Notebook Template for Johnson and Shot Noise

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CQRRRR#5733

A. Experiment operation (Quanrui)

1. Exercise 1: Estimate of signal magnitudes from noise.
   At 300K:
   $$V_{Johnson} = \sqrt{4kTRB} = \sqrt{4 \cdot 1.38 \times 10^{-23} J/K \cdot 300K \cdot 10k\Omega \cdot 10kHz} = 1.29\mu V\ (rms)$$
   At 77K:
   $$V_{Johnson} = \sqrt{4kTRB} = \sqrt{4 \cdot 1.38 \times 10^{-23} J/K \cdot 77K \cdot 10k\Omega \cdot 10kHz} = 0.65\mu V\ (rms)$$

   $$I_{shot} = \sqrt{2e\bar{I}B} = \sqrt{2 \cdot 1.602 \times 10^{-19} C \cdot 1.0 \times 10^{-5} A \cdot 1.0 \times 10^{4} Hz} = 1.79 \times 10^{-10} A$$

2. Complete diagram(s) or annotated photograph(s) of the experiment: components, electrical connections and associated apparatus.

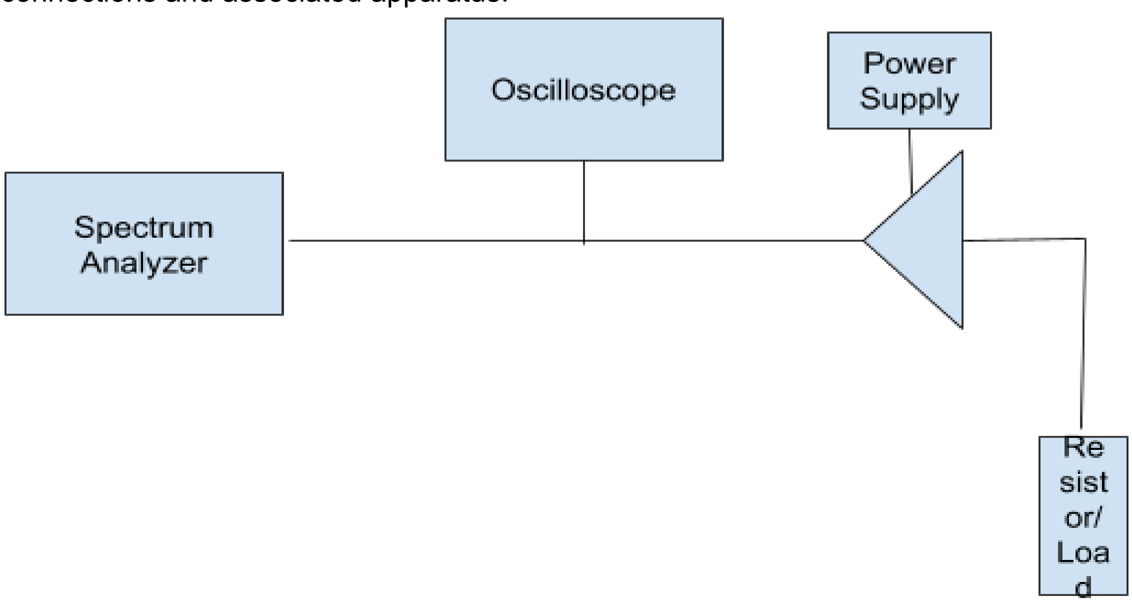
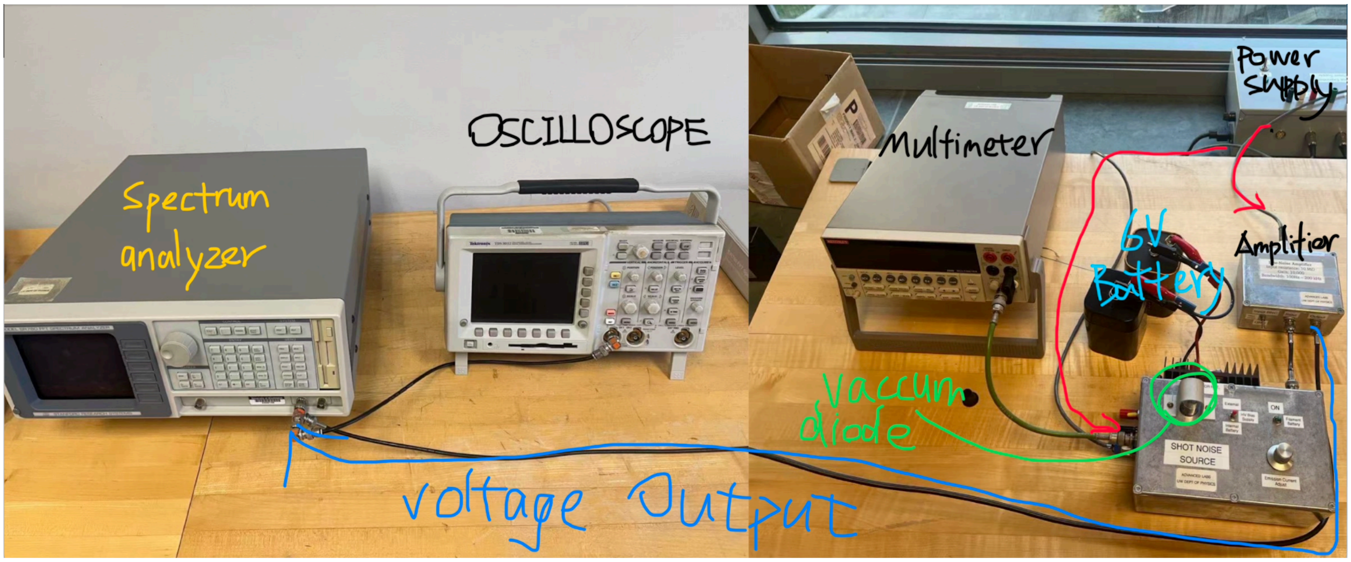


