Franck-Hertz measurement of the excitation energy of mercury

Objectives

In this experiment you will:

- Measure electron flow through mercury vapour as a function of energy
- Use a digital oscilloscope module and signal averaging to obtain clean data
- Extract values for the first excitation energy of mercury, and the mean free path of electrons in mercury vapour

1 Preparation

Safety issues

- The outside of the oven gets quite hot: do not touch it.
- In the unlikely event that the mercury vapour tube in the oven should break, switch off and alert lab staff immediately.
- To protect the apparatus, let the oven warm up before applying voltages from the control box. Do not exceed 6.5 V on the filament.

Leaving the "operating unit" control box switched off, turn on the heater of the oven unit, and set the target temperature to 200°C, so that the system can warm up while you read about the experiment.

2 Experimental principle

The mercury vapour used in this experiment is contained, with electrodes, in an otherwise evacuated glass tube which is mounted inside an oven, see figure 1.

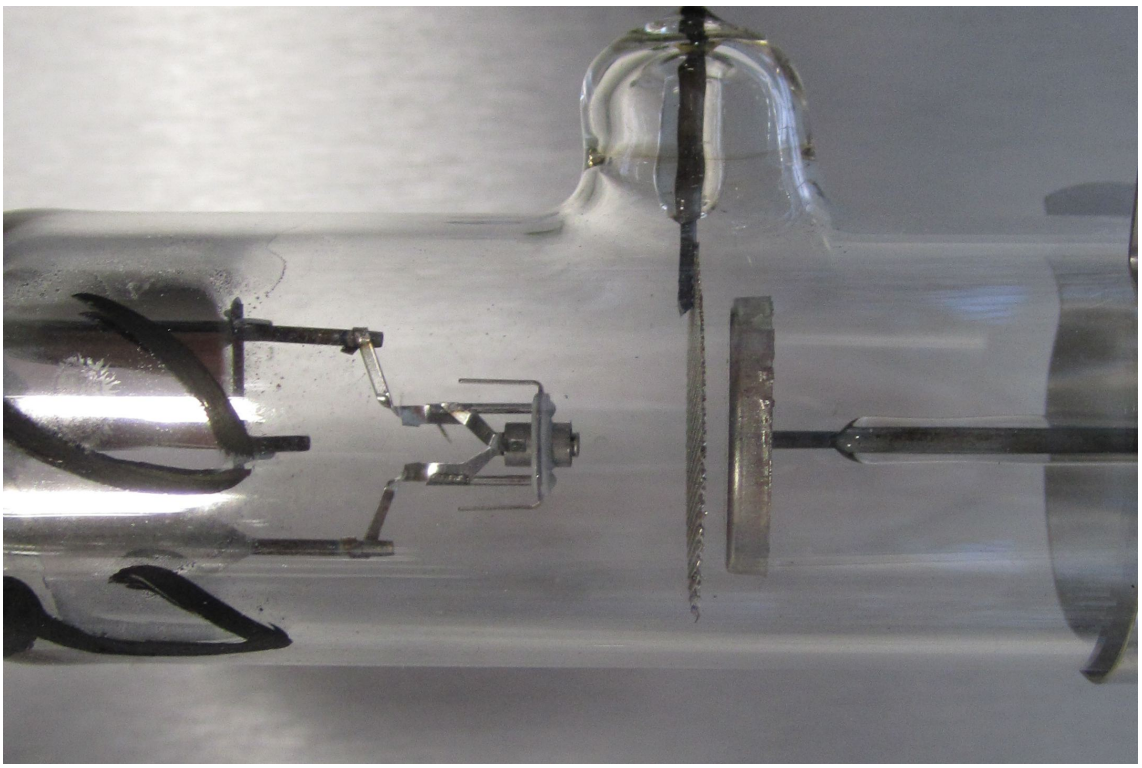

Figure 1: The mercury tube. Electrodes from left to right: heated cathode, anode (mesh), collector.

