# Experiment 6: Franck-Hertz Experiment v1.3

Background

This series of experiments demonstrates the energy quantization of atoms. The concept was first implemented by James Franck and Gustaf Ludwig Hertz in 1914. They showed that an electron must have a specific, well-defined energy to make an inelastic collision with a mercury atom. This energy corresponds to an excited quantum state. In 1926, Franck and Hertz were awarded the Nobel Prize in Physics for conclusively confirming the Bohr model.
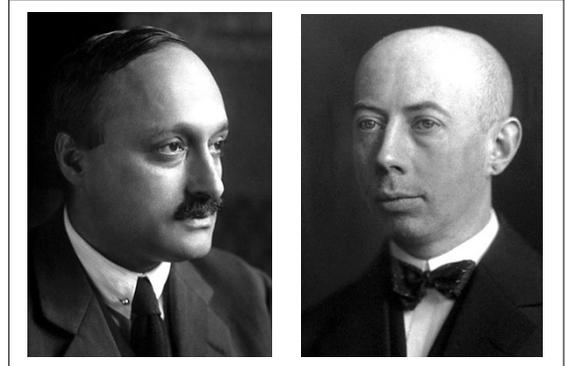
There are two parts of this lab. The first experiment is with helium gas and the second uses mercury vapor as was originally done by Franck and Hertz. The essential idea in both measurements is the same. Electrons are injected into an atomic gas at a tunable, precisely defined energy using an electron gun. The energy is set by an adjustable accelerating potential. When incident electrons have energy close to a quantum energy separation in the atoms, they can lose energy efficiently. This happens via inelastic collisions, which reduce the energy of the free electrons by the quantum excitation. The electrons slow down and this is observed as a change in the collector ring current. By recording current as a function of electron kinetic energy (i.e. accelerating voltage), distinct structure can be identified corresponding to quantum energy resonances.

The helium apparatus also allows the observation of ionization. If the energy of the free electrons is made sufficiently large, bound electrons in the helium atom can be liberated. An ionizing collision leaves a positively charged helium ion and two electrons (one incident and one knocked off the atom). Because an additional electron is created at each collision, the conductivity of the gas will increase leading to a corresponding sharp increase of detector current. Both resonant excitation and ionization can be observed with helium.

The experiment is automated using a data acquisition device (DAQ) controlled by a LabView program on a PC. The experimenter must carefully configure acquisition parameters with an understanding of the instrument capabilities and limitations. The block diagram of the LabView program contains its code. This can be inspected if desired, but should not be modified without permission of the instructor.

Part 1: Excitation and ionization of helium

1.1 Equipment

Hertz Critical Potentials tube filled with helium gas
0096 control unit
Pico-amplifier (Note: the detachable digital ammeter display is not used)

Filament power supply (≤ 2.5V at ~ 1 A)
Anode power supply (0—30V)
1.5V battery
PC with LabView program
Digital multimeter

The glass tube houses a cathode ray gun that injects a diverging beam of electrons into low pressure helium gas. Free electrons are created by thermionic emission at a heated tungsten filament. Electrons are accelerated from the cathode towards and past the anode ring into the main volume of the glass bulb. Their kinetic energy is precisely controlled by the anode power supply. A metal ring electrode functions as a collector and is positioned along the perimeter of the bulb so that it does not collect electrons directly from the source beam. Instead, it detects primarily scattered electrons, aided by a small potential from the 1.5 V battery. The ring current flows to a sensitive electrometer through a shielded coaxial cable terminated by a BNC connector. The glass bulb is covered with a thin metallic coating that is at the same potential as the anode, but electrically isolated from the wire ring.

1.2 Objectives
1) Determine energy levels in helium and report their values in units of *eV,* along with estimated uncertainties. Compare to the established values.
2) Determine the ionization energy of helium in *eV* and compare to the known value.
3) Measure the full-width at half-maximum of each peak; determine other sources of error.
4) Study the effect of filament voltage, while keeping it below 2.5V.

1.3 Procedure
Make the electrical connections as shown in Fig. 1. First, wire the filament ports F3 and F4 to a low voltage power supply capable of delivering ~ 1 A. Be sure to observe the indicated polarity. Connect a digital multimeter to the supply to monitor the filament DC voltage. It is important that this voltage does not exceed 2.5V. Turn on the power supply and increase the voltage to > 2V. You should observe current flowing on the power supply ammeter accompanied by an orange glow emanating from the filament inside the tube.

Turn off the filament and connect the DC anode supply (0—30V) to the control unit as shown. If a female banana connector is unavailable, use an alligator clip on connector A1. Be sure to connect C5 to F4.

The 1.5V battery provides a DC bias voltage to collect electrons at the wire ring. When the battery positive terminal is grounded to the amplifier as shown in the figure, the circuit can detect peaks in the current as the anode voltage is varied. These peaks correspond to energy resonances in helium.

