University of Rochester

Laboratory XV

The Franck-Hertz Experiment

Department of Physics & Astronomy

PHYSICS 123 - 183
Waves and Modern Physics

May 26, 2026

Name: ________________________________ **Date:** ________________________

Collaborators: ______________________________ **Lab Section:** ____________

PRELAB EXERCISES (2 points)

This prelab must be completed and handed in to the lab TA at the start of the lab.

Question 1 **½ point**

Why should the mercury pressure in the vacuum tube in the Franck-Hertz experiment be low?

Question 2 **½ point**

Draw an atomic model of a ground-state argon atom.

Question 3 **1 point**

Calculate the binding energy of the outermost electron in the Ar atom. According to Bohr's model, the energy of an electron in the n^{th} orbital of an atom of atomic number Z is

$$E = -13.6\frac{Z^2}{n^2}\text{ eV}.$$

Objective

In this lab, you will find the energy required to excite an argon atom from its ground state to its first excited state. This will repeat the experiment performed using mercury vapor by James Franck and Gustav Hertz in 1914, which definitively demonstrated the quantum nature of atoms.

Theory

The Franck-Hertz experiment, performed by James Franck and Gustav Hertz in 1914, is the first direct demonstration of the existence of discrete electron energy levels in an atom.

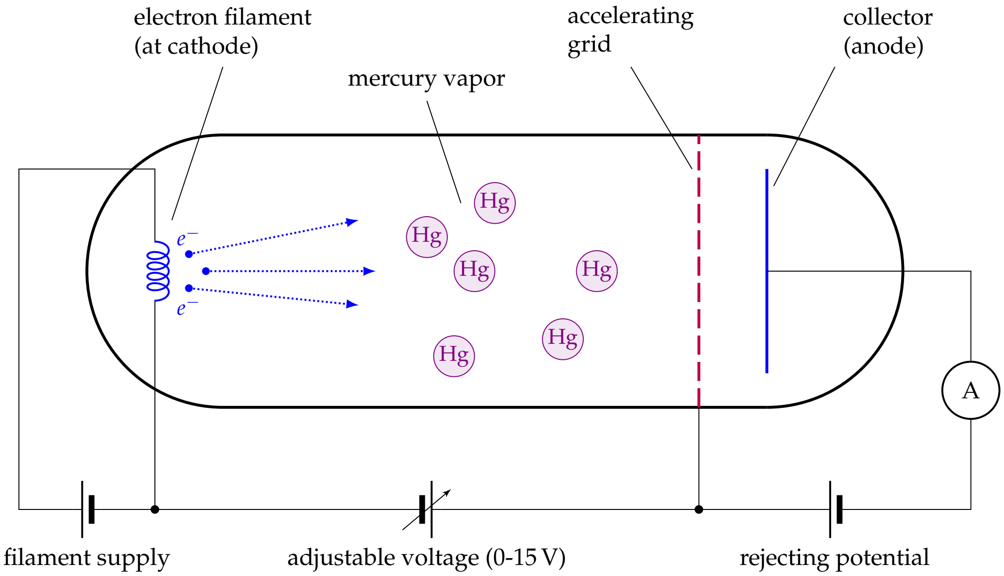

Figure 1: *A schematic diagram of the original Franck-Hertz vacuum tube.*

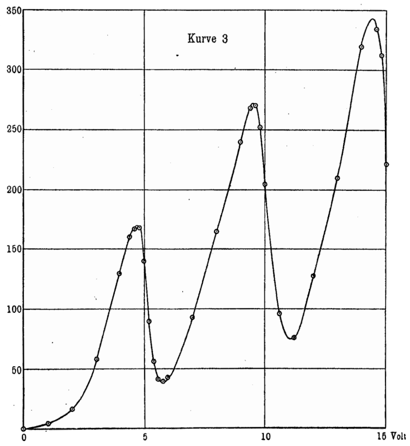

Figure 2: *Anode current in the vacuum tube (y-axis) versus cathode-grid voltage (x-axis). Credit: J. Franck and G. Hertz, Verh. Dtsch. Phys. Ges. 16:457, 1914.*

Franck and Hertz studied energetic electrons traveling through a glass vacuum tube (Fig. 1) filled with a small amount of gaseous mercury (Hg). The electrons were emitted from a hot electrode inside the tube next to a low-voltage contact called the **cathode**. A metal grid held at an adjustable voltage relative to the cathode caused the electrons to accelerate toward the grid. On the far side of the grid, another electrode called the **anode** collected the electrons, allowing Franck and Hertz to measure the current of the electron beam after it passed through the Hg vapor.

