oscillator to a frequency near your resonance, and then change the oscillator frequency measuring the peak-to-peal voltage as you go, mapping out this resonance. Make a plot of the square of this voltage (proportional to the *power*) vs frequency.



Now inject wideband noise into the LC circuit from your noise generator, and send the output (either via another 1-2 turn pickup coil placed some distance from your input coil, or via a very small capacitor in the pF range connected to the output of the LC circuit) to a preamp and the spectrum analyzer. You can use the small battery operated preamp (voltage gain of 20). However, try first with the preamp in the PicoScope spectrum analyzer itself. Observe that the power spectrum of the filtered noise is the same as the power vs frequency relation you observed with the oscillator. Discuss in terms of transfer functions in the frequency domain.

EXPERIMENT 3.

In this experiment you will measure the shot noise in a stream of random uncorrelated photons coming from a Sylvania 7377 light bulb with a small adjustable DC current. To count individual photons you need a very sensitive low noise detector: a PMT. *Use extreme care: this PMT uses high voltage and it can also be damaged if you put too much light on it with the HV on.* The setup is shown in the following figure.

Begin with a contest to see how few photons you can count with your eye. There is an identical Sylvania 7377 light bulb set up at the end of a black tube. Hook this to your

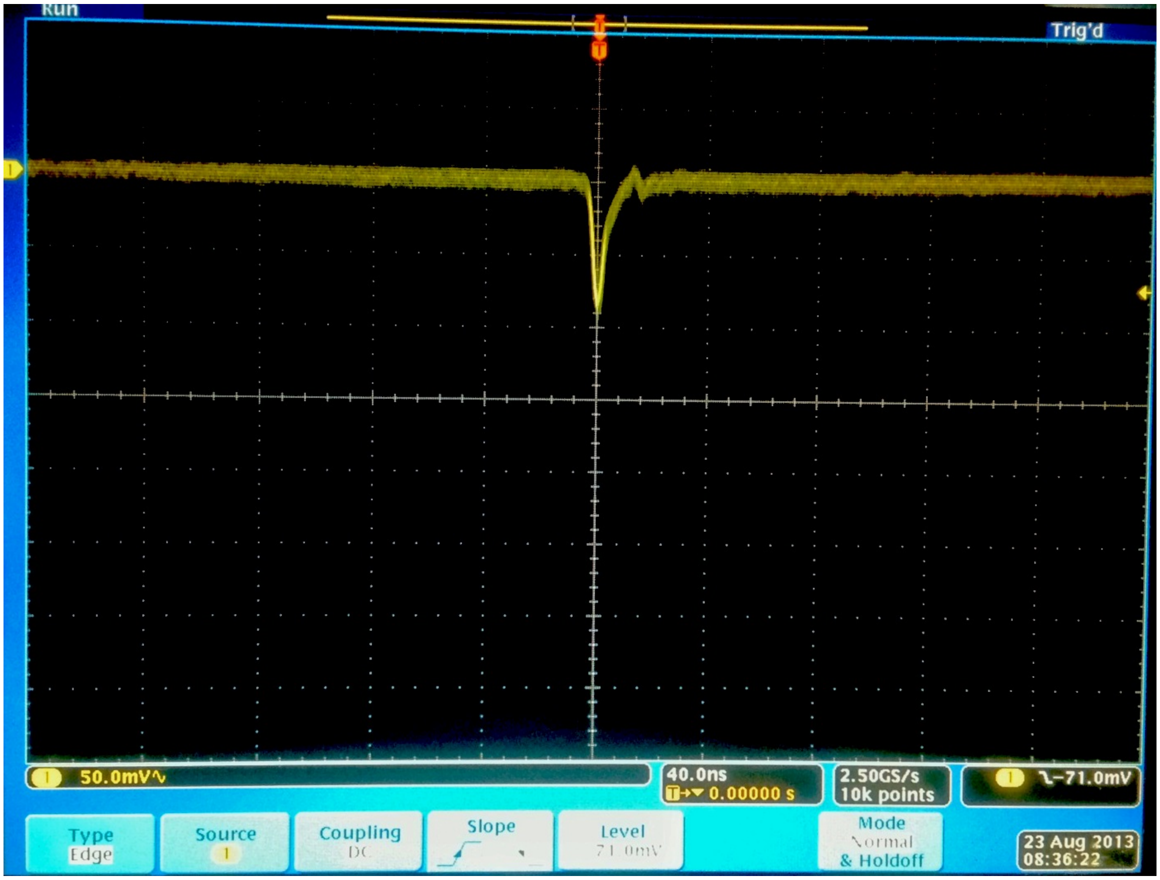
0-10V DC power supply with 100 Ω series resistor. Route this through a precision ammeter so you can measure the bulb current in the mA range. In a darkened room have your partner tell you when they can see your random secret brief (approx. 1 sec) circuit closures. Ask your partner to say YES when they see a flash. Start at 0 V and gradually increase the voltage (thus current) until your partner begins getting the right answer about 70% of the time. Of course you will have to go to higher currents to define this 70% point. You will be able to convert to number of photons after you do the PMT counting measurement.