Reversing the polarity will attract positive charges instead of negatively charged free electrons. Question 1: What is the source of this positive charge? Question 2: How does this current help determine the ionization threshold potential?
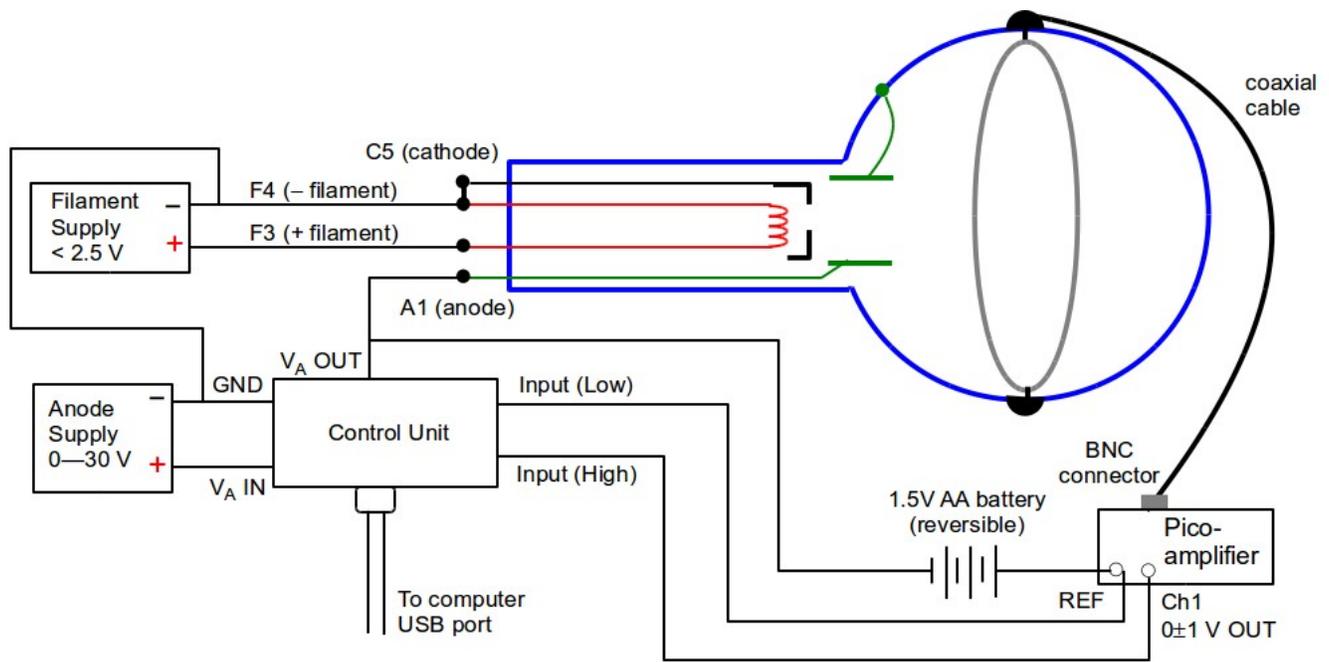
Fig. 1 Franck-Hertz experiment with helium gas

The DAQ device in the control unit reads a voltage at the pico-amplifier output that is directly proportional to the detector current. Connect the amplifier output to the control unit inputs as shown. The reference potential of the pico-amplifier (REF) must be allowed to float with respect to circuit ground (GND). Do not connect GND to REF. This is a differential measurement so the polarity only affects the sign of the signal. Turn on the filament supply (< 2.5V) and let it warm up for about a minute. Turn on the anode supply and set the voltage (V_A IN) to 3—4 V higher than the maximum anode voltage that will be applied (V_A OUT). Observe the proper polarity and never exceed 50V, otherwise the control unit will be damaged.

Open the LabView program named scan.vi. The program will instruct the control unit to quickly scan the anode voltage across a specified range and record a voltage corresponding to current in the collector ring electrode. The user must enter a starting and ending anode voltage as well as the voltage increment. The increment is the voltage step between successive data points. The finer the increment, the more data points will be taken.

It is important to understand that analog and digital instruments are not infinitely precise. The DAQ controller is a digital device with 10-bit resolution on its control voltage. This means its output voltage can be written with a precision of one part in 2^{10} or about 0.1%. As a result, the anode voltage cannot be specified to better than about 80 mV. It makes no sense to have a voltage increment smaller than this because it exceeds the resolution of the DAQ device.

