Collisions between Gas-Phase *Atoms*
& Accelerated *Electrons*

Here, you'll review *LabVIEW* data capture and *Igor Pro* analysis

Before coming to lab, you must *check de Podesta's index* for details on:

- **Mean free path *vs*. GAS pressure (Your pre-lab generalizes this for *electrons*)**
- **Crook's Dark Space**

Articles you find in *American Journal of Physics*, either on the Franck-Hertz experiment or on the Ramsauer Effect, could easily turn you into an experimental *GOD!*

According to the quantum theory only certain **discrete energy states** are allowed in an atom. Today's lab is a *test* of this claim. If an atom is to make a transition from the ground state to an excited state, it must absorb an amount of energy exactly equal to the energy difference between those two states. We call this amount the excitation energy.

Suppose a free electron collides with an atom. If the electron's kinetic energy is less than the excitation energy, then the atom cannot make a transition to the excited state. But if the electron's energy is greater than the excitation energy, then a transition can occur. A very energetic electron may be able to excite a number of atoms, for each time it collides with an atom its kinetic energy is diminished by only an amount equal to the excitation energy, normally a few electron volts (4.88 eV in mercury). [Note: we have versions of this experiment using a variety of vapors: mercury, neon, xenon, and argon. While this write-up details the particular version that uses mercury vapor, the others are similar *in spirit*, though not in strict detail.]

The basic setup of this experiment is as described in your Modern Physics textbook. You will accelerate electrons through a potential difference that you may vary from 0 to about 35 volts. This is done within a sealed tube containing a small amount of gas-phase atoms (in the case of mercury vapor, the whole tube is enclosed in an oven for the purpose of vaporizing the mercury). After passing through the gas, electrons are collected on a plate and are registered as current. The current is turned into a readable output signal (voltage) by the "black box" control unit.

Procedure: (While this was originally written with the mercury tubes in mind; we also have neon and argon and xenon tubes, which are already gases at room temperature, so you don't have to heat them up, … or wait for thermal equilibrium!)

1. **As you enter lab**, turn on the oven and allow it to warm to about 200 degrees. Keep an eye on the thermometer and adjust the thermostat accordingly; do not trust the thermostat readings. Allow a **20-minute warm-up period** before proceeding to the next step.
2. On the main control unit set the gain at maximum and the zero at midrange. Make sure the accelerating voltage is on "manual" and the voltage adjust is initially zero. Let the unit **warm up for a few minutes**.
3. Slowly turn the accelerating voltage from 0 to 30 volts. As you do so watch the output voltage for the characteristic Franck-Hertz dips at roughly 4.9-volt intervals. You may want to attach an analog voltmeter or the *x-y* plotter at this stage for a better visual representation of the output (this is one purpose for which a standard digital voltmeter is definitely not well suited!).
4. Take data (output voltage as a function of accelerating voltage) on the *x-y* plotter.
5. When finished turn off everything in reverse order.

Questions

1. The first peak you see may not be at 4.88 volts or a multiple thereof (even though subsequent peaks should occur at 4.88 volt intervals). Why not?

2. Mercury atoms should not remain in an excited state for long. Compute the wavelength of the radiation emitted when they return to the ground state.

3. If you answered Question 2 correctly, it should be a value in the **ultraviolet** portion of the spectrum. But consider the fact that you have run mercury vapor lamps before, and they definitely have several wavelengths in the **visible** part of the spectrum. Since transitions that produce visible photons are of lesser energy than those producing ultraviolet photons, why don't these transitions show up at less than 4.88-eV intervals in your Franck-Hertz data?

CENCO's OPERATING INSTRUCTIONS
for the
"Complete Franck-Hertz Experiment"
(Catalog No. 32047)

I. Introduction: You can use the modular components of this apparatus to duplicate the 1926 Nobel Prize winning experiment originally performed in 1913. The Franck-Hertz experiment verifies the concepts of quantum theory with an impressive proof. On your oscilloscope screen, well-defined periodic and equidistant maxima and minima show the quantum levels of mercury as the electrode current produced by the control unit excites the mercury resonance line at a 253.7 nm wavelength

II. Description: The Complete Franck-Hertz Experiment includes a mercury Franck-Hertz tube, an oven with a built-in temperature controller, a control unit, and a shielded cable with BNC connectors. You will need to supply an oscilloscope with an *X-Y* facility, such as our Dual-Trace 20 MHz Oscilloscope (Cat. No. 32046), and a thermometer with a 240 °C range. An alternative equipment setup using two voltmeters instead of an oscilloscope is presented in Section 3B.

