Introduction

In 1914, James Franck and Gustav Hertz discovered in the course of their investigations an "energy loss in distinct steps for electrons passing through mercury vapor", and a corresponding emission at the ultraviolet line (λ= 254 nm) of mercury. As it is not possible to observe the light emission directly, demonstrating this phenomenon requires extensive and cumbersome experiment apparatus. They performed this experiment that has become one of the classic demonstrations of the quantization of atomic energy levels. They were awarded the Nobel Prize for this work in 1925.

In this experiment, we will repeat Franck and Hertz's energy-loss observations, using argon, and try to interpret the data in the context of modern atomic physics. We will not attempt the spectroscopic measurements, since the emissions are weak and in the extreme ultraviolet portion of the spectrum.

Principle of the Experiment

The Franck-Hertz tube is an evacuated glass cylinder with four electrodes (a "tetrode") which contains argon. The four electrodes are: an indirectly heated oxide-coated cathode as an electron source, two grids G_1 and G_2 and a plate A which serves as an electron collector (anode A). Grid 1 (G_1) is positive with respect to the cathode (K) (about 1.5 V). A variable potential difference is applied between the cathode and Grid 2 (G_2) so that electrons emitted from the cathode can be accelerated to a range of electron energies. The distance between the cathode and the anode is large compared with the mean free path length in the argon in order to ensure a high collision probability. On the other hand, the separation between G_2 and the collector electrode (A) is small. A small constant negative potential U_{G2A} ("retarding potential") is applied between G_2 and the collector plate A (i.e. A is less positive than G_2). The resulting electric field between G_2 and collector electrode A opposes the motion of electrons to the collector electrode, so that electrons which have kinetic energy less than $e \cdot U_{G2A}$ at Grid 2 cannot reach the collector plate A. As will be shown later, this retarding voltage helps to differentiate the electrons having inelastic collisions from those that don't.

A sensitive current amplifier is connected to the collector electrode so that the current due to the electrons reaching the collector plate may be measured. As the accelerating voltage is increased, the following is expected to happen: Up to a certain voltage, say V_1, the plate current I_A will increase as more electrons reach the plate. When the voltage V is reached, it is noted that the plate current, I_A, takes a sudden drop. This is due to the fact that the electrons just in front of the grid G_2 have gained enough energy to collide inelastically with the argon atoms. Having lost energy to the argon atom, they do not have sufficient energy to overcome the retarding voltage between G_2 and collector electrode A. This causes a decrease in the plate current I_A. Now as the voltage is again increased, the electrons obtain the energy necessary for inelastic collisions before they reach the anode. After the collision, by the time they reach the grid, they have obtained enough energy to overcome the retarding voltage and will reach the collector plate. Thus I_A will increase. Again when a certain voltage V_2 is reached we note that I_A drops. This means that the electrons have obtained enough energy to have two inelastic collisions before reaching the grid G_2, but have not had enough remaining energy to overcome the retarding voltage. Increasing the voltage again, I_A starts upward until a third value, V_3, of the voltage is reached when I_A drops. This corresponds to the electrons having three inelastic collisions before reaching the anode, and so on. The interesting fact is that V_3 - V_2 equals V_2 - V_1, etc., which shows that the argon atom has definite excitation levels and will absorb energy only in quantized amounts.

When an electron has an inelastic collision with an argon atom, the kinetic energy lost to the atom causes one of the outer orbital electrons to be pushed up to the next higher energy level. This excited electron will within a very short time fall back into the ground state level, emitting energy in the form of photons. The original bombarding electron is again accelerated toward the grid anode. Therefore, the excitation energy can be measured in two ways: by the method outlined above, or by spectral analysis of the radiation emitted by the excited atom.