Diagram.1



Picture.1

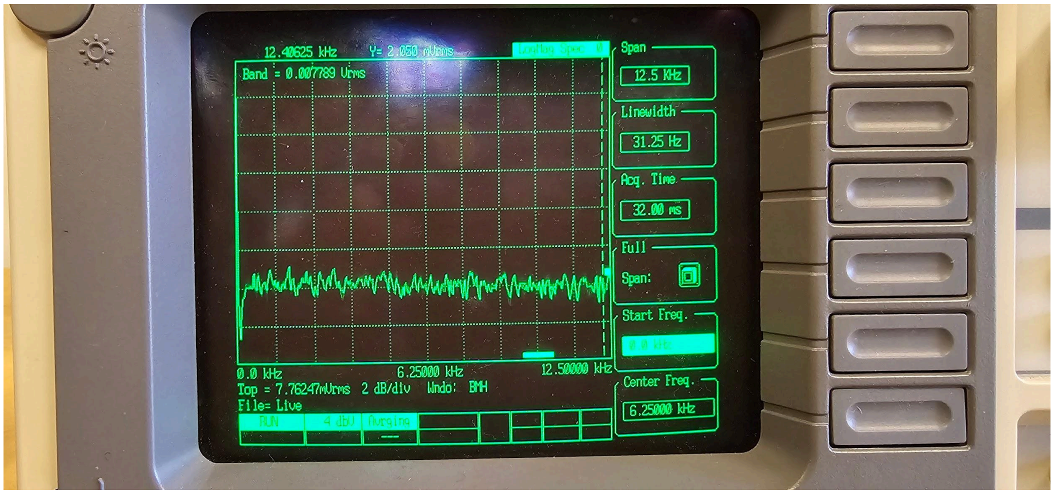
3. Additional text that explains the purpose and use of each part of the setup.
   Diagram 1 is the setup for Johnson noise. Johnson noise, namely thermal noise depending on conductor's resistance and temperature, can be measured by placing a resistor across the input terminals of an amplifier and then measuring the amplified output voltage. We can see above in the diagram we measure the output voltage by oscilloscope and spectrum analyzer.

   Picture.1 shows the setup of shot noise detection. Shot noise is due to fluctuations in the electric current. We create electron emission current in a vacuum diode. The current is collected by an anode and through a resistor. The voltage of the resistor passed to the amplifier. Then, we can measure the signal of shot noise from fluctuations in the voltage drop across this resistor. We also measure the output voltage by oscilloscope and spectrum analyzer.

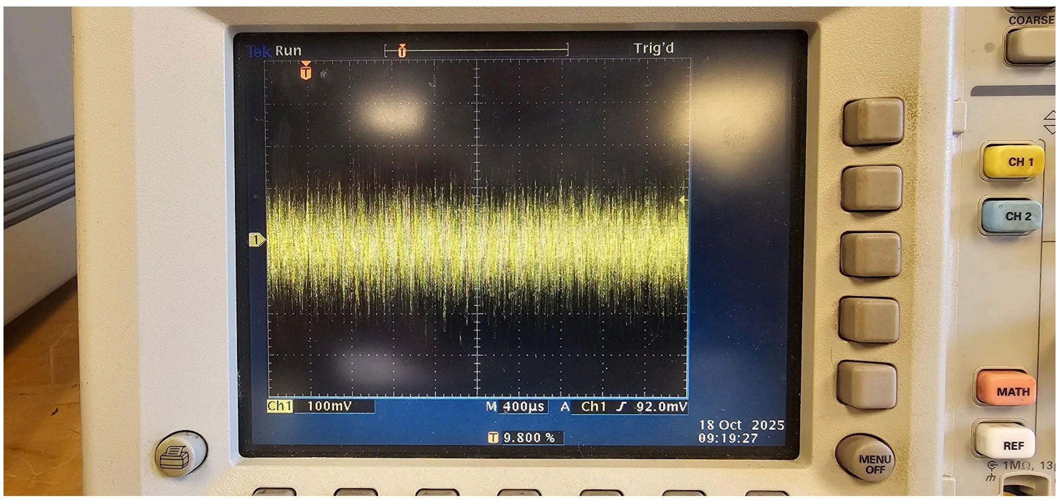
4. Record of parameters and settings used for the measurements. In particular, the values, units and uncertainties of every quantity that goes into the analysis calculations. (See equations 1, 3, and 6.)