COUNTING PHOTONS:

You have a Burle 8575 PMT in a light tight housing with a Sylvania 7377 light bulb mounted at the far end about 5 inches from the 2 inch diameter PMT photocathode. Read the file on the PMT, paying particular attention to its sensitivity and noise vs HV. Now set up to put very small currents through the light bulb mounted inside the PMT housing. Do not take it apart with the HV on! The PMT HV is maximum 1900V and you should turn up the (negative HV) slowly from zero. Observe the PMT output on a Tektronix MSO 4054 scope, triggering on negative pulses in the 40 nsec per division range. Before putting any current through the light bulb observe the PMT noise by adjusting the (negative) threshold down in the -50 mV range. Be sure the scope is running in “normal” trigger mode rather than “auto”. [To get started you may need to put the scope trigger on FIND]. The ~10-50 mV 10nsec pulses you see at PMT HV 1900V are coming from the thermal emission of the PMT photocathode. Change your scope threshold to -70mV to avoid most of these background pulses. In order to count your pulses hook the “Trigger Out” BNC connector on the back of the scope to the rate meter in the NIM BIN.

With no current to the bulb you should see background counts less than 1-2 Hz. Measure this background carefully by averaging. Use rate meter settings that average counts for about 1 sec. Now increase the light bulb current slowly from zero. Around 20 mA the filament in the bulb gets hot enough to emit a few photons per second, collected in the solid angle subtended by the PMT photocathode. You can see the individual detected photons on the scope. The light output of the bulb is a highly non-linear function of current. Photon count rates around 100 Hz occur at 23 mA, 1 KHz at 23.8 mA, and 5 KHz at 24.4 mA.

You can now use these data to calibrate the photon flux sensitivity of your eyes. Remember that the PMT, while it can detect individual photons, it does not detect them all; the photocathode has about 20% quantum efficiency, so your PMT detects about 1 in every 5 photons. Make this correction to calculate the actual photon flux per steradian from the bulb. Then correct for the ratio of steradians of the PMT setup and your eye (pupil). Now you can estimate your visual threshold in photons per second collected by your eye. How did you do? The winner will be awarded a cheap pair of sunglasses. A typical scope display at ~100 Hz photon count rate is shown below.



Next route the scope trigger output to your spectrum analyzer and look at the photon shot noise spectrum as a function of bulb current. Discuss. Repeat by inserting your bandpass filter for several choices of bandwidth. Discuss.

APPARATUS

Agilent 34401A Digital precision volt-amp meter (AC or DC)
Agilent 34410A Digital high precision volt meter with statistics
Tektronix MSO 4054 Oscilloscope
General Radio 1390B Noise Generator
Signal Recovery 5113 bandpass amplifier-filter
Computer with software for PicoScope and data analysis software
PicoScope ADC216 digital scope and spectrum analyzer
BURLE 8575 PMT and Ortec HV Power supply
Ortec 449 ratemeter