As they increased the adjustable voltage, Franck and Hertz found the anode current increased proportionally with the voltage until 4.9 V, at which point the anode current dropped close to zero. As they continued increasing the voltage beyond 4.9 V, the current again increased proportionally with the applied voltage until again dropping close to zero at 9.8 V (exactly twice 4.9 V). This pattern repeats in steps of 4.9 V. You can see the pattern in Fig. 2, which shows the anode current versus adjustable grid voltage published by Franck and Hertz in 1914.

In a follow-up experiment, Franck and Hertz noticed a blue-violet glow in the Hg gas in the tube, peaking almost entirely at

$\lambda = 254\,\text{nm}$. This wavelength corresponds to a photon energy of

$$E_{\text{photon}} = \frac{hc}{\lambda} = \frac{(4.15 \times 10^{-15}\,\text{eV s})(2.998 \times 10^{17}\,\text{nm/s})}{(254\,\text{nm})} \approx 4.9\,\text{eV}.$$

Note that 4.9 eV is the kinetic energy of an electron accelerated from rest by a potential difference (or voltage) of 4.9 V, the same voltage as the period observed with the Franck-Hertz tube (Fig. 2). This is not a coincidence! When the accelerated electrons collide with Hg atoms in the gas, at most energies they elastically scatter off the atoms, changing direction but not losing energy. However, at energies of 4.9 eV, the electrons collide *inelastically* with the Hg atoms, losing their energy to atomic electrons, which then re-emit the absorbed energy as 254 nm photons. The process is shown schematically in Fig. 3.

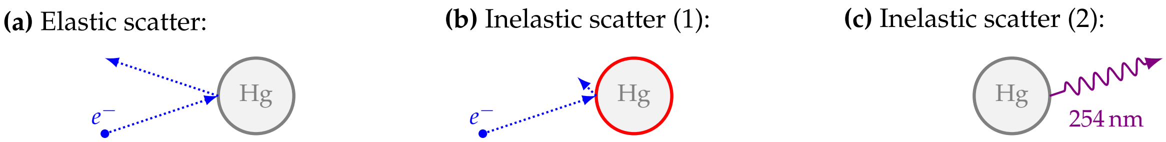
(a) Elastic scatter:
(b) Inelastic scatter (1):
(c) Inelastic scatter (2):

Figure 3: *In elastic scattering of an accelerated electron from an Hg atom (a), the electron changes direction but loses no energy. In inelastic scattering, the accelerated electron loses* 4.9 eV *to a valence electron in the Hg atom, promoting it from the ground state to the first excited state (b). The valence electron then de-excites and emits a* 254 nm *photon (c).*

In 1913, Niels Bohr published his atomic model of quantized electron energy levels. The Bohr model successfully describes the discrete emission and absorption spectra of hydrogen-like atoms[1], explaining the spectra as due to transitions of atomic electrons between the quantized energy levels. The Franck-Hertz experiment is consistent[2] with this picture:

- Accelerated electrons in the Franck-Hertz tube collide elastically with Hg atoms at most voltages.
- At 4.9 V and multiples of 4.9 V, beam electrons inelastically transfer kinetic energy to valence electrons in atomic mercury, exciting them from the atom's ground state, Hg($6\,^1S_0$), to the first excited state, Hg($6\,^3P_1$). These two states differ in energy by 4.9 eV.
- The excited electron then de-excites back to the ground state, causing the emission of a 254 nm photon.

For his theoretical work on atomic structure, Niels Bohr received the Nobel Prize in Physics in 1922. James Franck and Gustav Hertz were awarded the Nobel Prize in 1925 for their experimental verification of quantized atomic structure.