   For all measurements, the band width B is 1kHz; the amplifier gain G is 10000;
   Johnson we use two temperature T = 77k for liquid nitrogen and T = 295k for room temperature

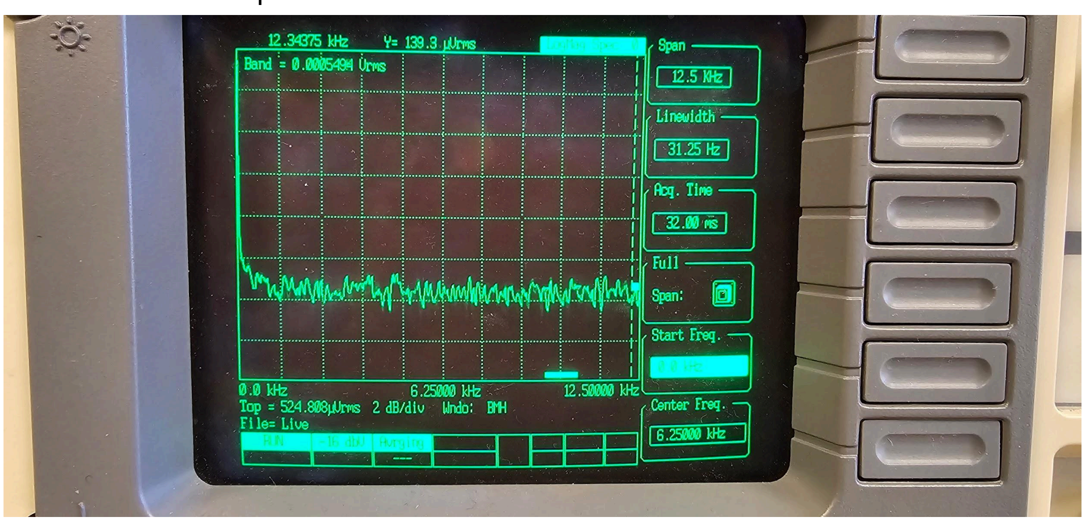
5. Pictures of
   a. FFT analyzer display and oscilloscope with 40k ohms and 0 ohms on amplifier input.