In operation, the cathode of the tube is heated by a resistive filament, which causes it to emit electrons. An electric field accelerates them towards the anode, through the mercury vapour in the tube. Because the anode is a metal mesh, many of the electrons pass through it to the collector plate, where they form the current that is measured by an amplifier. The tube contains a few milligrams of mercury; by controlling the temperature of the whole tube in an oven, we can control its vapour pressure.[1]

As the anode voltage is raised, the current arriving at the collector at first increases. But once the kinetic energy of an electron is sufficient to excite a mercury atom, the electrons lose energy to the mercury before arriving at the anode, and are unable to reach the collector, so the current falls. A small repulsive voltage applied to the collector helps ensure that the slowed electrons cannot reach it. Further increase in the anode voltage again causes the current to rise, only to fall again once the electrons have enough energy to excite two mercury atoms, and so on. Thus the collector current has a periodic dependence on anode voltage, with a period corresponding approximately to the first excitation energy of mercury.

[1]Note: some descriptions call the anode the grid, and the collector the anode.

Questions: **Q**

- Where do the electrons go when they cannot make it to the collector?
- What happens to the energy that the electrons lose to the mercury atoms?
- Why was this 1914 experiment so important as to merit a Nobel prize?

3 First measurements

There is no need for the wiring to be disturbed during the experiment, but check that it corresponds to Figure 2. In particular, note what is measured by the voltmeter, and by the two digital oscilloscope channels.

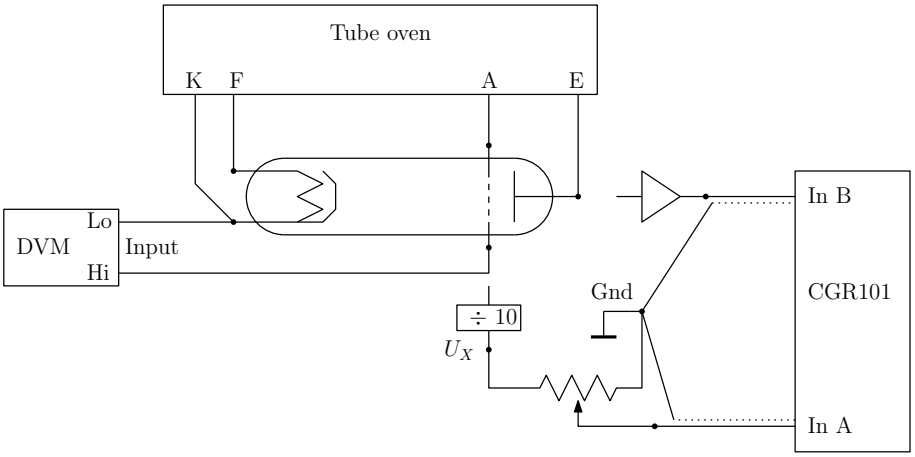

Figure 2: Circuit wiring

The digital oscilloscope module is controlled by the Cgr101 software on the PC. Only the oscilloscope functions matter, so the bottom and right hand parts of the display can be ignored, see figure 3.

When the oven has reached operating temperature, ensure all the control box knobs are fully anticlockwise, turn on the box, and then gently increase the filament voltage to 6 volts. **Do not exceed 6.5 volts on the filament, as it may burn out!** To start with, try setting a sweep from 0-50 V on the anode and a few volts negative on the collector. The current amplifier gain, along with the external potential divider (in the black box) set the size of the signals sent to the oscilloscope. Starting with the potential divider set for maximum signal, adjust these, and the other controls, along with the scope settings, to get a display similar to Figure 3, which shows the linear ramp of the anode

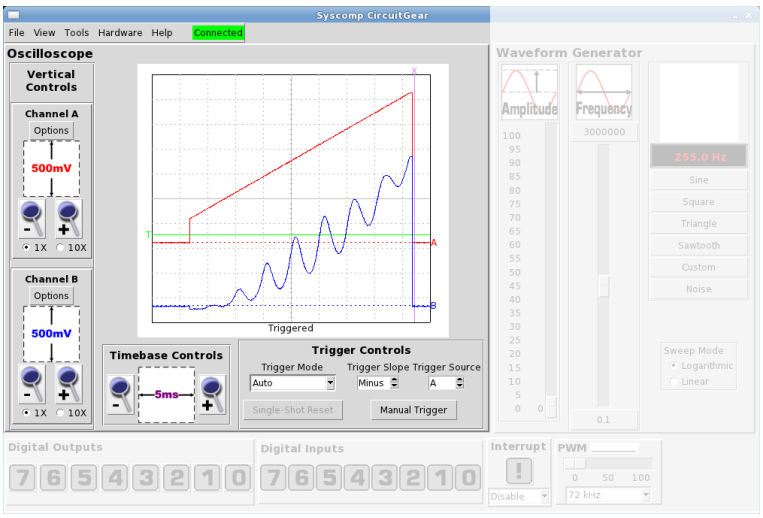

Figure 3: CGR-101 interface

voltage as well as the oscillations in the collector current. Optimise all the settings to produce a maximum number of clear peaks and valleys on the display: ultimately, you will need to measure the spacing between as many pairs of minima as possible.