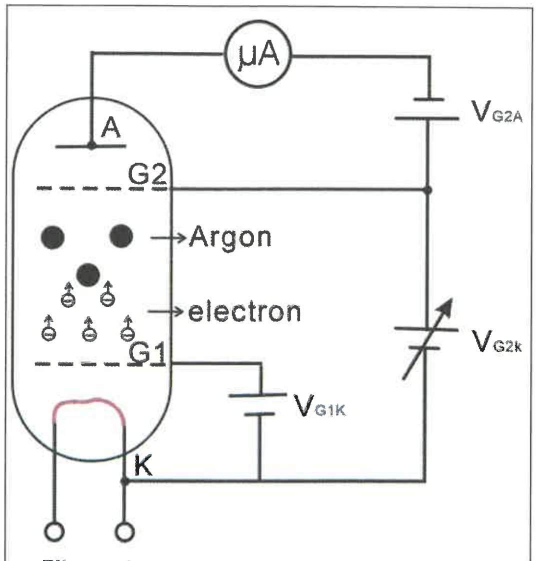


Figure 1.1: Franck-Hertz tube

Figure 2 displays a typical measurement of the anode current, I_A, as a function of the accelerating voltage. As soon as $V_{G2K} > V_{G2A}$ the current increases with rising V_{G2K}. Notice that the current sharply decreases for a voltage U_1 and then increases up to U_2, and then this pattern recurs. The interpretation of these observations is successful with the following assumptions:

- Having reached energy of about e•U_0, electrons can transmit their kinetic energy to a discrete excitement state of the argon atoms.
- As a result of the inelastic collision, they pass the braking voltage.
- If their energy is twice the required value, or 2 e•U_0, they can collide two times inelastically and similarly for higher voltages.

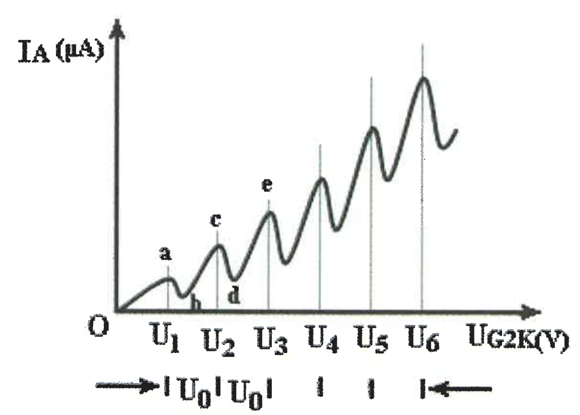


Figure 1.2: Anode current curve

- As a matter of fact, a strong line can be found for emission and absorption corresponding to an energy of e•U_0, the excitation energy of argon, in the optical spectrum (108.1 nm).

In figure 2, the resonance voltage is denoted by $\mathbf{U_0}$.