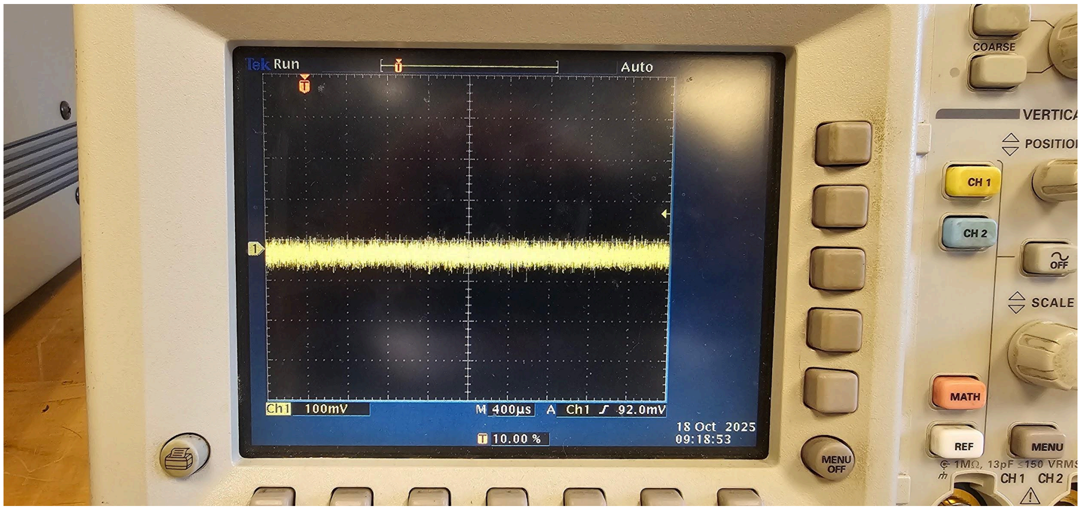
Picture.2 FFT analyzer for 40k ohms



Picture.3 Oscilloscope for 40k ohm



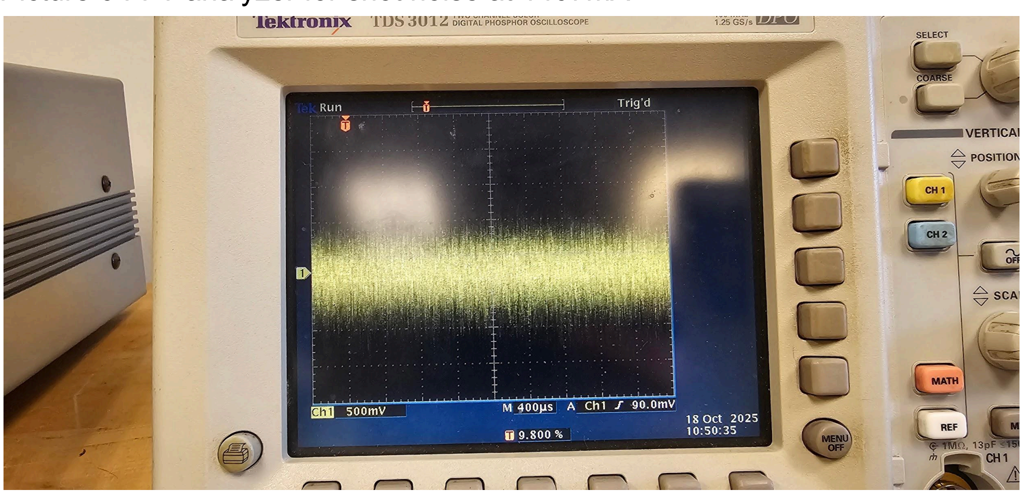
Picture.4 FFT analyzer for 0 ohms



Picture.5 Oscilloscope for 0 ohms

b. FFT analyzer display and scope screen showing shot noise.
1407mA

Picture.6 FFT analyzer for shot noise at 1407mA



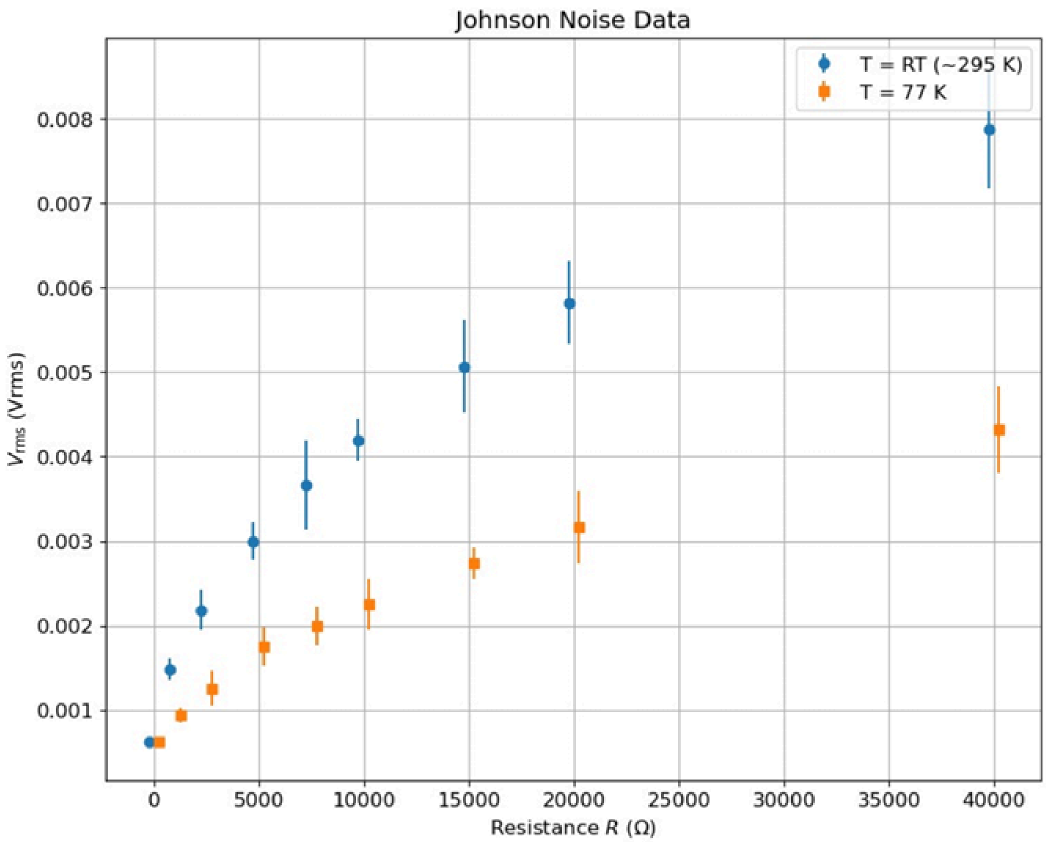
Picture.7 Oscilloscope for shot noise at 1407mA

6. Tables of averaged measurements of Johnson noise voltage (at room temperature and 77K) and shot noise voltage.

   Johnson data & Shot data table

B. Johnson noise analysis(Kaimu)

1. Plot of raw data (V_{rms} vs R). Look for any problems.



2. Exercise 2:
   a. Data reduction to obtain V^2_{rms} for Johnson noise.

RT (~295 K): mean Vrms

	R (ohms)	mean Vrms (V)	std Vrms (V)
8	0.0	0.000624	0.000005
7	1000.0	0.001478	0.000013
6	2500.0	0.002183	0.000023
5	4990.0	0.002999	0.000023
4	7500.0	0.003661	0.000052
3	9990.0	0.004195	0.000025
2	15000.0	0.005069	0.000055
1	20000.0	0.005823	0.000049
0	40000.0	0.007867	0.000069