Experiment

You will repeat the Franck-Hertz measurement in this lab, but instead of using Hg, we will use a tetrode (a vacuum tube with four penetrating electrodes) filled with argon (Ar) gas. Switching to Ar does not change the nature of the experiment, but it avoids the use of Hg, a neurotoxin that is a liquid at room temperature, and thus needs to be heated to become a vapor.

A schematic view of the setup is shown in Fig. 4. In contrast to the original Franck-Hertz device, our setup includes *two* accelerating grids with separate voltage adjustments. The four electrodes on the device give you control of four settings:

1. The potential at the cathode K, which will be connected to ground.
2. The voltage between the cathode and the first accelerating grid, $V_{\text{G1,K}} = 1.5\,\text{V}$.
3. The voltage between the cathode and the second accelerating grid, $V_{\text{G2,K}} = 0\,\text{V}$ to $100\,\text{V}$.
4. A small rejecting potential $V_{\text{G2,A}} < 10\,\text{V}$ between the second grid and the anode.

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[1] Atoms with one electron in the valence shell.

[2] Note that the Bohr model does not exactly describe the Hg line spectrum, since mercury is not a hydrogenic atom.

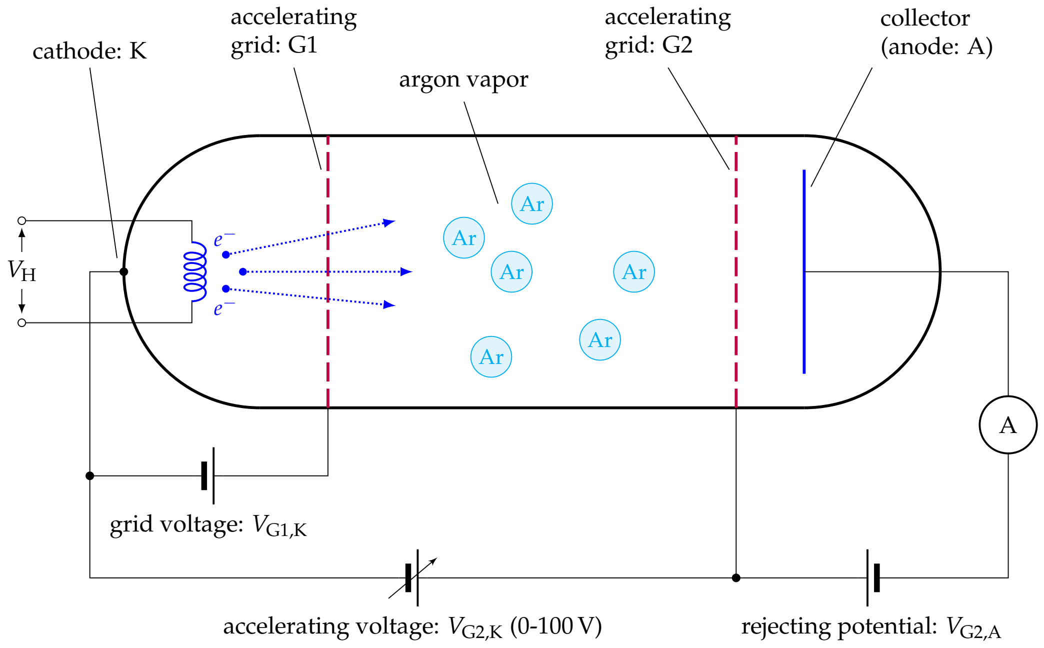

Figure 4: *The tetrode filled with Ar gas used in this lab.*

By measuring the anode current I_A with an ammeter, you will characterize the electron beam as a function of the adjustable voltage $V_{G2,K}$. You can also change the filament voltage, V_H, to alter the intensity of the electron beam.

Data Collection for the Experiment

During the experiment, you will start with a low value of $V_{G2,K}$. The accelerated electrons in the tube will collide elastically with the Ar gas, so you will see I_A increasing proportionally with $V_{G2,K}$.

When $V_{G2,K}$ reaches the first excitation potential[3] of Ar, the electrons colliding with Ar atoms near grid G2 will interact inelastically with the argon, transferring their kinetic energy to the atoms' valence electrons. The beam electrons will then have too little energy to overcome the reverse field created by the rejecting potential $V_{G2,A}$, causing I_A to drop significantly.