$\mathbf{e \cdot U_0 = h}f\mathbf{ = hc/\lambda}$

or

$$\mathbf{h} = e\lambda\left(\frac{\mathbf{U_0}}{\mathbf{c}}\right)$$

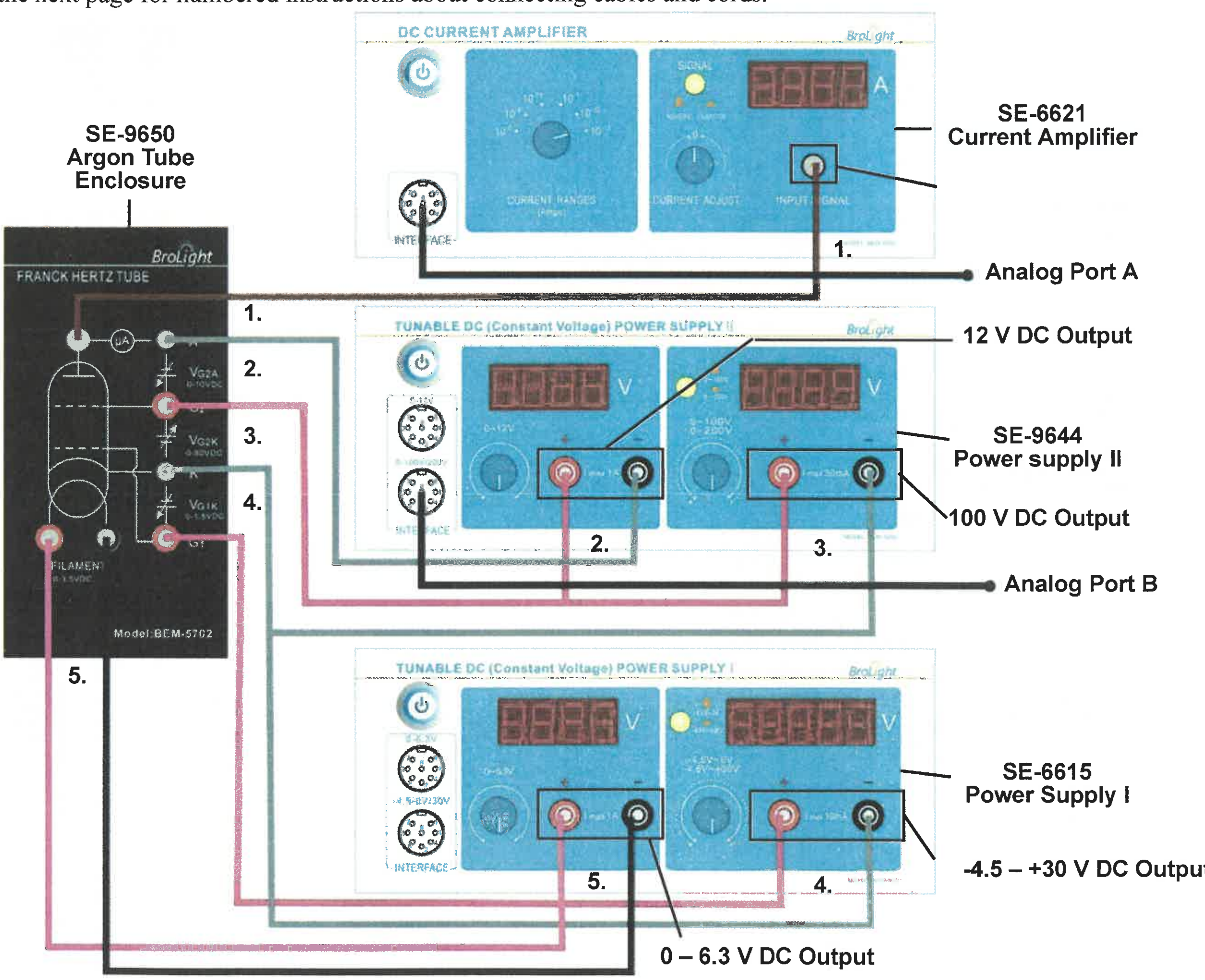
where **e** is the charge on an electron, **h** is Planck's Constant, and **c** is the speed of light.

Connect Cables and Cords

110 - 120 V or 220 - 240 V
Please make sure that you select the right setting according to your AC voltage level.

> **Note:** Before connecting any cords or cables, be sure that all power switches on the Power Supplies and Current Amplifier are in the OFF position and all voltage controls are turned fully counterclockwise.

See the next page for numbered instructions about connecting cables and cords.



1. On the DC Current Amplifier, connect the special BNC-to-BNC cable between the port on the amplifier marked "**INPUT SIGNAL**" and the port on the Argon Tube Enclosure marked "**μA**".

2. On Power Supply II, (SE-9644) connect the positive terminal of the **12 V DC** output to the grid-like electrode labeled "**G2**" (red sockets) on the Argon Tube Enclosure (SE-9650) and connect the negative terminal of the **12 V DC** output to the terminal labeled "**A**" (black sockets) on the enclosure.

3. On Power Supply II, connect the positive terminal of the **100 V DC** output on the power supply to the grid-like electrode labeled "**G2**" (red sockets) on the Argon Tube Enclosure and connect the negative terminal of the power supply to the terminal labeled "**K**" (black sockets) on the enclosure.

4. On Power Supply I (SE-6615), connect the positive terminal of the **-4.5 – +30 V DC** output on the power supply to the grid-like electrode labeled "**G1**" on the Argon Tube Enclosure and connect the negative terminal of the power supply to the terminal labeled "**K**" (black sockets) on the enclosure,

5. On Power Supply I, connect the positive terminal of the **0 – 6.3 V DC** output on the power supply to the red socket of the port labeled "**FILAMENT**" on the Argon Tube enclosure and connect the negative terminal of the power supply to the black socket of the "**FILAMENT**" port.

- **Note:** Before connecting the power cords, please check that the setting for the input voltage range (110 – 120 V or 220 – 240 V) matches the local AC voltage. For the two power supplies and the current amplifier, connect a power cord between the port on the back labeled "**AC POWER CORD**" and an appropriate electrical outlet.