RT (~295 K): mean Vrms^2

	R (ohms)	mean Vrms^2 (V^2)	d(Vrms^2) (V^2)
8	0.0	3.889601e-07	6.356588e-09
7	1000.0	2.183499e-06	3.869870e-08
6	2500.0	4.764034e-06	1.023265e-07
5	4990.0	8.994001e-06	1.351348e-07
4	7500.0	1.340536e-05	3.837152e-07
3	9990.0	1.759942e-05	2.105567e-07
2	15000.0	2.569476e-05	5.622341e-07
1	20000.0	3.390539e-05	5.727687e-07
0	40000.0	6.188182e-05	1.093404e-06

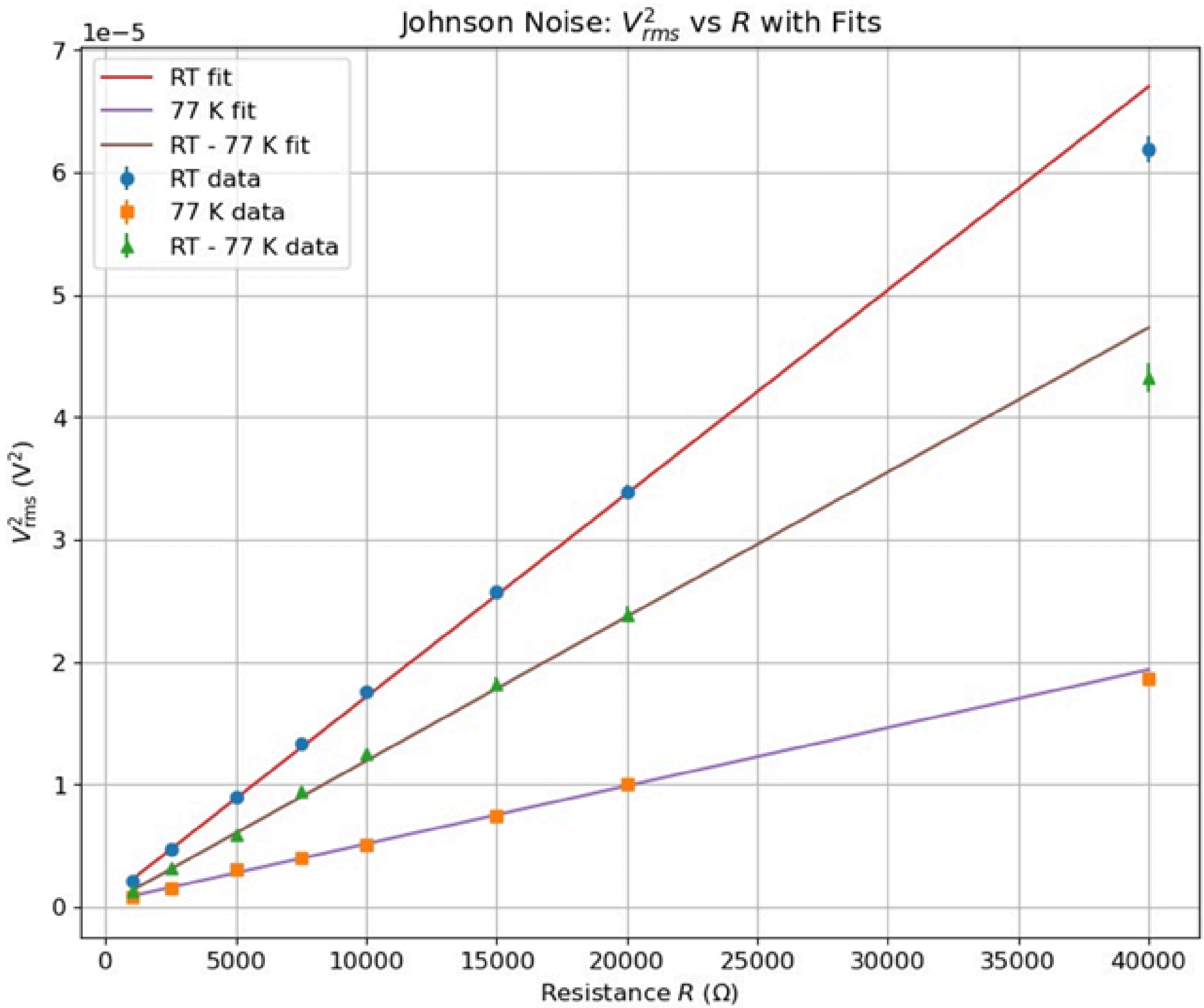
77 K: mean Vrms

	R (ohms)	mean Vrms (V)	std Vrms (V)
8	0.0	0.000624	0.000004
7	1000.0	0.000937	0.000008
6	2500.0	0.001260	0.000021
5	4990.0	0.001755	0.000022
4	7500.0	0.002000	0.000023
3	9990.0	0.002258	0.000030
2	15000.0	0.002733	0.000018
1	20000.0	0.003164	0.000043
0	40000.0	0.004322	0.000051

77 K: mean Vrms^2

	R (ohms)	mean Vrms^2 (V^2)	d(Vrms^2) (V^2)
8	0.0	3.893344e-07	5.242904e-09
7	1000.0	8.774381e-07	1.556074e-08
6	2500.0	1.586886e-06	5.340495e-08
5	4990.0	3.079440e-06	7.852299e-08
4	7500.0	4.000000e-06	9.201739e-08
3	9990.0	5.100822e-06	1.353217e-07
2	15000.0	7.467467e-06	1.010520e-07
1	20000.0	1.001090e-05	2.735278e-07
0	40000.0	1.868401e-05	4.439441e-07

b. Plot and fit to obtain slope and intercept of linearized data sets, for room temperature, 77K, and difference between data sets ate the two temperatures.