With a further increase of $V_{G2,K}$, the beam electrons will be **re-accelerated** by the larger grid voltage after their first inelastic collision with the Ar atoms. The re-accelerated electrons will obtain enough kinetic energy to overcome the reverse field created by $V_{G2,A}$, allowing them to reach the anode and causing I_A to rise proportionally with $V_{G2,K}$.

Eventually, $V_{G2,K}$ will be twice the excitation potential of Ar, and the electrons re-accelerated to grid G2 will inelastically collide a second time with Ar atoms, losing their energy and causing I_A to drop again. You can observe this pattern repeating every time $V_{G2,K}$ reaches an integer multiple of the excitation potential. An example of how your data will look is shown on the oscilloscope screen capture shown in Fig. 5. By measuring the first excitation potential of Ar in this pattern, we verify that the energy absorbed and emitted by the atom is discrete.

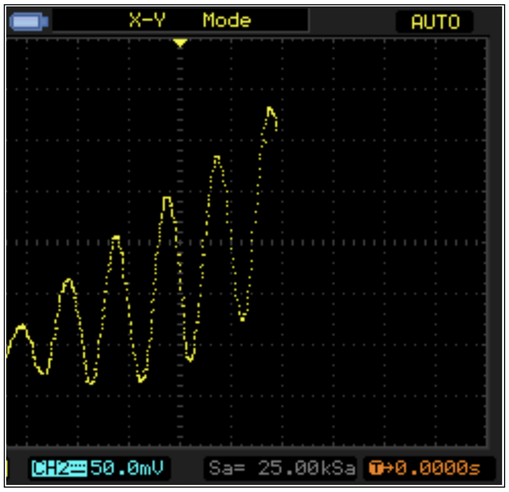

Figure 5: *Example oscilloscope trace of anode current I_A versus grid voltage $V_{G2,K}$ for Ar.*

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[3] Experimentally, you'll observe the Ar excitation potential somewhere between 10 V and 13 V.

Use of the Equipment

WARNINGS: Read the following directions before using the equipment.

1. During the experiment, pay close attention to the output current indicator when the adjustable voltage $V_{\mathrm{G2,K}} > 60\,\mathrm{V}$. This is especially important at the higher voltage (filament voltage) and sensitivity (current multiple) settings. If the current meter reading increases suddenly, decrease the voltage at once to avoid damage to the Franck-Hertz tube.
2. If you want to change the value of $V_{\mathrm{G1,K}}$, $V_{\mathrm{G2,A}}$, and V_{H} during the experiment, **first rotate the "0-100 V" voltage adjustment knob counter-clockwise all the way to the end** to turn off the grid voltage before making your changes.
3. The filament voltage of this instrument is $V_{\mathrm{H}} = 3\,\mathrm{V}$, $3.5\,\mathrm{V}$, $4\,\mathrm{V}$, $5\,\mathrm{V}$, $5.5\,\mathrm{V}$, and $6.3\,\mathrm{V}$. You can experiment with these filament voltages, but beware that too high a filament voltage can cause current distortion. In such a condition, V_{H} should be decreased.

Procedure

Adjust the Operating Voltages

Figure 6: *Voltage control panel of the Franck-Hertz apparatus.*

1. Make yourself familiar with the control knobs, shown in Fig. 6, and read the warning carefully before starting the experiment. Due to the risk of damage to the tube, the use of filament voltage $V_{\mathrm{H}} > 5\,\mathrm{V}$ **is discouraged** except under the direct supervision of a TA/TI.
2. Make sure the setup has a vacuum tube installed (ask the TA if unsure) and covered prior to use.
3. The 0-100 V knob is continuously adjustable with a soft stop. Use care to **slowly rotate** this knob during use and when zeroing. Turn all voltage adjustment knobs fully counterclockwise (make all zero). Turn the "Manual-Auto" switch to "Manual" and rotate the "Scan Knob" counterclockwise all the way to the end.
4. **Set the filament voltage $V_{\mathrm{H}} = 4$ V and the "Current Multiple" selector to 10^{-8}**. Turn on the device: the green power indicator will glow. **Preheat the bulb for 2 minutes before starting your experiment.**

   Warning: NEVER change the "Current Multiple" selector with the instrument powered on. When turning the unit off, the current meter will dip and hold under zero momentarily while the device is powering down.

