5. Franck-Hertz Experiment

5.1. Purpose

1. To demonstrate the quantization of the bound electron's energy level(s) for the Argon atom using electron atom collisions.
2. To determine a value of Planck's constant assuming the emission wavelength for the electron tran sition involved is $\lambda = 108.1nm$.

5.2. Apparatus

DC constant voltage supply SE 6615 $0V - 6.3V$ and $(-4.5 - 0V)/(-4.5V - 30V)$, DC constant voltage supply SE 9644 $0V - 12V$ and $(0V - 100V)/(0V - 200V)$, DC current amplifier SE 6621, Argon tube and enclosure SE 9650, connecting cable black EM 9745 (4 conductor), connecting cable red EM 9740 (4 conductor), BNC cable, AC power cords

5.3. Argon Tube Specifications

Filling gas: Argon, Filament voltage:$6.3V_{DC}$, Accelerating voltage:$100V_{DC}$, Wave crest (or trough) num ber: 6, Life span: 2000 hours

5.4. Safety Information

WARNING: To avoid possible electric shock or personal history, follow these guidelines.

- Plug into a grounded (earthed) outlet.
- Use caution when working with voltages above $30V_{AC}$, or DC. Such voltages pose a potentially lethal shock hazard.
- To avoid electric shock, do not touch any bare conductor with hand or skin.

5.5. Experiment Description

In 1914, James Franck and Gustav Hertz discovered in the course of their investigations an "energy loss in distinct steps for elec trons passing through mercury vapor", and a corresponding emis sion at the ultraviolet line ($\lambda = 254nm$) of mercury. As it is not possible to observe the light emission directly, demonstrating this phenomenon requires extensive and cumbersome experiment appa ratus. 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.

Figure 5.1.: Photo of Franck Hertz tube

5.5.1. Principle of the Experiment

The Franck Hertz tube in Figure 5.1 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 $1.5V$). 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 $G2$ 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 have don't.

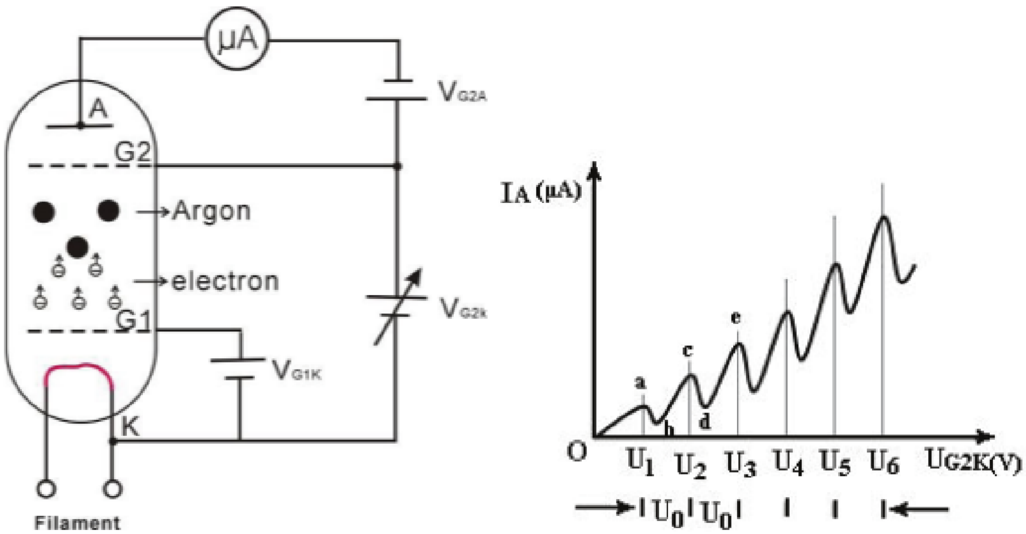

Figure 5.2.: Frank Hertz schematic and anode current

Figure 5.2 displays a typical measurement of the anode current I_A as a function of the accelerating voltage. Notice that the current sharply decreases for a voltage U_1 and then increases up to U_2, and then this pattern recurs.

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.

As the voltage is again increased, the electrons obtain the energy necessary for inelastic collisions before they reach the G_2. This moves the region of interaction away from G_2 and toward G_1. After the collision, by the time they reach the grid G_2, they have obtained enough energy to overcome the retarding voltage and will reach the collector plate. Thus I_A will increase.