For in room temperature

Slope: $(1.6608 \pm 0.0300) * 10^{-9} V^2/\Omega$

Intercept: $(5.5719 \pm 0.9486) * 10^{-7} V^2$

For in 77K:

Slope: $(4.7421 \pm 0.0863) * 10^{-10} V^2/\Omega$

Intercept: $(4.1247 \pm 0.2960) * 10^{-7} V^2$

For in difference between dataset:

Slope: $(1.179 \pm 0.0274) * 10^{-9} V^2/\Omega$

Intercept: $(1.4793 \pm 0.8460) * 10^{-7} V^2$

c. Calculation from fits to obtain Boltzmann constant and uncertainty.

$$\Delta V^2_{rms}(R) = V^2_{rms,295} - V^2_{rms,77} = m_\Delta R + b_\Delta$$

$$m_\Delta 4k_B BG^2(295K - 77K) \Rightarrow k_B = \frac{m_\Delta}{4BG^2(295K-77K)}$$

$$\sigma_{k_B} \approx k_B\sqrt{(\frac{\sigma_{m_\Delta}}{m_\Delta})^2 + (\frac{2\sigma_G}{G})^2}$$

3. Description of quantities that go into the uncertainty analysis, and how much each contributes to the final uncertainty.

We use

$k_B = \frac{m}{4TBG^2}$ for 295K and 77K fits, and $k_B = \frac{m_\Delta}{4\Delta TBG^2}$ for the difference fit.

With G=10122 ± 35 and $B = 1000Hz$. The uncertainty is dominated by the fit slope m_Δ, with smaller contributions from G and ΔT.

For 295K fit, contribution to variance≈slope 84.6%, gain 12.4%, temperature 3.0%

For 77K fit, contribution to variance≈slope 60.3%, gain 30.9%, temperature 8.8%. Temperature matters more as 1K/77K is relatively large.

For difference fit, contribution to variance≈slope 85.4%, gain 7.8%, temperature 6.9%

4. Discussion that compares results from the ΔT

295K: $(1.374 \pm 0.027) * 10^{-23} J/K$

77K:$(1.503 \pm 0.035) * 10^{-23} J/K$

Difference:$(1.302 \pm 0.033) * 10^{-23} J/K$

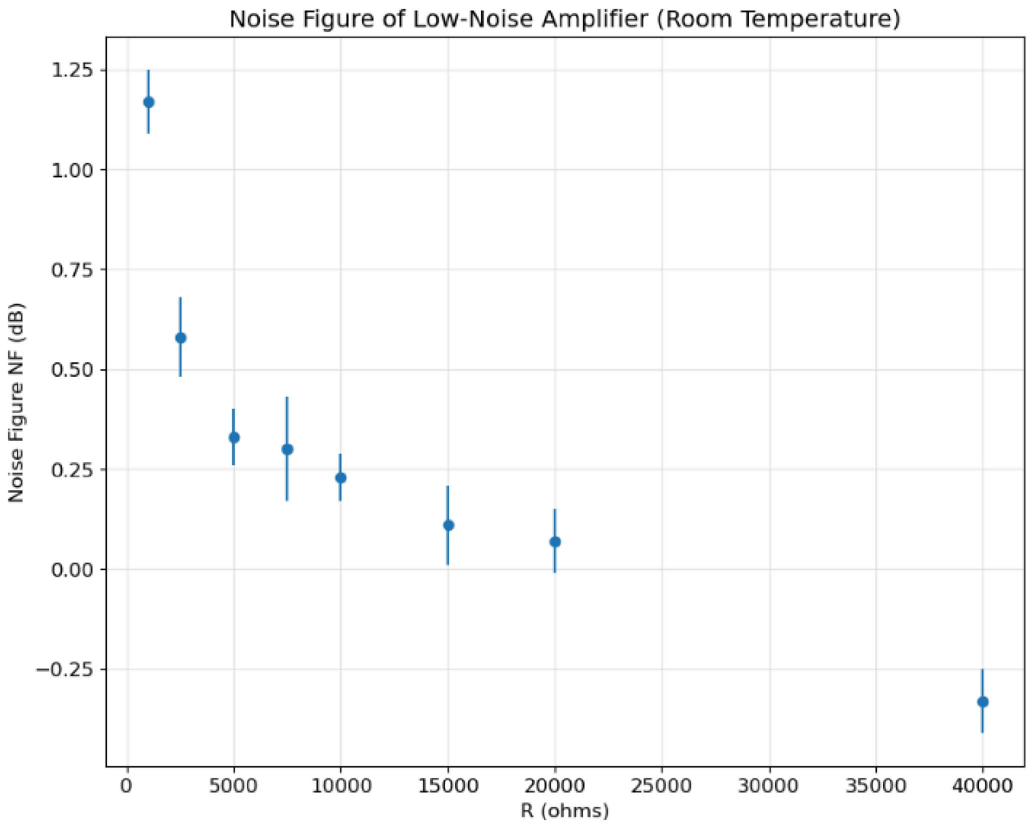
Compared to the accepted value of $1.381 * 10^{-23} J/K$, the 295 K result is closest, the 77 K result is high, and the difference method is low for this dataset. The difference method is designed to reduce amplifier noise effects, but here its uncertainty is still mainly set by the slope uncertainty, some ΔT and gain contribution.