DANGER:

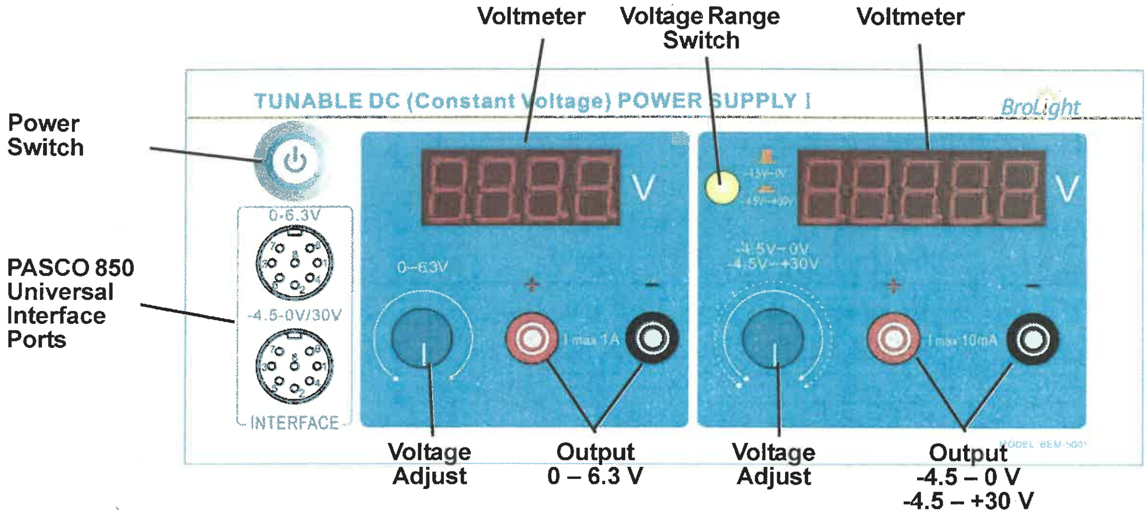
High Voltage is applied to the Argon Tube. Avoid contact with any part of the body.

- Only use safety equipment leads (shrouded patch cords) for connections.
- Make sure that the power supplies and current amplifier are OFF before making the connections.
- Make sure that the power supplies and current amplifier are OFF before installing or replacing the argon tube in the Argon Tube Enclosure

Cables and Cords	**Specification**
Power Cord	Length: 1.5 m, 16 A / 250 V
Connecting Cable, Red (EM-9740)	Length: 0.85 m, 10 A / 300 V
Connecting Cable, Black (EM-9745)	Length: 0.85 m, 10 A / 300 V
BNC-to-BNC Cable	Length: 1.0 m, 1 A / 300 V

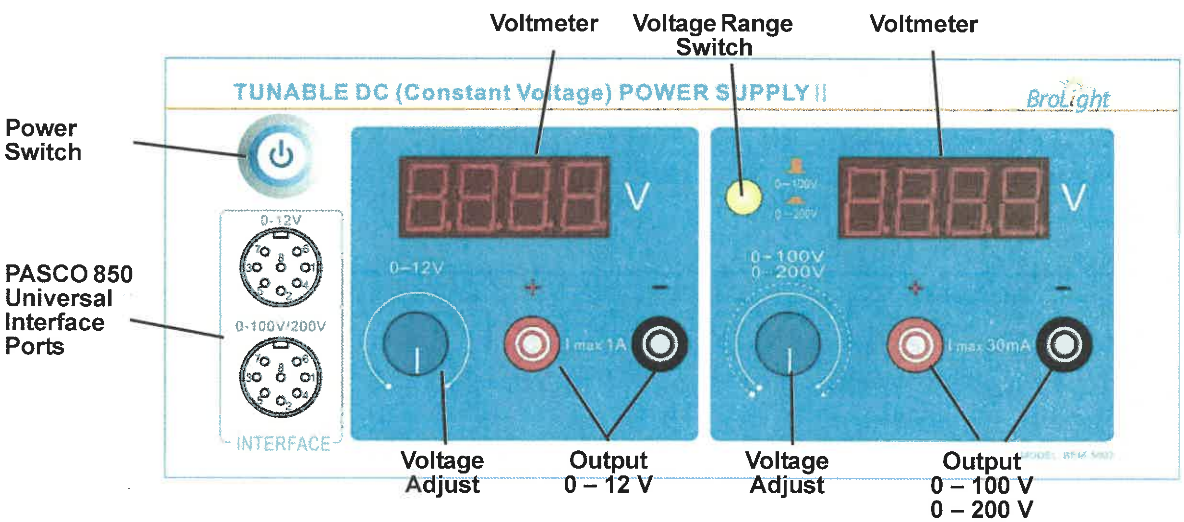
Note: Replace the cables and power cords with the same type.