When a certain voltage V_2 is reached we again 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 after the second collision do not have enough remaining energy to overcome the retarding voltage.

Increasing the accelerating voltage again shows I_A increases until a third value, V_3, 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

$$V_3 - V_2 = V_2 - V_1,$$

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 with 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 G_2. 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.

5.6. Experimental Procedure

NB: Before connecting the power cords, please check that the setting for the input voltage range ($110-120V\ or\ ,220-240V$) 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.

5.6.1. Precautions

- 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.
- ***NB:*** Have your lab instructor review your connections before applying power.

5.6.2. Connections

See Figure 5.3 for the connections required. Below is a description of the numbered connections. Analog ports A and B will not be used, they are used to acquire the plots on digital equipment.

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 "A".
2. On Power Supply II, (SE 9644) connect the positive terminal of the $12VDC$ output to the 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 $100VDC$ output on the power supply to the 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 $-4.5-30VDC$ output on the power supply to the 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 $0-6.3VDC$ 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.

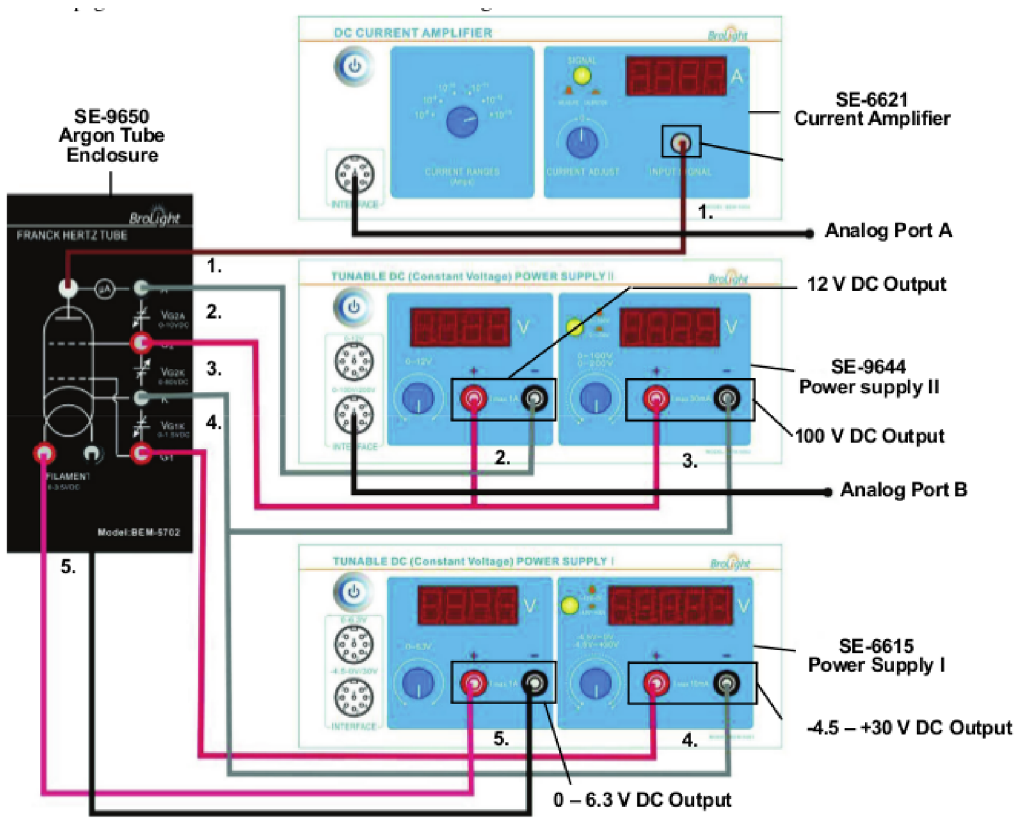

Figure 5.3.: Connections

5.7. Procedure: Voltage Settings and Acquiring Data

The essential task is to take sufficiently many voltage values so as to allow you to determine the positions of the peaks and valleys. A detailed set of steps follows.

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.

5.7.1. Setting voltages and tube warm-up

On the top of each black tube enclosure are specifications for operating each tube. Record and use these values if they differ from the following.

**During the experiment, pay attention to the output current ammeter at all times. If the ammeter's reading increases suddenly, decrease the voltage at once to avoid the damage to the tube. A sudden increase in ammeter current indicates a gas discharge[1] has occurred.