5. Exercise 3: Calculation and plot of noise figure for the low-noise amp. Comments on results.

From the room-temperature Johnson-noise data,

$$NF(R) = 20log_{10}(\frac{V_{rms,meas}(R)}{G\sqrt{4k_B TRB}})$$

T=295K, B=1000Hz.



NF is smaller than 1dB for most R, indicating a good low-noise amplifier. It increases at small R because the amplifier's own noise becomes more significant when the source resistance and Johnson noise are smaller. The slightly negative value at 40 kΩ is best attributed to calibration uncertainty and should be interpreted as NF≈0dB within error.

C. Shot Noise Analysis (Nathan)

1. Plot of raw data (V_{rms} vs I_{em}). Look for any problems. **(See Figure C1)**
2. Exercise 4:
   a. Data reduction to obtain V^2_{rms} for shot noise. **(See Table C1)**
   b. Plot and fit to obtain slope and intercept of linearized data set. **(See Figure C2)**
   c. Calculation from fit results to obtain electron charge and uncertainty.
3. Comparison, discussion of result to accepted value of e.
4. Discussion of evidence for $1/f$ noise in shot-noise data. If you see evidence, explain what you would/did do to minimize its effect on the calculation of the electron charge.

For this section, the primary goal is to obtain e. Following a very similar procedure to the Johnson Noise analysis, we can obtain this. After linearizing the data (Figure C1, shows the raw data, while Figure C2 shows the Linearized and Fit data)

The fit parameters given by the provided function were:

All Data	[[Model]] Model(linear) [[Fit Statistics]] # fitting method = leastsq # function evals = 4 # data points = 21 # variables = 2 chi-square = 2.0107e-10 reduced chi-square = 1.0583e-11 Akaike info crit = -528.809393 Bayesian info crit = -526.720348 R-squared = 0.99961758 [[Variables]] **slope: 3.28674301 +/- 0.01474829 (0.45%) (init = 3.286743)** **intercept: 2.6791e-05 +/- 1.1372e-06 (4.24%) (init = 2.679105e-05)**
Partial Data	[[Model]] Model(linear) [[Fit Statistics]] # fitting method = leastsq # function evals = 4 # data points = 7 # variables = 2 chi-square = 4.4992e-11 reduced chi-square = 8.9984e-12 Akaike info crit = -176.393090 Bayesian info crit = -176.501270 R-squared = 0.97744034 **[[Variables]]** **slope: 3.58792818 +/- 0.24376977 (6.79%) (init = 3.587928)** **intercept: 2.2700e-05 +/- 2.8473e-06 (12.54%) (init = 2.270023e-05)**

To calculate e, recall the original equation:

$$I_{shot} = \sqrt{2e\bar{I}B} \quad \text{(eq.C1)}$$

Lets use Ohms law, and say that $I_{shot} = \frac{V_{shot}}{R_{shot}}$, we can rearrange the equation to get:

$$\left(\frac{V_{shot}}{R_{load}}\right)^2 * \frac{1}{2\bar{I}B} = e \quad \text{(eq.C2)}$$

If we then take $V_{shot}^{\ 2} = V_{ms}$, and $m_{slope} = \frac{V_{ms}}{\bar{I}}$, we can get

$m_{slope} * \frac{1}{2R_{load}^{2}B} = e$	(eq.C3)

Important note: Strictly speaking, $V_{shot} = V_{instrument}/ Gain$. In our calculations, we would just add another factor of $1/G^{2}$ to the result.

Finally, from the data, we get:

Electron charge from whole data set = $(1.604 \pm 0.014) \times 10^{-19}$ C
Electron charge from partial data set = $(1.75 \pm 0.12) \times 10^{-19}$ C

Accepted value = 1.602e-19 C

The collected data is consistent with the accepted value for e, and is actually closer with the entire data set.

This data seems to indicate that the new system has very little $1/f$ interference at the range of currents that we used. This seems to be consistent with the recent edition of a new shot noise box.