A. The mercury Franck-Hertz tube is a 3-electrode tube with an indirectly heated oxide-coated cathode, a grid-form anode and a collector electrode. The electrodes are arranged in a plane-parallel format. The 8-mm distance between the anode and the cathode is large compared to the *mean free path* length of an electron in the mercury vapor atmosphere (190 °C); this ensures a high collision probability. [Think about this!]

During manufacturing, the mercury tube is provided with a highly activated contact getter and exhausted to high vacuum. The getter ensures a long tube life free of energy-consuming contamination gas.

The envelope wall between the anode and the collector electrode carries a vacuum-proof sealed-in protective ring made of sintered carborundum (a trademark name for silicon carbide). This ring prevents leakage currents via the ion-conducting hot glass wall. The tube contains a drop of highly purified mercury.

B. The oven consists of a steel-plated cabinet with the dimensions 24 × 16 × 14 cm. The oven is heated with a tubular radiator mounted on its floor. Its power consumption is 400 watts. You use the bimetal switch, which can be adjusted with a control knob from the exterior, to set and stabilize the oven temperature.

CAUTION! Only connect the oven heater to a 110 Volt AC supply. If you connect the oven to a DC supply, arcing will damage the bimetal contact when the circuit is active.

C. The control unit provides all voltages required for performing. the Franck-Hertz experiment. It also contains a *highly sensitive* DC amplifier for measuring the collector current. It's very simple to set up the apparatus using the control unit. Just make four connections to the Franck-Hertz tube and hook up the measuring equipment.

The power supply component of the control unit delivers:

1. The accelerating voltage U_b, which is a DC voltage which is continuously variable from 0 to 60 V (available when you switch U_b to the "-" setting).

2. The filament heating voltage for the tube U_H, which is an AC voltage ranging up to 8 V. The filament current is adjustable from 270 - 350 mA.

3. The opposing voltage U_G, which is a DC voltage continuously variable from 0 to 1.5 V. [Larger U_G yields less noise, but if U_G is *too* large you lose signal]

The control unit also has the following voltage controls, so you can display the Franck-Hertz curve on a cathode ray oscilloscope screen:

4. A sawtooth-waveform accelerating voltage, U_b, with a maximum amplitude adjustable from 0 - 70 $V_{p\text{-}p}$ (available when you switch U_b to the "ramp" setting).

5. Voltage for the *x*-deflection on the oscilloscope; this is a "half-wave" voltage (*i.e.*, it is obtained by half-wave rectification), and is equal to (U_b/10).

The DC amplifier included in the control unit consists of two cascaded operational amplifiers (integrated circuits). You use the first amplifier as an *electrometer* amplifier. The current to be measured is applied to the non-inverting input. The input impedance is 680 kΩ. The gain can be adjusted with a variable negative feedback resistance.

The second operational amplifier amplifies the signal further and inverts it. The output display voltage is proportional to the measured current. A 1.0-volt output voltage corresponds to a 0.7 pA input current at the minimum sensitivity setting (*i.e.*, when the control knob is turned to the far left), and to a 7 nA input current at the maximum sensitivity setting (*i.e.*, when the control knob is turned to the far right).

III. Setup and Operation: If you are using an oscilloscope, follow the instructions in Section A. Section B describes an alternative procedure using two voltmeters to measure the output, allowing students to collect and plot the data themselves.

Using the oscilloscope method *prior* to using the voltmeter method can be beneficial for students. It lets them view the Franck-Hertz curve on the oscilloscope screen, providing a means of comparison when they plot their own curves using the voltmeter data.

A. Oscilloscope Method: Make sure the power is turned off before making connections. Again, all connections should be made with the power turned off! Connect the control unit to the measuring oscilloscope as shown in Fig. 1. Connect the voltages as follows:

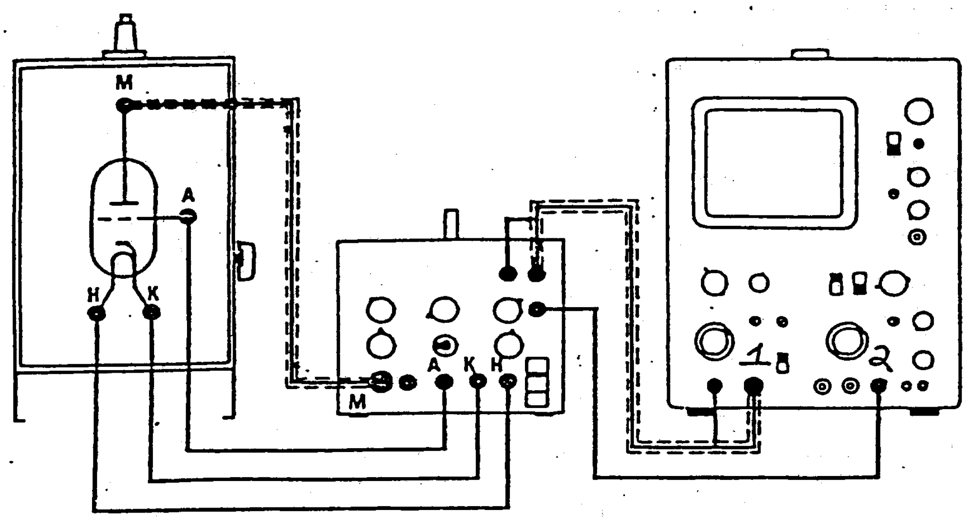
1. Connect the accelerating voltage, U_b, across the tube's cathode (-), and anode (+) by connecting "K" on the control unit to "K" on the oven face. Similarly, connect "A" on the control unit to "A" on the oven face.

2. Connect the filament heating voltage, V_h, across "H" and "K" on the tube; that is, connect "H" on the control unit to "H" on the oven face.

3. Connect the opposing voltage, U_G, from "M" on the control unit to "M" on the oven. To reduce electronic noise, use the shielded cable with BNC connectors.

4. Connect the oscilloscope according to Fig. 1: from (V_+) to Channel 1 (y-deflection), and from (U_b/10)) to Channel 2 (x-deflection). Also connect from (V_-) to the ground of the oscilloscope.

5. Set switch U_b to the "ramp" setting.



To perform the Franck-Hertz Experiment, first connect the heating oven to a grounded AC line voltage using the supplied main cable. Set the bimetal contact switch to the desired temperature (*e.g.*, 190 °C). To read the temperature, insert a thermometer into the center of the oven. The oven initially "hunts" for the temperature set on the control knob by cycling on and off until it finds it. **The oven will take about 10 - 15 minutes to stabilize** at the set temperature.

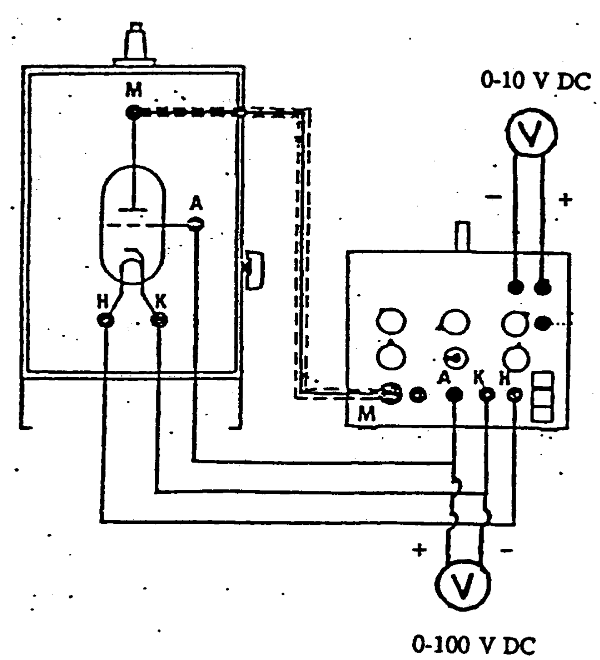
Switch on the operating unit. Make sure that the black toggle switch for U_b is set to the "ramp" position. Set the red acceleration control knob for U_b to zero volts. Set the filament "adjust" knob about midway. Set the signal "gain" knob to the *maximum* sensitivity by turning it to the right as far as it will go. Adjust the "opposing voltage" knob so the meter reading is zero (or less) at the amplifier output (V_+, V_-).

The indirectly heated **cathode requires a warm-up time of about 90 seconds** after you switch on the operating unit. Slowly increase the accelerating voltage (starting from zero volts) while reducing the "gain" setting to prevent the output from saturating the amplifier. Amplifier saturation is indicated by the waveform peaks becoming "clipped" on your oscilloscope display.

The Franck-Hertz curve should appear on the oscilloscope screen. To improve the display, carefully adjust the "gain" control and the cathode temperature "heater" control settings. Make sure that the accelerating voltage is set such that no self-sustained discharge occurs inside the tube. This discharge would be indicated by a rapid rise in the output voltage.