If you get excessive collector current, possibly accompanied by visible light coming from the tube, turn down the filament and the anode voltage for a few minutes, then turn them up more cautiously.

You can print a screen capture (TOOLS -> SCREEN CAPTURE) to record the result, but for proper analysis, use TOOLS -> EXPORT WAVEFORM to save the numerical data. The resulting file can be read into Qtiplot, where you should plot the current as a function of anode voltage. When examined closely, the data are probably quite ugly, see Figure 4.

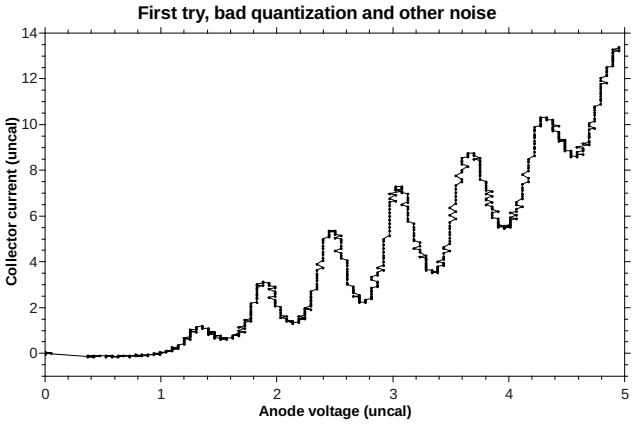

Figure 4: Non-optimised data record

4 Getting cleaner data

Important note: You must get the calibration data, as described in Section 5, at the same setting of the potential divider as that used for the data files in this section, so make sure to do both in the same lab session.

Figure 4 suffers from three kinds of noise: random noise from the electronics, electrical interference (e.g. from the heaters) and "digitisation noise", i.e. the step-like distortions caused by the finite resolution of the analogue to digital converters in the scope module.

A close reading of the manual for the scope module reveals that the smallest digitisation noise occurs on the 500 mV ranges. Therefore, you should always set both inputs to this range, and keep the signals on scale by adjusting the current amplifier gain, and the external potential divider (in the black box).

We can improve the other noise components by averaging many cycles of the data: so long as the desired signal is stable on every cycle, it will persist in the average, but noise that is random, or at least uncorrelated with the desired signal, will average towards zero. Over 100 cycles, we might hope for an improvement of $\sqrt{100} = 10$ times in the signal:noise ratio. Why the square root? **Q**

Since this process will create 100 data files, first create a new directory (folder) using the file manager. Then select TOOLS -> DATA RECORDER and choose this as the export directory (probably at a location like **`/home/y2x/Documents/mydata1`**). Select a log period of 1 second, and log, for example, 100 traces. Make sure the display is stable throughout.


File manager

5 Voltage Calibration

The scale used on the voltage axis is critical to getting accurate results. Since neither the setting of the potential divider nor the true calibration of the scope is known with great accuracy, we must calibrate the voltage scale with the external voltmeter. Set the anode voltage control to manual (rather than the repetitive ramp), adjust the voltage to a stable setting near the top of the range used, and read the cathode-anode voltage from the voltmeter. Record also the voltage indicated by the oscilloscope. Repeat with a voltage near the bottom of the range used. This is sufficient information to convert all the other (averaged) voltages recorded by the scope into accurate cathode-anode voltages.

You should consider how to get the best value for the indicated scope voltage in the above procedure. Perhaps the average computed by the scope will do (VIEW->AUTO

MEASUREMENTS). Or maybe the whole 100-cycle average procedure of section 4 (twice!) is better.