Notes:

1. *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.*

2. *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.*

3. *As soon as you have finished the experiment, return the V_{G2A} voltage to 0V to prolong the life of the argon tube.*

[1] This is also known as arcing. Norm

Before switching on the power, be sure that all voltage controls are turned fully counter-clockwise.

1. Connect all the cables and cords as shown in the section 5.6.2.
2. Turn on the Tunable DC (Constant Voltage) Power Supply I, Tunable DC (Constant Voltage) Power Supply II, and the DC Current Amplifier
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. Then return the SIGNAL button to MEASURE.
4. On the DC (Constant Voltage) Power Supply I, set the VOLTAGE RANGE switch to $-4.5 - 30V$. On Power Supply II, set the VOLTAGE RANGE switch to 0 $100V$.
5. Record the the Argon tube's filament voltage and report this in your lab write up. $Filament\ V_H =$
6. On Power Supply I, rotate the $0 - 6.3V$ adjust knob until the voltmeter reads your tube's filament voltage. This sets the **Filament Voltag**e V_H.
7. Record the Argon tube's grid1 to cathode voltage. $V_{G1K} =$
8. On Power Supply I, rotate the $-4.5 - 30V$ adjust knob until the voltmeter reads your tubes V_{G1K} voltage. This sets the **voltage between the first grid and the cathode.**
9. Record your tube's V_{G2A} voltage. $V_{G2A} =$
10. Rotate the $0 - 12V$ adjust knob until the voltmeter reads your tube's specified V_{G2A} voltage. This sets the the **Retarding Voltage** V_{G2A}.
11. Rotate the $0-100V$ adjust knob until the voltmeter reads *0V*. This sets the **Accelerating voltage** $V_{G2K} = 0V$.
12. Allow the argon tube and the apparatus to warm up for 15 minutes. It is very important to allow the argon tube and apparatus to warm up prior to making any measurements.
13. When you have finished the above steps, check that filament voltage V_H, grid1 voltage V_{G1K}, retarding voltage V_{G2A}have not significantly changed. If changed, reset the voltages as per above. The equipment is now ready to do the experiment.

5.7.2. Collecting Data

If the current I_A exceeds the meter's range, reduce the filament voltage (for example, 0.1V) and start over again.

Try to identify the "peak positions" and "valley positions", i.e. watch for those values of the accelerating voltage V_{G2K} for which the current reaches a local maxima or minima. If possible take extra data (V_{G2K}, I_A) around these locations by reducing the voltage V_{G2K} step size.

1. Increase the accelerating voltage V_{G2K} by a small amount (for example, $1 - 3V$).
2. Record the new accelerating voltage V_{G2K} (value read on voltmeter) and current I_A (read on "Am meter") in a table for plotting later.
3. Continue to increase the voltage by the same small increment and record the new voltage and current each time.
4. **Stop when the accelerating voltage** $V_{G2K} = 85V$.

5.8. Results

1. Plot the graphs of Current (y axis) versus Voltage (x axis) in xmgrace.
2. Find the peak (or valley) positions which match the accelerating voltages labeled "V_1, V_2, V_3, V_4, V_5, and V_6". Assign a reasonable error to each voltage and table these values.

5.9. Analysis

1. Obtain the value of argon atom's first excitation potential $V_0 \pm \sigma_{V0}$ by calculating the average of the differences (adjacent peak to peak and valley to valley). For example, if six values are available:

$$V_0 = \frac{V_2 - V_1 + V_3 - V_2 + V_4 - V_3 + V_5 - V_4 + V_6 - V_5}{5}$$

   and σ is the mean error.

2. Calculate the value of Planck's Constant, $h \pm \sigma_h$:

$$h = e\lambda \cdot \frac{V_0}{c}$$

   where $e = 1.602 \times 10^{-19}$ *coulombs*, $\lambda = 108.1nm$*, and* $c = 2.998 \times 10^{-8} m/s$. Assume negligible error for e, λ, and c.

3. Does your value of Planck's constant agree with the accepted values?

5.10. Questions

1. Should you use the positions of the peaks or of the valleys to determine the excitation energy? Or both? Explain.
2. Why are the peaks and valleys smeared out rather than sharp?
3. How precisely can you determine the peak/valley position? Explain and justify your estimates.
4. How would molecular contaminants in the tube affect your results?