5. Set $\mathbf{V_{G1,K} = 1.5\ V}$:
   Move the "Voltage Stepper" switch to 1.3–5 V, and rotate the 1.3–5 V adjustment knob until the voltmeter reads 1.5 V.

6. Set $\mathbf{V_{G2,A} = 7.5\ V}$:
   Move the "Voltage Stepper" switch to 1.3–15 V, and rotate the 1.3–15 V adjustment knob until the voltmeter reads 7.5 V (rejecting voltage).

Operation in Manual Mode (OPTIONAL)

Skip to the next section unless you are explicitly asked by the TA to run in manual mode.

Once you have completed the voltage setup described above, move the "Voltage Stepper" switch to 0-100 V and rotate the 0-100 V adjustment knob until the voltmeter reads 0 V to set $V_{G2,K} = 7.5$ V (accelerating voltage). Normally, this is fully counterclockwise. Remember that this knob is continuously adjustable with a soft zero. Now you can gradually increase $V_{G2,K}$ and record measurements of I_A with the ammeter and voltmeter.

Operation in AUTO Mode (DEFAULT)

1. Complete the voltage adjustment steps described above.

2. Turn on the oscilloscope. Press the **Menu** button and set it to **XY** mode by using buttons on the right side of the display.

3. Set up marker channel using the **Cursor** button. Once you set it properly, the X and Y markers control could be changed using the **Off** button.

4. Connect the oscilloscope to the Franck-Hertz kit as shown in Fig. 7. Connect the instrument X output to channel 1 of the oscilloscope and the Y output to channel 2 of the oscilloscope. Don't forget that you also have to connect the instrument's ground to the ground of the oscilloscope.

Figure 7: *Oscilloscope probe connection to the voltage panel of the Franck-Hertz kit.*

5. Move the **Voltage Stepper** on the Franck-Hertz kit to 0–100 V and the operation switch to **Auto**. If you have connected everything properly, the signal should look as shown in Fig. 8.

6. Measure the peak-to-peak voltage differences using the oscilloscope cursors and fill in Data Table 1 in the Postlab exercises.

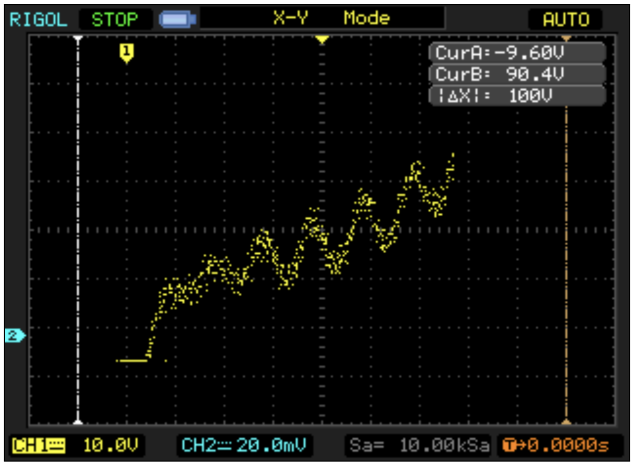


Figure 8: *Oscilloscope display of an auto-scanned signal from the Franck-Hertz kit.*

7. You can also save your data in a flash drive in a different format. For that, use the **Acquire** button on the top panel.

Name: ______________________ **Date:** ______________________

Collaborators: ______________________ **Lab Section:** ______________

POSTLAB EXERCISES (20 points)

Submit the postlab to the TA at the end of the lab.

Data Acquisition - AUTO Mode (10 points)

Question 4 **7 points**

Using the vertical cursor on the oscilloscope, measure the voltage spacing between adjacent dips in the trace.