6 Processing the data

The 100 data files consist of three columns of numbers: time, V_A and V_B. You can use any method to add them in parallel, for example the **`franck_hertz`** Python script provided on the lab PC, which in essence is shown in Figure 5.[2]

```
tot = zeros([1024,3])                              # Empty matrix
files = !ls /home/y2x/Documents/mydata1/*.csv      # List of file names

for ff in files:                                   # Loop over file names
    dat = loadtxt(ff, skiprows=1, delimiter=',')   # Read, skipping header line
    tot = tot + dat                                # Add into matrix

ave = tot / len(files)                             # Divide by number of files

# Multiply voltages by calibration factor (replace 4.2 by the real value)
ave = ave * [1, 4.2, 1]

# Save as csv file
savetxt('/home/y2x/Documents/aves.csv', ave, delimiter=',')
```

Figure 5: Python script to average data files

You can then import the averaged data file into Qtiplot (FILE->IMPORT->IMPORT ASCII *separator=comma*), where it should produce a clean plot, see Figure 6.

7 Interpretation

To a first approximation, the voltage interval between successive current minima is equal to the first excitation energy of mercury (measured in electron-volts). Using your best averaged and calibrated curve, make a table of the minima positions. For a first attempt, you can probably locate the minima by eye, see Figure 6. Given more time, you could use Qtiplot to fit a little parabola of the form **`y=a+b*(x-c)^2`** near each minimum, using the fitted value of **`c`** as the minimum position.

Plot a graph of interval voltage $\Delta E_N = E_N - E_{N-1}$ *vs.* interval number N (be aware that the first minimum may be difficult to see). According to the model in the paper

[2] You could alternatively use Matlab outside the lab. A suitable script is at www.cm.ph.bham.ac.uk/y2lab/manuals.html

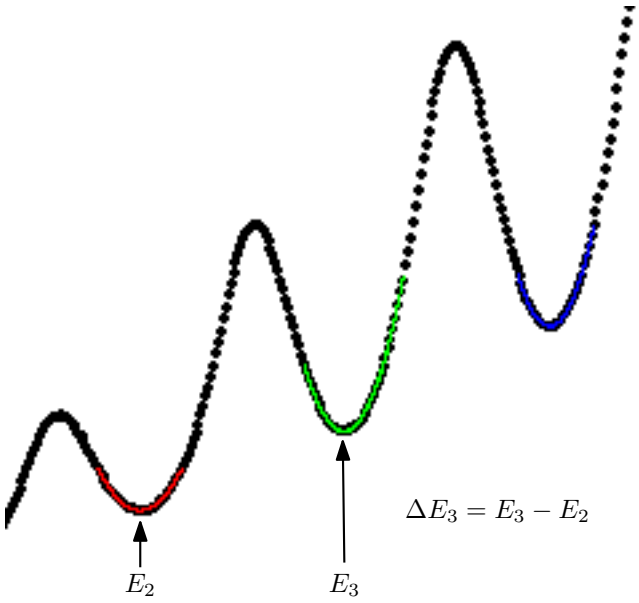

Figure 6: Locating the minima

by Rapior[3], the best value for the first excitation energy E_A (in electron volts) is $\Delta E_{\frac{1}{2}}$, obtained by extrapolating to an interval number of 0.5. Assign an error to your result, and compare it with the accepted value for the lowest excitation energy of mercury (4.67 eV, according to Rapior).

The model also tells us that the mean free path λ of the electrons in mercury vapour is given by $\lambda = \frac{L}{2E_A}\frac{d(\Delta E_N)}{dN}$, where L is the distance between cathode and anode, which in the tube we are using has been measured as 5.93±0.05 mm. Calculate λ from your data.

Notice that the above expression for λ implies that for ΔE_N to be independent of N, λ would be have to be zero. In this case, electrons would lose exactly E_A as soon as they acquired it, rather than continuing to accelerate while waiting for a collision, and hence losing more than E_A; this is the essence of the model.

8 Temperature dependence

Repeat the measurements for other temperatures - a range of 150 to 210 °C is feasible. The plot of ΔE_N vs. N should always yield the same value for the first excitation

[3] "*New features of the Franck-Hertz experiment",* Gerald Rapior, Klaus Sengstock and Valery Baev, American Journal of Physics **74**, 423-428 (2006).

energy E_A, but the mean free path should be strongly temperature dependent, because the mercury vapour pressure increases rapidly with temperature. Plot your values for $\lambda(T)$ and compare with Rapior.

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