Orient the 1.5V bias battery as shown in the above figure. Plug in the power supply of the pico-amplifier and set it for maximum gain by sliding the selector switch to the level marked 10^{-12}. It is a good idea to begin with a coarse scan over a range of 10—25V (not critical) to verify proper setup of the experiment. Press the run button (horizontal arrow) on the LabView front panel to start the program. The goal is to identify four peaks corresponding to energy levels 2^3S, 2^1S, 3^1S,

and 4^1S (overlaps with 4^3S) in helium.

The detected voltage is directly proportional to the current in the ring electrode. The control unit reads it using an 11-bit A-D (analog-to-digital) converter. Its resolution accuracy is a factor of 2 better than the anode voltage controller. The sensitivity of the input A-D converter can be adjusted on the LabView interface. Highest accuracy is attained when the converter is set for the minimum voltage level that does not cause saturation, i.e. when the input voltage exceeds the selected sensitivity. Example: If the maximum absolute detected voltage from the scan is slightly higher than 1V, set the input sensitivity to 1.25V. The pico-amplifier will clip any voltage greater than about 4V. If this occurs, reduce the gain to 10^{-11}. When you have the desired data, save it to disk. The data is written as a two-column spreadsheet.

You should be able to identify four peaks before ionization of the gas commences. The ionization threshold is characterized by an abrupt increase of the slope of absolute current with anode voltage. Note: The collected current is very small and can be disturbed by potentials from objects outside of the glass tube (eg. the experimenter's body). Repeat the experiment at a higher or lower filament voltage, making sure not to exceed 2.5V. Comment on any differences in the shape of the emission spectra; the peaks should be seen at the same anode voltages.

Reverse the 1.5V battery to collect positive charge and repeat the scan. The experiment is much less sensitive to resonant excitation of the atoms, but one can expect an increase of the current slope in the vicinity of the ionization potential, i.e. the inflection point of the curve defines the ionization threshold. The anode voltage does not need to exceed 30V.

At this point, sufficient data has been collected to complete the Objectives of Part 1.2.

Troubleshooting
- If the LabView program cannot communicate with the DAQ device (Measurement Computing 1208LS), check that the USB interface cable is properly connected. Open the installed program InstaCal, verify that the device is recognized, and attempt to communicate with it. Check that it is configured with 4 inputs in differential mode.

- If the LabView program cannot reach the specified maximum voltage, check that the anode power supply is properly connected to the control unit. If this is correct, either the power supply voltage must be increased or the upper limit scan voltage reduced.

- Absence of a detector current may indicate that the pico-amplifier is off or the glass bulb is not fully pressed into its socket.

Part 2: Excitation of mercury

2.1 Equipment
Triode tube filled with mercury (Manufactured by Neva)
AC heater cord
Thermometer
0096 Control unit

Pico-amplifier (Note: the detachable digital ammeter display is not used)
Filament power supply (6V at ~ 0.3 A)
Anode power supply (0—50V)
1.5V battery
PC with LabView program
Digital multimeter

The mercury tube replaces the helium bulb. The 0096 control unit and LabView program from Part 1 are used.

2.2 Objectives
1) Identify the first excited state of mercury in units of eV. Compare to the established value.
2) Study the effect temperature, while keeping it below 200C.
3) Determine the work function of the oxide coated cathode.

2.3 Procedure
The tube must be uniformly heated to a temperature in the range 150—200C to produce mercury vapor. This is accomplished with a 400W heating element inside the enclosure. AC power is applied to the heater using the 2-pin connection on the lower left side panel. Insert the thermometer about halfway into the box at the access hole on the top. A clip holds it in place. Turn on the heater AC power switch and set the temperature using the thermostat control dial on the right side panel. An initial dial setting of about 6—7 should be adequate. Allow about 15 minutes for the temperature to stabilize. Do not exceed 200C.

> **Caution:** The enclosure will get hot enough to cause skin burns. Take proper safety precautions.

Make the electrical connections as shown in the schematic diagram below, using a shielded BNC cable between the collecting electrode and amplifier. The filament power supply should provide 300 mA of current at 6V. Wait 90 seconds for it to heat the oxide-coated cathode (K).

Take data in the same way as the helium experiment in Part 1. Set the anode supply voltage (V$_A$ IN) to 3—4 V higher than the maximum anode voltage that will be applied (V$_A$ OUT). Observe the proper polarity and never exceed 50V, otherwise the control unit will be damaged. In addition, the reference potential of the pico-amplifier (REF) must be allowed to float with respect to circuit ground (GND). Do not connect GND to REF.