The measuring amplifier's output is displayed on Channel 1 of the oscilloscope via the “FH signal out” (V_+) and the ground (V_-) terminals on the control unit. The indicated collector current shows equidistant minima as a function of the accelerating voltage. For information on the theory involved in this experiment, see Section 5.

B. Voltmeter Method: This alternative method requires students to plot their own Franck-Hertz curves. You may disregard this section if you are only going to use an oscilloscope to display the Franck-Hertz curve. Make all connections with the power turned off, as shown in Fig. 2. Connect the voltages as follows:



1. Connect the acceleration voltage, U_b, across the tube's cathode (-), and anode (+) by connecting "K" on the control unit with "K" on the oven face. Similarly, connect "A" on the control unit to "A" on the oven face.

2. Connect the filament heating voltage, V_h, across "H" and "K" on the tube; that is connect "H" on the control unit to "H" on the oven face.

3. Connect the opposing voltage, U_G, from "M" on the control unit to "M" on the oven. To reduce electronic noise, use the shielded cable with BNC connectors.

USE a LabVIEW-based *XY graph* INSTEAD OF STEPS 4 and 5:

4. Connect a voltmeter capable of measuring 10 volts DC across the amplifier output (V_+, V_-).

5. Connect a second voltmeter capable of measuring between 0 and 70 volts DC across the accelerating voltage, U_b (A, K).

6. Set the black toggle switch for U_b to the "-" position. This step makes the accelerating voltage, U_b, straight DC instead of ramped DC.

To perform the Franck-Hertz Experiment, first connect the heating oven to a grounded AC line voltage using the supplied main cable. Set the bimetal contact switch to the desired temperature (*e.g.*, 190 °C). To read the temperature, insert a thermometer into the center of the oven. The oven initially "hunts" for the temperature set on the control knob by cycling on and off until it finds it. **The oven will take about 10 - 15 minutes to stabilize** at the set temperature.

Switch on the operating unit. Verify that the toggle switch for U_b is set on the "-" position. Set the red acceleration control knob for U_b to zero volts. Set the filament "adjust" knob about midway. Set the signal "gain" knob to the *maximum* sensitivity by turning it to the far right. Adjust the "opposing voltage" knob so the meter reading is zero (or less) at the amplifier output.

The indirectly heated **cathode requires a warm-up time of about 90 seconds** after you switch on the operating unit.

Collect data by recording the accelerating voltage, U_b, and the amplifier output V_+ as you increase the accelerating voltage from 0 to 70 volts in 1-volt increments. Then, to produce the Franck-Hertz curve, use curve-fitting software to plot the data points. For more information on the theory involved in this experiment, see Section 5.

4. Notes on Operation: The emission current in the tube and the collector electrode current are affected by the cathode's temperature. If the current is too small, it can be increased by increasing the cathode heater voltage (*e.g.*, to 8 V).

A 10 kΩ resistor in the tube's anode circuit prevents the tube from overloading. Thus, the tube is not endangered even if a discharge (by collision ionization) occurs inside it (due to excessively high applied voltages).

To verify from the spectrum that the gas filling the tube is mercury vapor, you can observe the luminous discharge with a spectroscope through the glass side panel.

The Franck-Hertz tube is mounted on the rear side of the front panel so the entire tube, including the connecting wires, is heated to a constant temperature. This is absolutely essential because the vapor pressure of the mercury is always determined by the temperature of the tube's coldest point. Plots of the vapor pressure of mercury as a function of temperature are available in the laboratory.

The front panel carries the ceramic-insulated connecting sockets for the tube. The collector electrode is connected to a BNC-type jack, which is connected to the shielded lead of the operating unit (measuring amplifier). The tube's designation is marked in **bold** lines on the front panel, and the connections are marked by *thinner* lines. You can observe the tube and the heater spirals through the oven's two windows. The oven's cover plate has a hole for inserting the thermometer, which is held in place with a clamp spring.

A permanent 10 kΩ current-limiting resistor is located between the connecting socket for the accelerating voltage and the tube's anode. This safety resistor protects the tube in case a continuous discharge occurs inside it when an excessively high voltage is applied. For normal measurements, the voltage drop across the safety resistor can be ignored because the tube's working anode current is less than 5 μA (*i.e.*, the voltage drop across the safety resistor is less than 0.05 V).

The front panel *with the tube* can be taken off after releasing the six milled screws. Thus, you can use the oven for other purposes such as the sodium fluorescence experiment.

5. Theory: The Franck-Hertz Experiment makes it possible to observe the energy transitions produced by collisions between electrons and mercury atoms. The tube contains a small amount of mercury, some of which vaporizes when you heat the tube in the oven. At 180 °C, the mercury vapor pressure is about 20 millibar. (Again, plots of the vapor pressure of mercury as a function of temperature are available in the laboratory.)