Tunable DC (Constant Voltage) Power Supply I



- Voltmeter: Displays voltage across the argon tube.
- Voltage Range Switch: Sets the voltage range as -4.5 – 0 V ( ) or -4.5 – +30 V ( ).
- Power Switch: Turns the power to the instrument ON or OFF.
- Voltage Adjust: Sets the voltage across the argon tube.
- Output: Output power.
- Data Interface: Connect to the analog channels of the PASCO 850 Universal Interface.

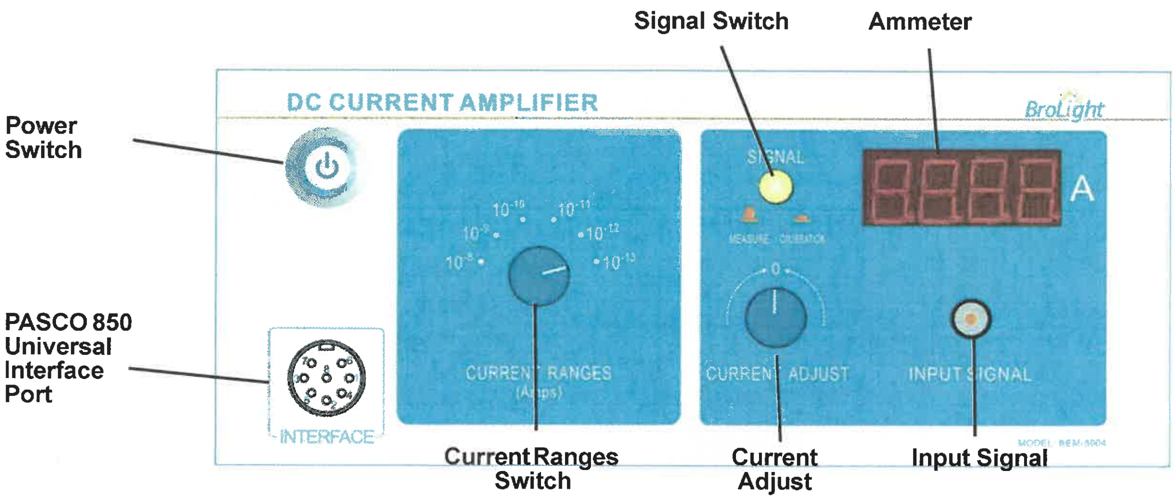
Tunable DC (Constant Voltage) Power Supply II



- Voltmeter: Displays voltage across the argon tube.
- Voltage Range Switch: Sets the voltage range as 0 to 100 V ( ) or 0 to 200 V ( ) for the accelerating voltage.
- Power Switch: Turns the power to the instrument ON or OFF.
- Voltage Adjust: Sets the voltage for both voltage ranges.

- Output: Output power.
- Data Interface: Connect to the analog channels of the PASCO 850 Universal Interface.

DC Current Amplifier



- Power Switch: Turns the power to the instrument ON or OFF.
- Data Interface: Connect to the analog channels of the PASCO 850 Universal Interface.
- Current Range Switch: Sets the current range for the instrument's current amplifier (10^{-8} to 10^{-13} A).
- Signal Switch: Sets the signal to MEASURE ( ) or CALIBRATION ( ).
- Current Adjust: Sets the current through the instrument to zero.
- Ammeter: Displays the current through the argon tube.
- Input Signal: Input current signal.

Experiment Procedure 1

Adjust Operating Voltages

> **Note:** Before switching on the power, be sure that all voltage controls are turned fully counterclockwise.