Emission Current (mA)	Average (Vrms)	(Data Reduced) Average (Vms)
0	*0.004807*	*0.000023*
0.01	*0.00745*	*0.000056*
0.011	*0.007873*	*0.000062*
0.012	*0.008101*	*0.000066*
0.013	*0.008657*	*0.000075*
0.014	*0.008493*	*0.000072*
0.015	*0.008643*	*0.000075*
0.02	0.00994	0.000099
0.03	0.01128	0.000127
0.04	0.01266	0.00016
0.05	0.01375	0.000189
0.06	0.01488	0.000221
0.07	0.01591	0.000253

0.08	0.01714	0.000294
0.09	0.01799	0.000324
0.1	0.01881	0.000354
0.11	0.01971	0.000388
0.12	0.02054	0.000422
0.13	0.02136	0.000456
0.14	0.02214	0.00049
0.15	0.02268	0.000514

Table C1: Data in grey represents the data we collected to help mitigate the 1/f issue.

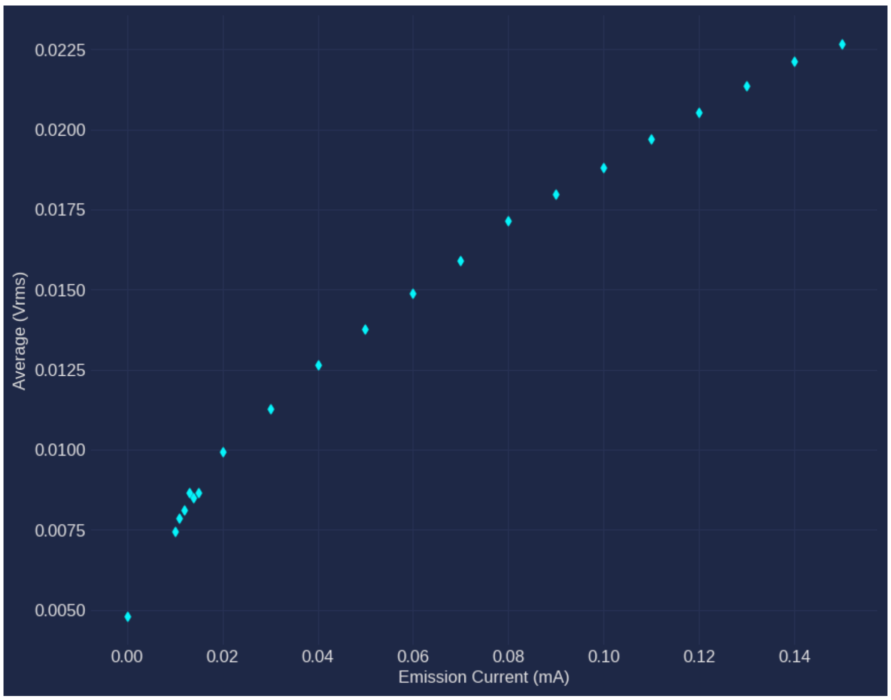


Figure C1: Raw Data

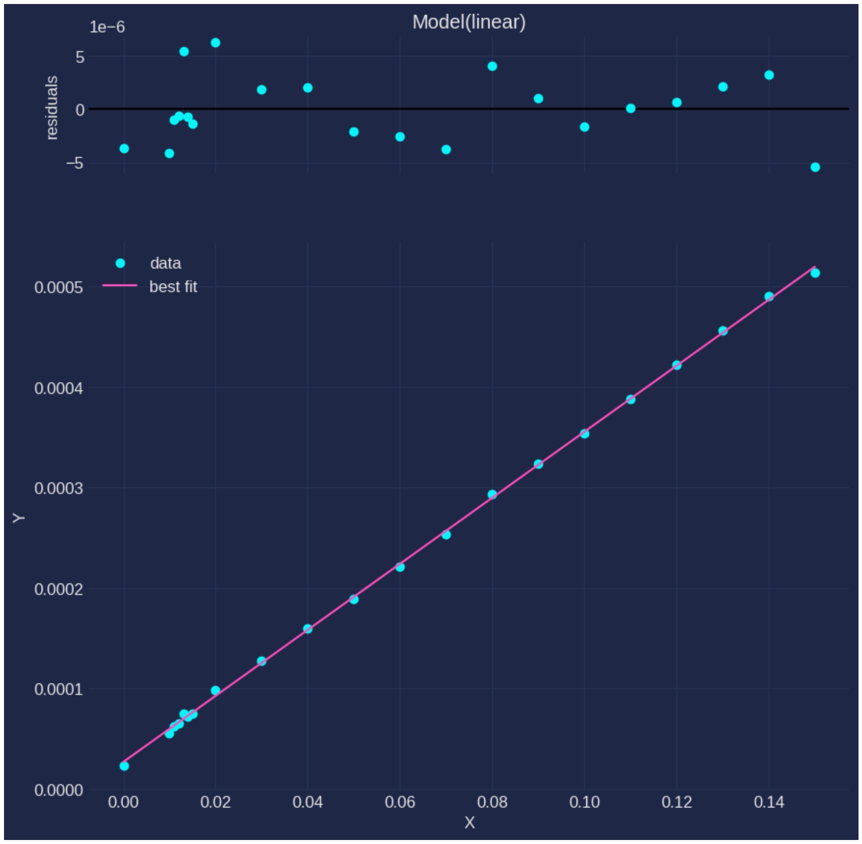


Figure C2: Fitted Vms (squared data)