The oxide-coated, heated cathode emits electrons. The kinetic energy of these electrons increases as the accelerating voltage (U_b) is increased. Consequently, the electrons fly through the grid-form anode and then against an opposing voltage of 1.5 V to the collector electrode. Typically, only around 10^{-10} amps of current flows from the collector electrode to the anode. The measuring circuitry must amplifies this signal substantially, and there is always the danger, in dealing with low-level signals, that any “extraneous noise” might *also* be amplified!

Initially, the collisions between electrons and mercury atoms occur elastically, without significant energy transfer to the mercury atoms. However, when the accelerating voltage is increased significantly, the electrons' kinetic energy is large enough to excite the mercury atoms directly in front of the grid-form anode. The electrons lose their kinetic energy and can no longer reach the collector electrode against the braking voltage (-1.5 V). Thus, the current reading given by the measuring amplifier decreases.

When the accelerating voltage is increased further, the collision zone moves closer to the cathode. The electrons braked by collisions are accelerated again. Thus, they can reach the collector electrode until their kinetic energy has become so large they are braked by a second non-elastic collision with a mercury atom. This energy transfer recurs periodically with an increasing accelerating voltage.

On the Franck-Hertz curve, this periodic energy-transfer is indicated by the recurrent and equidistant maxima and minima of the collector electrode current as a function of the accelerating voltage. The minima are spaced at intervals of 4.9 V, showing that the excitation energy of the mercury atoms is 4.9 eV.

The spectral frequency corresponding to this energy is:

$$\nu = \frac{E}{h}$$

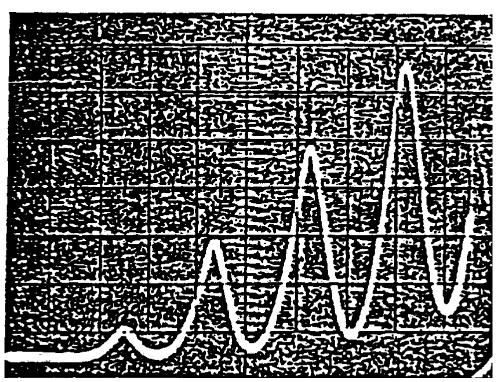
where:

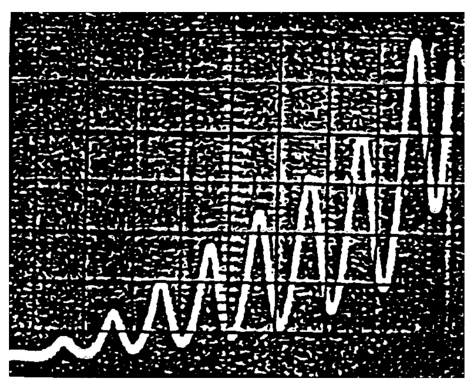
$$\frac{E}{h} = \frac{4.9 \text{ eV}}{4.136 \times 10^{-15} \text{ eV} \cdot \text{s}} = 1.18 \times 10^{15} \text{ Hz}$$

and the corresponding wavelength is:

$$\lambda = \frac{c}{\nu} = 253.7 \text{ nm}$$

Franck and Hertz verified the presence of this ultraviolet radiation with the aid of a spectrograph. (Normal glass lenses absorb UV radiation, but quartz does not - so the lenses of their spectrograph were made of quartz). A contact potential of about 2 V exists in the tube between the cathode and the anode. Thus, the first current minimum lies at about 7 V.





Figures 3 and 4 show the collector current as a function of the accelerating voltage. The form of the curve depends strongly on the oven temperature. At low temperatures (around 160 to 185 °C), the first minima are developed more fully, but the curve rises rapidly so only the first few peaks are seen (see Fig. 4). The tube produces a continuous discharge at about 30 V. At higher oven temperatures (185 to 200 °C), more minima are obtained, but at a lower current range. Eventually, the first minimum becomes less defined and may even be undetectable.

DATA SHEET

There should be at least 7 clear minima on your *x-y* graph if you are using mercury vapor, but only three for Neon.

Total voltage difference between, say, FIVE (5) consecutive minima: ________________ volts

Average voltage between successive minima: ______________________ volts

Voltage corresponding to UV line of 253.7 nm: _____________________ volts

Error: ________________ %

Use this space for a compelling display of initiative and insight:

Specific **Conclusions and Critical Analysis:**