Location of first dip = ______________ V

Data table 1: *Voltage period measurements from the Franck-Hertz Kit.*

Pairs of dips	$\Delta V = V_{i+1} - V_i$ [V]	Average ΔV [V]
1-2		
2-3		
3-4		
4-5		
5-6		
6-7		
7-8		

Question 5 **1 points**

(a) ($1/2$ point) Calculate the standard deviation in average voltage spacing.

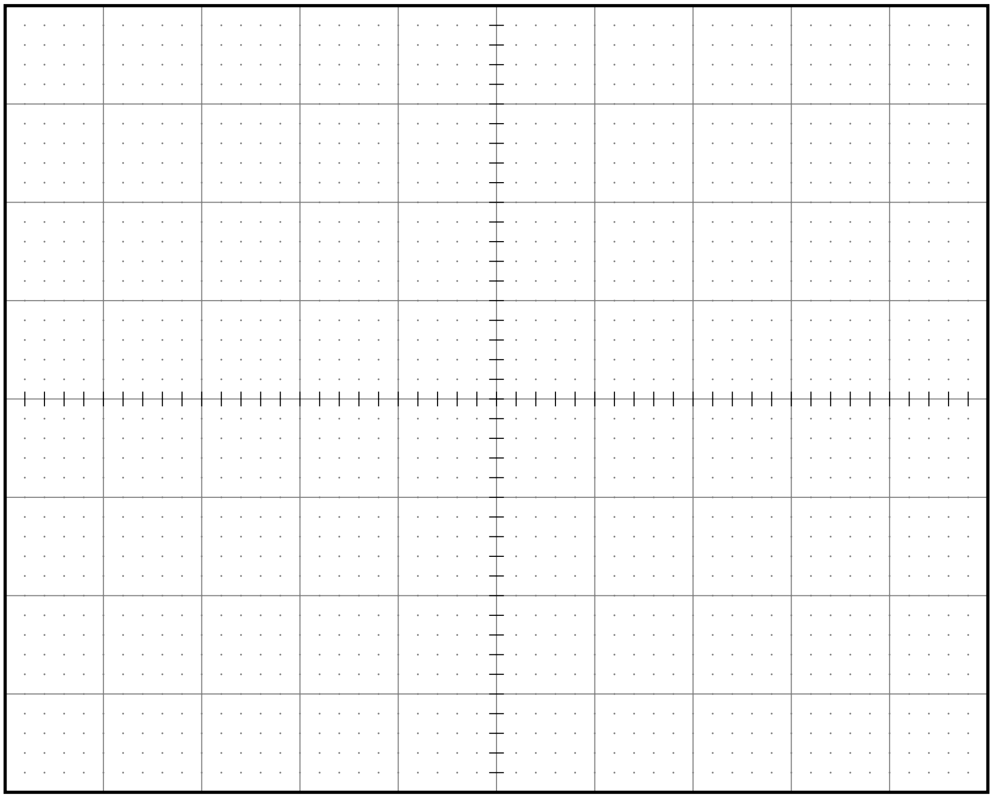
(b) ($1/2$ point) What does average voltage spacing physically correspond to?

Question 6 **2 points**

Sketch the current versus grid voltage as seen in the oscilloscope. Add a title, axis labels, and units.

Alternatively, you can save the oscilloscope window in picture format and attach it to your hand-in.

Graph 1: *Current versus grid voltage* $V_{G2,K}$.



Data Analysis (10 points)

Question 7 **1 point**

How much energy is required to excite an electron in the valence shell of Argon to its first excited state?

Question 8 **2 points**

Atoms do not stay in their excited states for long. After some time, the excited Ar atoms return to the ground state by releasing excess energy in the form of electromagnetic radiation. If you were to measure the frequency of radiation from your Franck-Hertz experiment, what would be the frequency?

Question 9 **2 points**

Suppose you want to excite Ar to the first excited state by shining electromagnetic radiation on it. What should be the wavelength of the radiation?

Question 10 **1 point**

If everything went correctly, you should have seen that the current at the higher-order dips was greater compared to the current at the lower-order dips. What could be the reason?

Question 11 **1 point**

How might contamination of other gases in the tube affect your result?

Question 12 **3 points**

What is your overall conclusion about energy levels in the atom/atomic model from this experiment? Describe its connection to Bohr's atomic model.