The helium experiment measures a secondary current from scattered electrons such that resonances occur at current peaks. In the mercury setup, *minima* in the plot of collector current vs anode voltage identify the quantum energy excitations. The collector electrode (M) monitors current due to electrons passing directly through the mesh anode (A). Different pico-amplifier and DAQ settings in the LabView program will also be needed to get clean data. The 1.5V battery provides a decelerating potential to slow electrons before they strike the collector. Electrons that have lost most of their energy through inelastic collisions cannot overcome this potential.
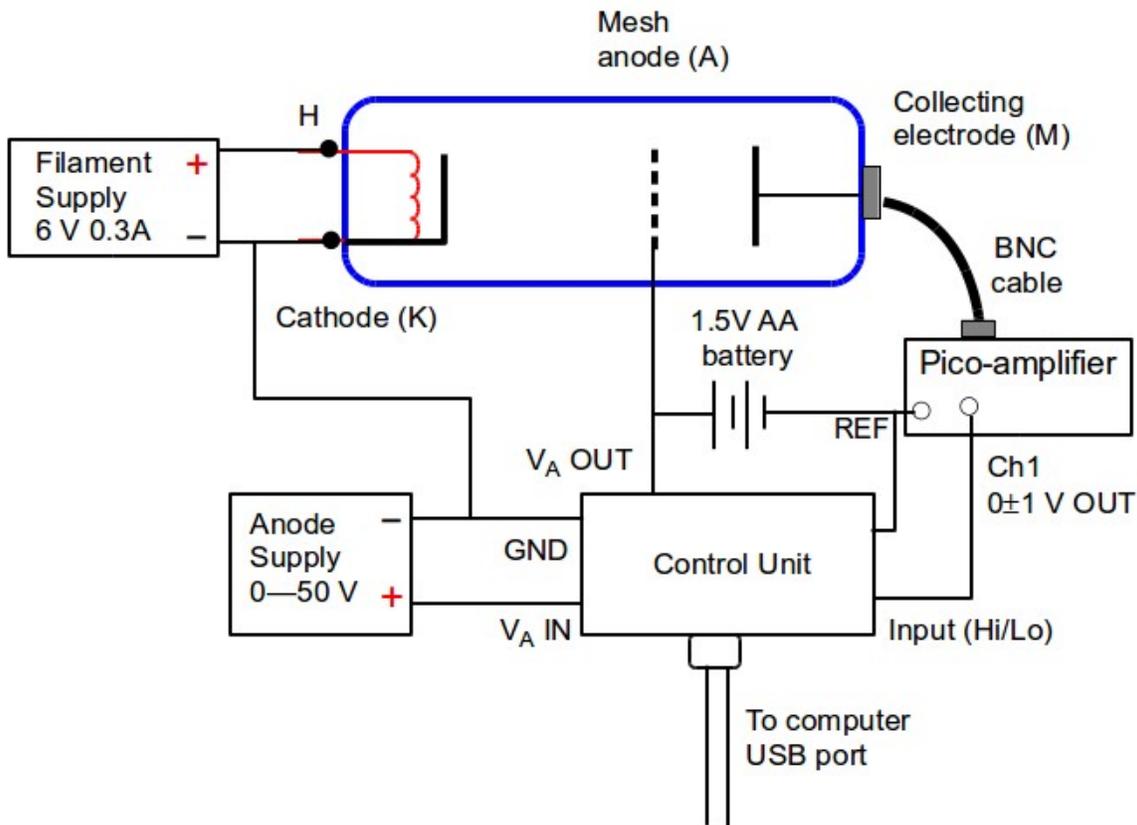
Fig. 2 Franck-Hertz experiment for mercury vapor

When configured correctly, the collected current data will show a sequence of peaks and valleys with increasing anode voltage. The voltage separation of the valleys should be nearly identical and correspond to the excitation energy of a mercury atom. Away from resonance, collisions are purely elastic – no energy is transferred to the mercury atoms. Near the resonant energy, electrons will lose a quantum of energy via inelastic collisions causing the current to drop dramatically. At higher anode voltage, elastic collisions resume and current goes back up. Increasing the voltage further will again lead to inelastic collisions from resonant excitation. This secondary excitation region moves away from the mesh anode, closer to the cathode. The electron has enough energy remaining after its first inelastic collision to excite a second atom on its way to the anode. With more voltage the electron can excite a third atom, then a fourth and so on, as it traverses the path to the anode. This is the cause of the observed integer-multiple sequence.

Note that the absolute value of the first valley will have a positive offset due to the work function of the cathode. Report this value. (This offset was not relevant in the helium experiment) Using the collected data, determine the resonant excitation energy of mercury atoms. Perform a statistical analysis of your data set and interpret the results. What are the sources of measurement uncertainty? What is the total uncertainty of your measurement?

The characteristics of the plot are affected by temperature. Obtain data at 150C and a higher temperature around 190C (do not exceed 200C). Describe the differences. Note: If the temperature in the enclosure is too low and the anode voltage set too high, breakdown in the tube may take place. The tube has an internal resistor to protect it from breakdown, but this condition should be avoided.