1. Connect all the cables and cords as shown in the section "Connect Cables and Cords" (page 7).
2. On the Tunable DC (Constant Voltage) Power Supply I, Tunable DC (Constant Voltage) Power Supply II, and the DC Current Amplifier, push in the Power Switch to the ON position.
3. On the DC Current Amplifier, turn the CURRENT RANGES switch to 10^{-10} A. To set the current amplifier to zero, press the SIGNAL button in to CALIBRATION. Adjust the CURRENT CALIBRATION knob until the current reads zero. Press the SIGNAL button to MEASURE.
4. On the DC (Constant Voltage) Power Supply I, set the Voltage Range switch to -4.5 – +30 V. On Power Supply II, set the Voltage Range switch to 0 – 100 V.

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> *NOTE: It is very important to allow the argon tube and apparatus to warm up for 15 minutes prior to making any measurements.*

5. On Power Supply I, rotate the 0 – 6.3 V adjust knob until the voltmeter reads 3.5 V. This sets $\mathbf{V_H}$ = 3.5 V (Filament Voltage). Note: The Argon Tube Enclosure may have a different suggested filament voltage. If so, use it instead of 3.5 V.
6. On Power Supply I, rotate the -4.5 – +30 V adjust knob until the voltmeter reads 1.5 V. This sets $\mathbf{V_{G1K}}$ = 1.5 V (the voltage between the first grid and the cathode)
7. Rotate the 0 – 12 V adjust knob until the voltmeter reads 10.0 V to set $\mathbf{V_{G2A}}$ = 10.0 V (Retarding voltage).
8. Rotate the 0 – 100 V adjust knob until the voltmeter reads 0 V. This sets $\mathbf{V_{G2K}}$ = 0 V (Accelerating voltage).
9. Remember, allow the argon tube and the apparatus to warm up for 15 minutes.
10. When you have finished the above steps, check that $\mathbf{V_H}$ = 3.5 V (Filament voltage), $\mathbf{V_{G1K}}$ = 1.5 V (the voltage between the first grid and cathode), and $\mathbf{V_{G2A}}$ = 10.0 V (voltage between the second grid and anode – "retarding voltage"). If so, the equipment is ready to do the experiment. Note: These are suggested settings for the experiment, but other values could be tried. You can do the experiment by parameters that are marked on the Argon Tube Enclosure.

Manual Measurements

> Note:
>
> - During the experiment, pay attention to the output current ammeter when the voltage is over 60 V. If the ammeter's reading increases suddenly, decrease the voltage at once to avoid the damage to the tube.
> - If you want to change the value of V_{G1K}, V_{G2A} and V_H during the experiment, rotate the "0 ~ 100 V" adjust knob fully counter-clockwise before making the changes.
> - The filament voltage is tunable from 0 to 6.3V. If the anode output current is too high and causes the amplifier to overflow, the filament voltage should be decreased.
> - As soon as you have finished the experiment, return the V_{G2A} voltage to 0 V to prolong the life of the argon tube.

1. Increase the accelerating voltage V_{G2K} by a small amount (for example, 1 V). Record the new accelerating voltage V_{G2K} (value read on voltmeter) and current I_A (read on "Ammeter") in Table 1:1. Continue to increase the voltage by the same small increment and record the new voltage and current each time in Table 1:1. Stop when the accelerating voltage V_{G2K} = 85V. (If the current I_A exceeds the range, reduce the filament voltage (for example, 0.1V) and start over again.)
2. Try to identify the "peak positions", i.e. watch for those values of the accelerating voltage V_{G2K} for which the current reaches a local maximum and begins to drop on further increase of the accelerating voltage. Take a few data points (V_{G2K}, I_A) around these peak positions and record them in Table 1:2. Try to identify the "valley positions", i.e. watch for those values of the accelerating voltage V_{G2K} for which the current reaches a local minimum and begins to rise on further increase of the accelerating voltage. Take a few data points (V_{G2K}, I_A) around these valley positions and record them in Table 1:2.
3. Take sufficiently many voltage values so as to allow you to determine the positions of the peaks and valleys.

Table 1.1: Accelerating Voltage and Tube Current

V_{G2K} (V)									
I_A (x 10^{-10} A)									

Table 1.2: Peak and Valley Voltages

		V_1	V_2	V_3	V_4	V_5	V_6
Peak positions	V_{G2K} (V)						
	I_A (x 10^{-10} A)						
Valley positions	V_{G2K} (V)						
	I_A (x 10^{-10} A)						

Analysis

1. Plot the graphs of Current (y-axis) versus Voltage (x-axis).